Journal of Stored Products Research 104 (2023) 102187

Contents lists available at ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

Quality and mass transport properties of sugar beet roots under short duration, high airflow post-harvest storage

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ARTICLE INFO

Handling Editor: Dr Manoj Nayak

Keywords:
Convective mass transfer
Diffusivity
Dehydration
Forced ventilation

ABSTRACT

Active ventilation of stored sugar beet roots is used to control system temperature and slow the loss of quality that occurs with plant respiration and the growth of pathogens. Ventilation can at the same time increase rates of dehydration and dehydration related stresses of the stored sugar beet roots. Recent research into the use of forced ventilation to modify temperature in in-field sugar beet root stores has suggested that a controlled dehydration of roots could lead to improvements in quality. This work aimed to investigate the impacts to sugar beet root quality from short-term, high volume airflow during post-harvest storage. A modified environment experimental setup was developed. The experiment tested four airflow rates over three levels of ventilation duration, with the longest duration being seven days. Air temperature and relative humidity was constant within each seven day run, but varied between runs. Results showed that a mean weight loss of 11.7% with a corresponding increase in sucrose content of 13.2% was achieved at the highest airflow rate and ventilation duration. These changes in quality were a result of the transfer of water from the sugar beet roots. No reduction in total sucrose or other quality parameters was observed. The dependence of the rate of water transfer from the roots on airflow rate was quantified as the convective mass transfer coefficient. Estimates are given and cross-validated using dimensional analysis.

1. Introduction

Harvested sugar beet roots are stored as a bulk as a means of minimising losses of extractable sugar during the phase between when growth stops and processing can occur. In Europe, post-harvest storage generally occurs in-field in systems referred to as clamps. Clamps are generally up to 9 m wide, 3 m high, and can be hundreds of meters in length. The in-field location and the size of these clamps means they are exposed to natural weather variations. The application of different covers is the main management strategy for modifying the storage environment in clamps. In North America, a larger storage system located at the processing plant is commonly employed. These can be, for example, 5 m in height and 25 m in width (Shaaban, 2020) and are referred to as piles. Forced ventilation has been employed in the piles of North America as a means of controlling temperature and reducing storage losses since at least the 1940s (see for example Downie (1950) or Hansen (1950)). In Europe, projects by the national sugar beet research organisations in the Netherlands and in Sweden have investigated forced ventilation for the in-field clamp storage system (Ekelöf and English, 2022; Leijdekkers, 2020). Under natural ventilation in the open environment, all sugar beet root storage systems are exposed to higher airflow at the outer edges of the bulk.

With increased airflow comes increased dehydration of the stored sugar beet roots (Cannon, 1950). The transfer of water from the stored root to the surrounding environment - i.e. dehydration - is driven by the conditions at the interface of these two phases. This includes both the vapour pressure differential between the phases (Δc) and the resistance of the surface the water must pass over. The vapour pressure differential depends on the relative humidity and temperature. Forced ventilation in post-harvest storage system will often result in air of lower relative humidity entering the storage bulk. The resistance of the surface is defined as the convective mass transfer coefficient (CMTC, k_c). In the study of post-harvest storage systems, the CMTC is commonly modelled through the Lewis analogy which equates k_c to the convective heat transfer coefficient (see for example Hoang et al. (2003)), or it is assessed by dimensional analysis coupled with experimentation. The dimensional analysis approach sees the application of the Sherwood-Reynolds-Schmidt correlation (Carta, 2021). The

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https://doi.org/10.1016/j.jspr.2023.102187
Received 30 June 2023; Received in revised form 28 August 2023; Accepted 12 September 2023
Available online 25 September 2023

Sherwood-Reynolds-Schmidt correlation allows experimental data on weight loss per unit surface area and time (mass flux, $\dot{m}_w$) to be equated to known physical properties of air, the air speed (U), a baseline level of resistance (diffusivity, D_{ab}), and the size of the object being stored (L). The physical properties of air include density (ρ) and dynamic viscosity (μ). The objects of study are often assumed to be spherical in shape, and thus L will be the equivalent diameter of the object. Estimates of diffusivity and CMTC for sugar beet roots are not available in the literature. Estimates are available for many fruits and vegetables such as pears (Xanthopoulos et al., 2017), pomegranate (Caleb et al., 2013), grape tomatoes (Xanthopoulos et al., 2014) and mushrooms (Mahajan et al., 2008).

Dehydration can affect the processing quality and the economics of sugar beet roots. To assure a good industrial process, sugar beet roots should have a high sucrose content and a low content of invert sugars (fructose and glucose) and soluble non-sugars such as K, Na and α-amino acids; that is, be of high quality. Dehydration of stored sugar beet roots has been shown to stress metabolic pathways and negatively impact quality parameters. Pack (1926) was one of the first to observe the negative effects dehydration had on quality, and tested the rates of weight loss in sugar beet roots packed in sand. Bugbee and Cole (1979) were some of the first to empirically test the effects of dehydration for roots stored in air, showing it caused an increased loss of total sucrose over long storage periods (106 days at 10 °C). According to Lafta and Fugate (2009), sugar beet roots stored at low relative humidity (40 %r.h.) and 10 °C had a significantly higher respiration rate and thus total sucrose loss compared to those stored at 85 %r.h. Lafta et al. (2020) reported that mildly dehydrated sugar beet roots (stored at 85 %r.h. for 28 days) showed an increased raffinose concentration, while severely dehydrated roots (stored at 40 %r.h. for 28 days) showed reduced levels of raffinose and several other compounds involved in carbohydrate metabolism and respiration. Interestingly, they also showed that the invert sugars were almost unaffected by dehydration. Apart from an impact on the carbohydrate metabolism, long-term storage may increase the hydrolyzation of proteins, leading to a higher amino N content that could impair the sugar quality (Vukov and Hangyal, 1985). Outside of the metabolic pathways, the mechanical properties of sugar beet roots have been linked to quality after storage, with varieties that test higher for penetration resistance also losing less sucrose during storage (Hoffmann et al., 2022). Gorzelany and Puchalski (2000), Nedomová et al. (2017), and Kleuker and Hoffmann (2022) have all looked at the changes to mechanical properties during storage but have contrasting results: the former found decreases, while the later two found increases in tissue strength during storage. From Nedomová et al. (2017) it can also be concluded that the apparent modulus of elasticity - the force required to penetrate the surface divided by the distance the surface moves during testing - increased with storage duration. Following Vukov (1977), this would lead to increased difficulties in slicing the roots at processing.

There may also be benefits to an induced dehydration. Cannon (1950) observed that managing dehydration in commercial storage piles could be used to better manage temperature. The payment schedules of many commercial processors of sugar beet incentivise higher quality, while also including disincentives for the delivery of non-processable material. This non-processable material is known commercially as dirt-tare and includes leaf material, small or rotten root material, soil, and the water in the soil. If water can be removed from the roots without causing an increased loss of sucrose or an increase in the non-sucrose component, the quality of the roots increases. Further, the removal of water from the dirt-tare component could potentially decrease its weight at delivery.

The aim of this current work was to investigate whether airflow could be used to remove water from a bulk of sugar beet such that the quality of the bulk improves. Quality parameters were assessed using commercial testing procedures and included: sample weight; the content in the roots of sucrose, N, K, Na and dry matter; dirt-tare; and mechanical properties. To support the analysis of quality, root density was also assessed. Estimates for the degree to which the rate of water removal and thus changes to quality depend on the magnitude of airflow were also sought. This was quantified as the convective mass transport coefficient of whole sugar beet roots. For this purpose, a modified atmosphere experiment was established in Sweden during the 2019-20 sugar beet campaign in which airflow rate, duration of ventilation, humidity and temperature were controlled or modified during five one-week periods of storage. Each week had the same duration and airflow rate treatments, but temperature and humidity were varied.

2. Method

2.1. *Sugar beet material*

Sugar beet was grown under commercial management during the 2019 growing season, in a field in Sweden with loam soil, at 55.663N, 13.191E. The variety was a market leading high root yield variety, known to score low with respect to mechanical properties. The sugar beet roots were harvested on 15 October and 9 November with a self-propelled harvester, with normal levels of harvester cleaning. They were stored for up to three weeks in a bulk under commercial conditions until sampling. At sampling, the outer layer of roots was removed from the bulk to minimise any pre-ventilation dehydration. Samples were of 25 roots and a target net weight of 30 kg.

2.2. *Modified atmosphere ventilation experiment*

2.2.1. *Modified atmosphere system*

The modified atmosphere ventilation experiment was undertaken in a custom built system. The system allowed temperature and relative humidity to be modified using a refrigerated shipping container, heaters, and humidifiers or dehumidifiers (Fig. 1). Air was forced with a 2.2 kW centrifugal fan and distributed using a system of distributors (Fig. 2). The primary distributor had valves to limit airflow to the three secondary distributors. Each secondary distributor had 16 outlets, each of which lead to an open top box upon which a ventilation box sat. Ventilation boxes were 91 l, with dimensions of 0.365 × 0.570 m (W x L), hydraulic diameter of 0.445 m, and had 47% air by volume at the level of the ventilation grate. Airflow through the system was monitored using grid sampling in the inlet pipes to the secondary distributors and single measurements on each outlet of the secondary distributors.

2.2.2. *Treatments*

The experiment ran across five week-long runs. *Run* 1 and 2 sampled roots from the first harvest, and Run 3, 4 and 5 from the second harvest. Temperature and humidity had target values that varied between each Run. Actual temperature and relative humidity was monitored continuously using HOBO U23 Pro v2 loggers (Onset, Bourne, MA, USA) and is reported in Table 1. Mean water vapour pressure deficits (Δc) are also reported in Table 1. Airflow and duration treatments were fixed within each Run, and each airflow:duration treatment combination was in four replicates. Airflow was delivered to the ventilation boxes at four rates of 0, 11.2, 46.5 and 81.5 $m^3\ h^{-1}$ (Table 2). These treatment levels are hereafter referred to by their approximate relative levels, as *Air* 0, 1, 4 and 7, respectively. These values represent a zero airflow control and the airflow rates at approximately 1.5, 1.0 and 0.5 m from the ventilation pipe in a commercial clamp ventilation system under development in Sweden at the time of this experiment. Duration of ventilation - referred to as *Days* - was set at 1, 4 and 7 days. A Days 0 control was sent directly for quality analysis, with six replicate samples analysed per Run. At the end of each duration treatment, the four replicate ventilation boxes were removed from dispersed points on each of the secondary distributors, prepared for quality analysis, and refilled to ensure minimal disruption to the airflow distribution.

Fig. 1. Airflow through climate control system. Ground level, facing South. Fan, heaters, de-/humidifiers housed in shipping container. Photo taken during construction - ventilation boxes are not in position (see Fig. 2), enclosure only partially constructed.

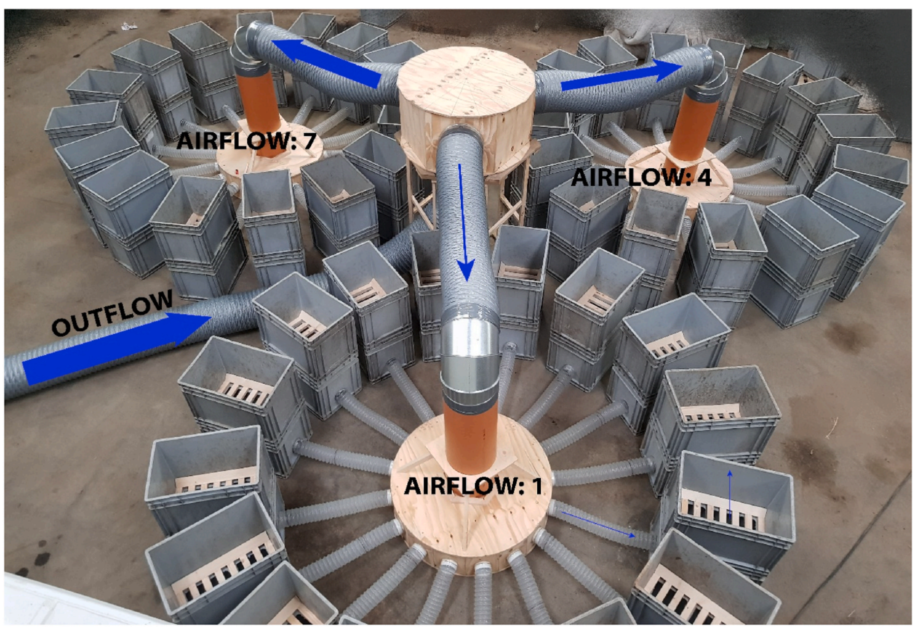


Fig. 2. Airflow distribution in ventilated storage system. From above, facing West. Grates in ventilation boxes shown.

2.2.3. *Washed roots and soil*

In addition to the roots taken directly from the harvester (*normal roots*), two replicates of *washed roots* and of *soil* were included in each Air treatment (Fig. 3). These samples were included in the system to give indication if the mass transfer properties of roots are dependent on the attached soil. The roots were washed by hand with a high volume, low pressure water flow to minimise surface damage. These samples had the same pre-washing initial weight as the normal samples, were weighed at Days 1, 4 and 7 and sent for quality analysis only after Days 7. The samples of soil were taken from a bulk dug at harvest and kept in an air-tight box, had initial net weights of 3.0 kg per replicate, and were weighed with the washed roots.

2.3. *Analysis*

2.3.1. *Cleaning effect*

A simulated cleaning of roots was conducted immediately post-ventilation and prior to delivery for quality analysis, by rolling the roots down inclined rubber mating with a short fall at the end (Fig. 4). The weight difference between pre- and post-cleaning is termed *weight cleaned*. Weight cleaned is reported as decagrams per kilogram clean sugar beet root pre-ventilation (dag kg_{int}^{-1}). The units dag kg_{int}^{-1} are used here and elsewhere to permit a comparison at the level of harvest weight so as to directly show any changes to the parameter as a result of the ventilation treatment. These units are equivalent to percent by harvest weight (e.g. 0.54 dag kg_{int}^{-1} can also be read as 0.54% w/w). Any change to weight cleaned will include changes to the water content of the soil on the root surface.

Table 1
Mean temperature, relative humidity and water vapour pressure deficit during the experiment, by Run and Days.

Run	Days	Mean Temperature	Relative Humidity	Water vapour pressure deficit
		°C	%r.h.	mol m^{-3}
1	1	12.6	91.6	4.25E-02
1	4	12.3	90.2	5.02E-02
1	7	12.0	89.9	5.09E-02
2	1	11.6	87.1	6.59E-02
2	4	11.5	87.3	6.40E-02
2	7	11.6	84.8	7.87E-02
3	1	7.0	82.9	6.70E-02
3	4	7.0	82.1	7.08E-02
3	7	7.1	79.8	8.09E-02
4	1	6.9	86.9	4.95E-02
4	4	6.9	86.4	5.19E-02
4	7	6.6	86.5	5.04E-02
5	1	5.9	79.7	7.55E-02
5	4	6.0	78.8	7.94E-02
5	7	6.3	77.9	8.46E-02

Table 2
Flow of air applied in the experiment, by Air treatment. ε = porosity of ventilation boxes.

Air	Airflow rate per box	Superficial velocity	Physical velocity at ε = 0.465
	m^3 h^{-1}	m s^{-1}	m s^{-1}
0	0	0	0
1	11.2	1.49E-02	3.22E-02
4	46.5	6.21E-02	1.34E-01
7	81.5	1.09E-01	2.34E-01

2.3.2. Mechanical properties

The mechanical properties of the normal roots were assessed post-cleaning and prior to quality analysis using a handheld penetrometer with a 2 mm cylindrical probe, to a depth of approximately 5 mm (English et al., 2022). Maximum resistance is recorded and is here referred to as *firmness* (Abbott, 1999). The handheld penetrometer does not give the range or detail of metrics of a laboratory penetrometer as outlined in Kleuker and Hoffmann (2019), but was practically the most suitable device for this experiment.

2.3.3. Quality

Quality was assessed in the commercial analysis laboratory of Nordic Sugar in Örtofta. Sucrose content was determined polarimetrically (ICUMSA, 1994). Alpha-amino nitrogen (N) was determined from the "blue-number" (ICUMSA, 2007a). Potassium (K) and sodium (Na) content was determined by flame photometry (ICUMSA, 2007b). Dry matter percent is achieved by drying to a stable weight. The analysis of invert sugars was not possible. Total sucrose is computed as the net sample weight multiplied by the sucrose content and reported as decagrams per kilogram clean sugar beet root pre-ventilation (dag kg_{int}^{-1}). Dirt-tare percent is reported here simply as (gross weight - net weight)/gross weight x 100, and does not include the industry agreed additional fixed deduction applied in commercial operation in Sweden.

2.3.4. Root density

During Run 1, 2, 3 and 5, the roots used to refill the ventilation boxes after Days 1 were also used to assess changes to the density of individual roots. 10 roots with a target weight of 1.0 kg each were assessed at the start and end of the run (6 days of ventilation) from both Air 0 and 7. Volume was calculated as the weight of water dispersed during the immersion of the root.

2.3.5. Mass flux and convective mass transfer coefficients

Mass flux and the convective mass transfer coefficients were calculated assuming an idealised single spherical sugar beet root, using average per root data from the experiment.

Convective mass flux of water per root is given as

$$\dot{m}_w = k_c \Delta c \left[\text{mol m}^{-2}\ \text{s}^{-1}\right] \quad (1)$$

where k_c is convective mass transfer coefficient [m s^{-1}], and Δc is the water vapour pressure deficit [mol m^{-3}]. Assuming thermal equilibrium

Fig. 3. Examples of the three different materials during ventilated storage. Left: soil. Middle: Normal sugar beet roots. Right: Washed sugar beet roots.

Fig. 4. System for simulated cleaning of sugar beet roots in the experiment.

between the air and the roots, Δc can be calculated from Tetens equation (Monteith and Unsworth, 2008) as

$$\Delta c = (a_w - r.h.) \times 6.1078 \times e^{\frac{17.27\times(T-273.15)}{T-36}} \times \frac{1}{R \times T} \quad (2)$$

where a_w is the water activity of the solid [%] and can be assumed 98.5% for fresh sugar beet roots (Chirife and Fontan, 1982). *r.h.* is the relative humidity [%] and *T* is the dry bulb temperature [K]. *R* is the gas constant, 8.314472 m^3 Pa mol^{-1} K^{-1}. The water vapour pressure deficit is reported in Table 1. k_c can then be calculated for all samples using the mass flux values from the experiment.

When mass flux values are not available, the Sherwood-Reynolds-Schmidt correlation can be considered. This will permit the estimation of mass flux as a function of airspeed. The dimensionless Sherwood number is given as

$$Sh = \frac{k_c L}{D_{ab}} \quad (3)$$

where *L* is the characteristic length [m], and D_{ab} is mass diffusivity [m^2 s^{-1}]. The Sherwood-Reynolds-Schmidt correlation as applied to a sphere is given as

$$Sh = 2 + 0.552 Re^{0.5} Sc^{0.33} \quad (4)$$

where *Re* is the Reynolds number and *Sc* the Schmidt number. The Reynolds number for a sphere is defined as

$$Re = \frac{\rho_{air}\, U\, L}{\mu} \quad (5)$$

where ρ_{air} is the density of air for the mean treatment temperature [kg m^{-3}], *U* is the velocity magnitude [m s^{-1}], *L* is again the characteristic length and μ is the dynamic viscosity of air for the mean treatment temperature [kg m^{-1} s^{-1}]. *U* is taken as the physical velocity at a porosity (ε) of 0.465 (Table 2). While the porosity of an infinite stack of sugar beet roots has been estimated at 0.45 (Tabil et al., 2003), at a channel-to-particle ratio of approximately 3.5 ($D_h/L = 0.445/0.127$) it is expected that the confinement effect on fluid flow is significant (Eisfeld and Schnitzlein, 2001). This is considered currently simply by ensuring the increased porosity at the walls is considered in the calculation of porosity and thus physical velocity. *L* is taken as the equivalent diameter of the sphere [m]

$$L = (6V\pi)^{\frac{1}{3}} \quad (6)$$

where *V* is the mean sugar beet root volume, taken as sample weight/(number of roots per sample x density) = sample weight/(25 × 1.089). Density is taken from Section 2.3.4.

The Schmidt number is defined as

$$Sc = \frac{\mu}{\rho_{air} D_{ab}} \quad (7)$$

For Air 0, $U = 0$ and thus $Re = 0$. Thus, from equation (4), $Sh = 2$. Transferring $Sh = 2$ to equation (3), $D_{ab} = (k_c\, L)/2$. k_c can be calculated from equation (1) using $\dot{m}_w$ from the experiment (Table 4), Δc from equation (2), and the transformed equation (3), and thus D_{ab} can be calculated for the Air 0 treatment. When equations (3) and (4) are equated and D_{ab} for $U = 0$ is applied to the treatments from the same Run with positive *U* values, k_c can be solved for all treatment levels.

2.4. *Statistical analysis*

Data management and statistical analysis was completed using the open source software R (R Core Team, 2021), version 4.1.2. The packages lme4 and emmeans are used for the statistical analysis and ggplot2 for the production of graphs. Marginal means are computed within each Run, with fixed effects for Air and Days. Post-hoc Tukey tests were used to identify individual pairwise differences as needed.

3. Results

3.1. *Cleaning effect*

The weight of soil cleaned from the roots post-ventilation showed no statistically significant changes with treatment level (Table 3 and Appendix 1).

3.2. *Mechanical properties*

Root firmness did not show any changes during the experiment (Table 3 and Appendix 1). An observation made during the experiment was that the roots exposed to higher airflow began to assume a rubbery feel. There is no data available to quantify this.

Table 3
Mean value of quality parameters of sugar beet root after ventilated storage, by treatment levels and overall. The units dag kg_{int}^{-1} indicates a parameter converted to per unit of pre-ventilation clean mass of sugar beet root and can be read as percent by weight. *na*: dry matter only measured after Days 7. *Statistics col.* gives reference to table of statistical analysis results in Appendix 1.

Treatment			Normal roots								Washed roots	Soil
Run	Air	Days	Weight cleaned	Firmness	Total sucrose	α-amino N	K	Na	Dry matter	Dirt-tare	Weight loss	Weight loss
			dag kg_{int}^{-1}	MPa_{max}	dag kg_{int}^{-1}	mmol kg^{-1}	mmol kg^{-1}	mmol kg^{-1}	%	%	dag kg_{int}^{-1}	dag kg_{int}^{-1}
All	0	0	0.43	5.8	17.7	8.0	35.6	2.8	22.5	4.7	0.0	0.0
All	7	1	0.56	5.8	17.7	7.9	35.8	2.8	na	5.0	2.0	5.5
All	7	4	0.62	5.9	17.6	8.1	36.7	2.7	na	4.4	7.9	8.8
All	7	7	0.67	5.7	17.6	8.1	38.6	2.9	25.9	4.3	13.4	9.2
All	0	7	0.73	6.0	17.6	7.9	35.2	2.7	22.8	4.6	0.9	0.0
All	1	7	0.57	5.9	17.5	8.1	37.2	2.8	23.6	4.3	5.3	7.8
All	4	7	0.80	6.0	17.5	7.8	38.1	2.8	24.9	4.4	10.3	8.3
1	All	7	0.49	5.9	17.4	7.3	34.6	2.1	23.9	3.5	6.2	5.6
2	All	7	0.58	5.8	17.5	7.8	37.6	3.0	25.1	3.3	8.2	3.7
3	All	7	0.67	5.9	17.5	7.9	38.4	2.9	24.3	5.2	8.9	7.1
4	All	7	0.76	6.0	17.4	8.4	37.4	2.8	23.4	5.3	5.1	7.1
5	All	7	0.96	5.9	17.9	8.5	38.4	3.1	24.9	4.6	8.7	8.1
All	All	+ve	0.66	5.9	17.6	7.9	36.2	2.7	24.3	4.7	4.2	4.4
Statistics col.			A	B	C	D	E	F	G	H	I	J

Table 4
Mass flux, convective mass transfer coefficients, and diffusivity of sugar beet roots during ventilated storage. Mass flux and CMTC mean of all Air at Days 1, 4 & 7 within Material and Run. Diffusivity based on weight loss at Days 7 and Air 0. Mass flux shown in two units. CMTC shown as calculated direct from the experiment (CMTC-direct), or via the Sherwood-Reynolds-Schmidt correlation (CMTC-S-R-S). *Statistics col.* gives reference to table of statistical analysis results in Appendix 1.

Material	Run	Mass flux	Mass flux	CMTC direct	CMTC S-R-S	Diffusivity
		$\dot{m}_w$	$\dot{m}_w$	k_c	k_c	D_{ab}
		mol m^{-2} s^{-1}	mg cm^{-2} h^{-1}	m s^{-1}	m s^{-1}	m^2 s^{-1}
Normal	1	1.19E-04	0.770	2.48E-03	2.30E-03	2.14E-05
	2	1.43E-04	0.926	2.06E-03	2.44E-03	2.32E-05
	3	1.80E-04	1.165	2.49E-03	3.02E-03	3.10E-05
	4	1.09E-04	0.707	2.16E-03	2.32E-03	2.15E-05
	5	1.73E-04	1.118	2.17E-03	2.54E-03	2.43E-05
	All	1.45E-04	0.937	2.27E-03	2.52E-03	2.43E-05
Washed	1	1.39E-04	0.904	2.94E-03	2.24E-03	2.04E-05
	2	1.47E-04	0.952	2.11E-03	1.65E-03	1.33E-05
	3	1.80E-04	1.169	2.49E-03	2.66E-03	2.58E-05
	4	1.14E-04	0.741	2.26E-03	1.27E-03	9.16E-06
	5	1.90E-04	1.230	2.39E-03	1.56E-03	1.23E-05
	All	1.54E-04	0.999	2.44E-03	1.88E-03	1.62E-05
	Air					
Normal	0	2.08E-05	0.135	3.21E-04	3.80E-04	2.43E-05
	1	9.35E-05	0.606	1.45E-03	1.87E-03	2.43E-05
	4	2.04E-04	1.320	3.20E-03	3.42E-03	2.43E-05
	7	2.61E-04	1.689	4.11E-03	4.41E-03	2.43E-05
Statistics col.				K	L	

3.3. Quality

During the ventilation treatment, sugar beet roots lost weight with increasing airflow and duration (Fig. 5). Both Air 4 and 7 had a higher impact on weight loss compared to Air 1, when roots were ventilated for four days or more. After seven days, even Air 1 ventilated roots had lost weight compared to un-ventilated roots. After seven days at Air 7, the mean weight loss varied between 8.4% (Run 4) and 13.5% (Run 5), with a mean over all Run of 11.7%. Comparing different Days:Air combinations with the same total airflow by volume (e.g. 1:7 to 7:1), approximately half the pairs had significant differences. For the highest volume airflows with levels 4 and 7, the loss was greatest for Air 4:Days 7. The ventilation treatment also had an impact on the sucrose content (% polarimetrically). The change to sucrose content at any treatment level was inversely proportional to the weight loss, and as with the impact of the ventilation treatments to weight loss, the magnitude of the impact increased with airflow and duration (Fig. 6). After seven days the sucrose content in Air 4 and 7 were significantly higher compared to Air 1 and 0 for all runs. For two of the five runs, even Air 4 and 7 had significantly different sucrose content. After seven days at Air 7, the mean increase in sucrose content varied from 8.4% (Run 4) to 16.6% (Run 2), with a mean over all Run of 13.2%. The ventilation treatments showed no effect on total sucrose (Table 3). The soluble non-sugars, α-amino N, K and Na were in general not affected by the ventilation treatment (Table 3). When the mean of all runs at seven days are considered, a minor increase in K content with increased airflow is seen; from 35.2 mmol kg^{-1} at Air 0–38.6 mmol kg^{-1} at Air 7. Run 3–5 (6–7 °C) showed the same increasing pattern regarding α-amino N, K and Na, while run 1–2 (11.5–12.5 °C) were more scattered.

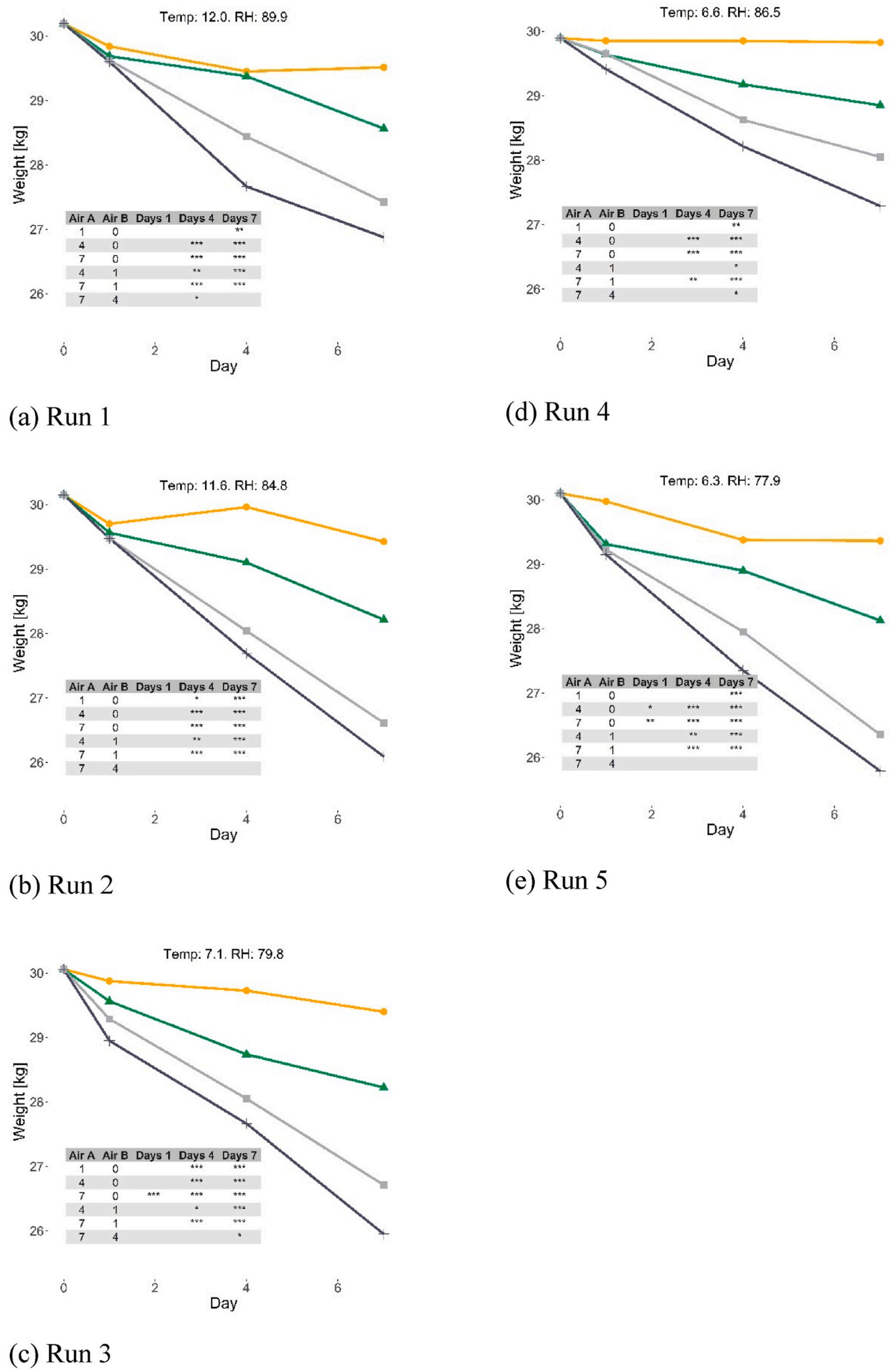


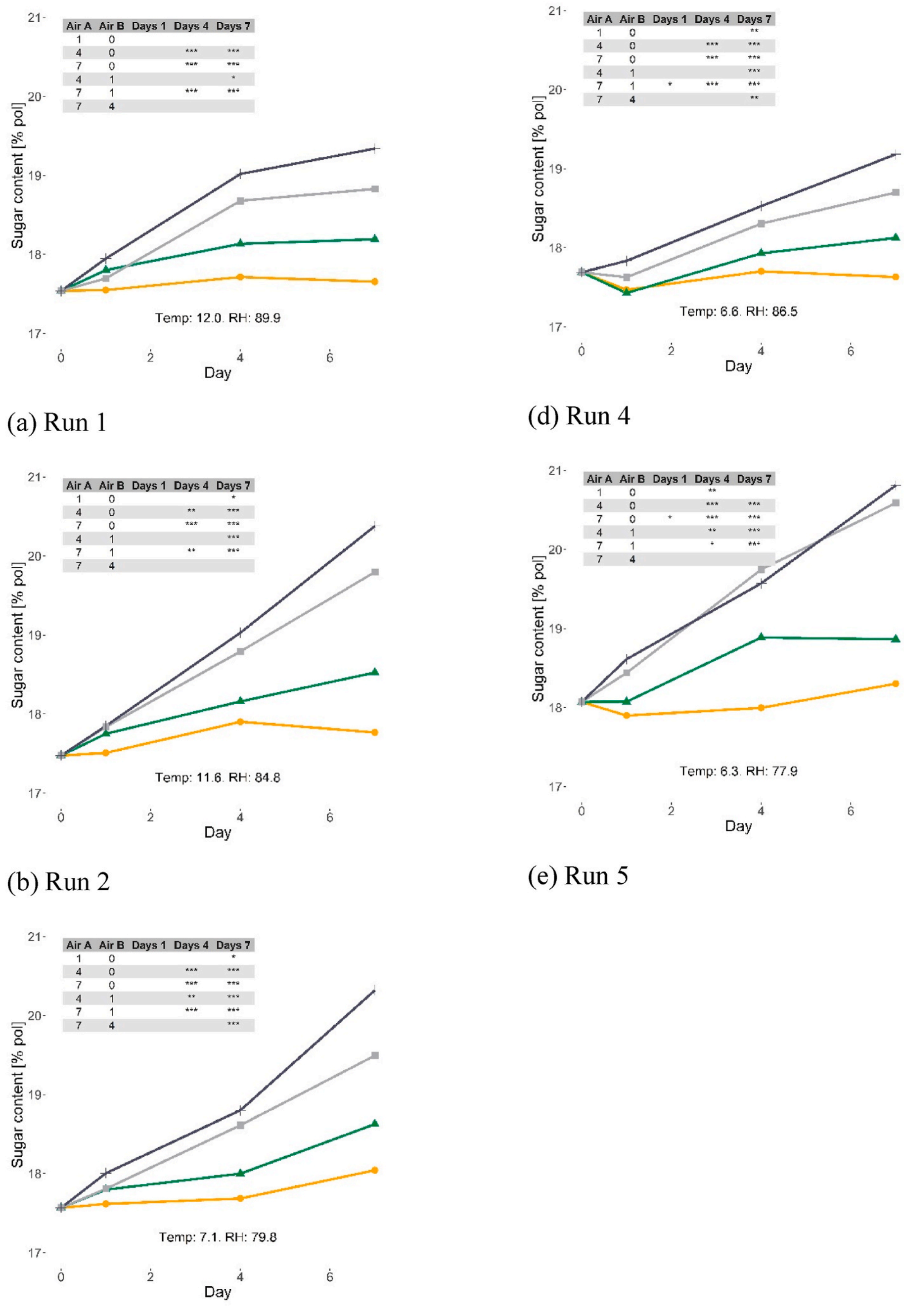
Fig. 5. Mean sample weight of sugar beet roots after ventilated storage, by Run and Air. Orange line: Air 0. Green line: Air 1. Grey line: Air 4. Blue line: Air 7. Weight at Days 0 is the mean of six replicates. Otherwise, each point is the mean of four replicates. Table shows results of post-hoc Tukey test pair-wise comparisons; Air A and Air B give Air treatment levels of comparison, stars under Days signify p-values at that time point; $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Mean temperature and relative humidity, by Run to Days 7, shown.

3.3.1. Washed roots and soil

Weight loss from the washed roots followed closely the pattern of the normal roots (Table 3). The calculations for mass flux suggest slightly higher rates of loss were observed in the washed roots (Table 4). Mean dirt-tare on the washed roots ranged between 0.0 and 2.4%. Other parameters follow closely the normal roots. The weight loss for soil occurred only in the presence of airflow and occurred rapidly. At Air 4 and 7, most samples had reached their Days 7 weight by Days 4. No soil was observed to fall from the ventilation boxes, suggesting all weight loss was from water leaving the soil.

3.4. Density

The mean density pre-ventilation was 1.089 g cm^{-3}, with a standard deviation of 0.0155. After six days of ventilation, the mean density for roots in Air 0 for Run 1, 3 and 5 reduced slightly to 1.084 g cm^{-3} (sd = 0.0155) (Fig. 7). For Air 0 in Run 2, post-ventilation mean density was 1.053 g cm^{-3}. For roots in Air 7 the mean density increased to 1.104 g cm^{-3} (sd = 0.0159). The weight loss in the refilled boxes over six days was in line with expectations when considering the weight loss from the other normal roots with the same Air treatment.



(a) Run 1

(d) Run 4

(b) Run 2

(e) Run 5

(c) Run 3

Fig. 6. Mean sucrose content of sugar beet roots after ventilated storage (percent polarimetrically), by Run and Air. Orange line: Air 0. Green line: Air 1. Grey line: Air 4. Blue line: Air 7. Sucrose content at Days 0 is the mean of six replicates. Otherwise, each point is the mean of four replicates. Table shows results of post-hoc Tukey test pair-wise comparisons; Air A and Air B give Air treatment levels of comparison, stars under Days signify p-values at that time point; $***p < 0.001$, $**p < 0.01$, $*p < 0.05$. Mean temperature and relative humidity, by Run to Days 7, shown.

3.5. *Mass flux and convective mass transfer*

The mean mass flux over all Run and Material was 1.49E-04 mol m^{-2} s^{-1} and variations in mass flux followed the weight loss results in Section 3.3, as expected (Table 4 and Fig. 5). The mean mass flux for Air 0 was 2.15E-05 mol m^{-2} s^{-1} or 0.139 mg cm^{-2} h^{-1}. Diffusivity was by definition fixed within Run, but Run 4 for the normal roots was significantly different from the other runs at $\alpha = 0.05$. The convective mass transfer values calculated from the Sherwood-Reynolds-Schmidt correlations (CMTC-S-R-S) tended to be higher than those calculated directly from the experiment (CMTC-direct) for the normal roots, with the difference ranging from −7 to 21%. For the washed root, CMTC-S-R-S tended to be lower for the washed roots, with the difference ranging from −44 to 7%. CMTC increased with airflow rate in a similar way for both calculations. Given the nature of dimensional analysis, CMTC-S-R-S should only vary with Air and not Days: statistical analysis confirmed this (Appendix 1). There were some diversions from this expectation for CMTC-direct.

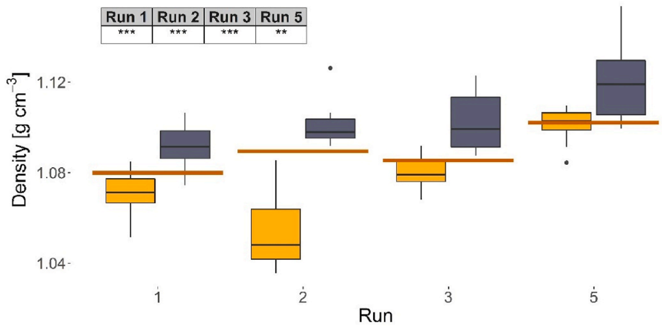


Fig. 7. Density of sugar beet roots after six days in ventilated storage, by Run and Air. Orange boxes: Air 0. Blue boxes: Air 7.10 observations per Run x Air. Dark orange lines show mean density prior to ventilation, by Run. Points in graph show outliers (more than 1.5 x inter-quartile range). Table shows *p*-values for ANOVA for comparison by Air, within Run: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

4. Discussion

4.1. Quality

Post-harvest ventilation treatment had the largest impact on the quality parameters of weight and sucrose content. Weight loss increased with increasing airflow rate and duration (Fig. 5). After 7 days at Air 7 approximately 10% of the initial weight was lost. This shows the impact of a positive airflow: in long-term storage trials without forced ventilation, sugar beet roots stored at 85 %r.h. took 2–3 weeks before reaching 10% weight loss (Lafta and Fugate, 2009). The sucrose content as percent by polarity also increased with airflow rate and duration (Fig. 6), showing the same pattern as weight loss. This combined with there being no change in the calculated total sucrose (Table 3) indicates that water loss was the reason for the decreased weight. Due to increased respiration rate, the sucrose content may decrease after storage, as respiration cause sucrose loss (Wyse and Dexter, 1971), but that was not seen in this study. In the long-term storage trial by Lafta and Fugate (2009), the respiration rate in roots stored at 10 °C and 85 %r.h. was almost constant during the storage period, while those stored at 40 %r.h. showed an increased respiration rate with time. They concluded that both the rate and the extent of root dehydration affected the amount of respiration and that there was a genotypic difference. Their experiment showed that a slower dehydration (at 10 °C 85 %r.h.) was less damaging than a faster dehydration (at 10 °C 40 %r.h.). Our experiment showed that a forced ventilation at high airflow rate for 7 days did not negatively affect the sucrose content. A recent study by Lafta et al. (2020), showed that dehydration largely affects the concentration of raffinose and glycolytic intermediates that are associated with both carbohydrate metabolism and respiration.

Other quality parameters including the soluble non-sugars, amino-N, K and Na, were not severely affected by the dehydration that occurred during the forced ventilation treatment. For some of the runs (those at 6–7 °C), the K content increased significantly with higher airflow, but the amount of K did not exceed any recommended maximum values. The tendency for the dirt-tare to decrease (Table 3) can likely be attributed to the loss of water from the soil attached to the surface of the roots as opposed to a more efficient cleaning for dehydrated root. These results, together with a higher sucrose content, indicates that the industrial sugar extraction process should not be negatively influenced by a short (7 days) forced ventilation treatment.

4.2. Mechanical properties and density

Following Nedomová et al. (2017) and Kleuker and Hoffmann (2022), it was expected that firmness may increase slightly during storage. The tactile observation of the rubbery feel for the roots exposed to the higher airflows gave the impression that these roots might test lower for firmness. The results did not show any change (Table 3). The observation of a rubbery feel was further tested by the current authors in a pilot study using roots exposed to a treatment similar to Air 7 and Days 7 and a laboratory penetrometer (Larsson Jönsson and English, 2022). This pilot study similarly did not find differences in the puncture resistance between the high airflow treatment and the control treatment. It did, however, find a significant decrease in the apparent modulus of elasticity for the roots from the high airflow treatment. This likely means an increase in the difficulty of slicing at processing for the dehydrated roots (Vukov, 1977).

The increases in density for Air 7 treatments (Fig. 7) reflects the quality analysis, that shows a relative reduction in water content (density = 1.00 g cm^{-3}) and increase of solids as sucrose content. Sucrose has a density of 1.59 g cm^{-3}. The reason for the relatively large decrease in density for Air 0 roots in Run 2 is not known. Density values are slightly lower than the mean of 1.169 g cm^{-3} reported in Tabil et al. (2003).

4.3. Mass flux and convective mass transfer coefficients

The mean mass flux for Air 0 of 0.105 mg cm^{-2} h^{-1} is similar to the values found for other food crops under similar temperature and humidity conditions. This includes 0.08–0.15 mg cm^{-2} h^{-1} for pear (Xanthopoulos et al., 2017), and 0.047–0.698 mg cm^{-2} h^{-1} for pomegranate (Caleb et al., 2013). It is lower than values reported for mushrooms (0.14–2.5 mg cm^{-2} h^{-1} (Mahajan et al., 2008)) and higher than values reported for grape tomatoes (0.012–0.058 mg cm^{-2} h^{-1} (Xanthopoulos et al., 2014)).

The comparison of the two methods for calculating CMTC supports the argument that these results could be applied in the modelling of the mass transfer of water in sugar beet post-harvest storage systems. CMTC-direct and CMTC-S-R-S were acceptably similar. Applying the Sherwood-Reynolds-Schmidt correlation with the overall mean diffusivity coefficient (D_{ab}) found here (1.14 E−06 m^2 s^{-1} - Table 4) will mean that the CMTC can be computed for the given airflow, characteristic length, and air physical properties. It should be tested whether the air physical properties can be dependent on temperature or not.

The changes to quality seen over the 7 days of each Run are generally linear or show a tendency for a decreasing rate of change (Figs. 5 and 6). This suggests that the mass flux and consequently the convective mass transfer coefficients will have been constant or slightly decreasing during the period of ventilation. It would be expected that these rates decrease as the roots become dehydrated and their water activity and consequently the vapour pressure differential in the system decreases. Decreasing rates of weight loss were observed by Lafta and Fugate (2009) over a four week storage period. Non-linear trends could also be associated with the transfer of water out of the soil attached to the root occurring more rapidly than out of the root. Decreases in mass flux could also occur with changes in the mechanical properties of the roots over longer periods of storage. It could be expected that dehydration would lead to decreases in the apparent modulus of elasticity, as seen in the complementary exploratory study conducted by the current authors (Larsson Jönsson and English, 2022). This would lead to a settling of the bulk of roots and a decrease in the actual surface area of the roots.

Beyond the deliberately limited storage period of this experiment, it must be remembered that these results were collected from within a limited range of temperature, relative humidity, and degree of root dehydration. Diffusivity has been derived from a system with dirty roots and with roots in contact with each other. The difference in D_{ab} between the normal and washed roots suggests that the soil that sits on the surface of the roots slows mass transfer (Table 4). The roots sitting in contact with each other will have impacted the surface area over which conductive mass flux occurred, so the rates of mass flux per unit area as calculated here likely under represent actual fluxes. That said, it is likely that the contact area in a commercial clamp, and similarly in a model, would be similar to that of the roots in the experiment. The pressure of the commercial bulk upon itself may increase the contact area relative to the experiment. An increase in contact area would mean applying the estimates for diffusivity from this work in a model will over predict actual rates of mass flux. No data on the contact area of sugar beet roots in bulk, for any system, are known to be available.

5. Conclusions

This experiment showed that a short and intense ventilation of sugar beet roots during post-harvest storage has the potential to benefit the industry, in that it can result in a much reduced weight of the bulk of raw material while not having negative impacts on quality. The reduction in weight results from a reduction in water content. This reduction in weight could have many benefits. In payment systems that incentivise higher sucrose content and lower dirt-tare, sugar beet growers could see increased gross incomes if ventilation occurs prior to delivery. Further benefits in the form of reduction in transport costs and environmental impact would also follow. The cost of ventilation needs to be assessed. If the decision was taken to reduce weight by a short, intense, forced ventilation, timing would be important. Ventilation early in the storage period has the risk of increasing rates of respiration over a long storage period. This is potentially a result of both dehydration induced stress, and of reduced wound healing from a reduced temperature should ventilation reduce clamp temperature. It would also be necessary to test the system in practice. Results from the commercial clamp ventilation system under development in Sweden at the time of this experiment suggest that both airflow and dehydration inside of the clamp are highly variable. The level of dehydration observed in the commercial system was also less than that found here with roots ventilated in boxes. These results can be used in the modelling of water movement in sugar beet post-harvest storage system.

Funding

This research was funded by NBR Nordic Beet Research foundation, and by LivsID (food science-related industry PhD-program) financed by the Swedish Government [governmental decision N2017/03895] and the Swedish University of Agricultural Sciences [SLU.ua.2017.1.1.1–2416].

Data and scripts

Data and scripts are available at the Github repository https://github.com/meranbioph/6030_Airflow-Quality.

Author statements

William English: Conceptualization, Methodology, Investigation, Data curation, Writing- Original draft preparation, Visualization, Investigation, Writing- Reviewing and Editing,

Helene Larsson Jönsson: Conceptualization, Writing- Original draft preparation, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

William English reports some of the equipment used in the construction of the experimental system was provided by Nordic Sugar AB.

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to thank our colleagues at NBR Nordic Beet Research, the staff at Hushållningssällskapet Skåne, and Nordic Sugar Sweden for assistance in the design, construction, and execution of this experiment. Thanks to Drew English for assistance in the construction of the modified atmosphere system experiment.

Appendix 1

Table A1
Statistical analysis results for pair-wise comparison of Air, within Run and Days, by parameter. Days shown on second row of header. Parameter indicated by letter, with key at bottom of table, also in Tables 3 and 4 * indicates p-value <0.05. - indicates no contrast possible.

Run	Air A	Air B	A			B			C			D			E			F			G			H			I			J			K			L		
			1	4	7	1	4	7	1	4	7	1	4	7	1	4	7	1	4	7	1	4	7	1	4	7	1	4	7	1	4	7	1	4	7	1	4	7
1	0	1																			–	–						*	*		*	*	*	*	*	*	*	*
1	0	4																			–	–	*				*	*	*		*	*	*	*	*	*	*	*
1	0	7																			–	–	*				*	*	*	*	*	*	*	*	*	*	*	*
1	1	4																			–	–	*					*	*				*	*	*	*	*	*
1	1	7																			–	–	*				*	*	*	*	*		*	*	*	*	*	*
1	4	7																			–	–						*	*	*			*	*	*	*	*	*
2	0	1														*	*				–	–	*					*	*				*	*	*	*	*	*
2	0	4																			–	–	*				*	*	*				*	*	*	*	*	*
2	0	7																			–	–	*				*	*	*		*	*	*	*	*	*	*	*
2	1	4																			–	–	*				*	*	*				*	*	*	*	*	*
2	1	7														*					–	–	*				*	*	*				*	*	*	*	*	*
2	4	7																			–	–						*	*				*			*	*	*
3	0	1															*				–	–	*					*	*		*	*				*	*	*
3	0	4															*				–	–	*				*	*	*	*	*	*	*	*	*	*	*	*
3	0	7															*				–	–	*				*	*	*	*	*	*	*	*	*	*	*	*
3	1	4																			–	–	*					*	*	*			*	*	*	*	*	*
3	1	7															*				–	–	*					*	*	*			*	*	*	*	*	*
3	4	7																			–	–	*					*	*				*			*	*	*
4	0	1																			–	–	*					*	*	*	*	*	*	*	*	*	*	*
4	0	4																			–	–	*					*	*	*	*	*	*	*	*	*	*	*
4	0	7																			–	–	*				*	*	*	*	*	*	*	*	*	*	*	*
4	1	4																			–	–	*					*	*	*			*	*	*	*	*	*
4	1	7																			–	–	*					*	*	*	*		*	*	*	*	*	*
4	4	7																			–	–	*					*	*				*	*	*	*	*	*
5	0	1															*				–	–						*	*		*	*	*	*	*	*	*	*
5	0	4															*				–	–	*				*	*	*	*	*	*	*	*	*	*	*	*
5	0	7															*				–	–	*				*	*	*	*	*	*	*	*	*	*	*	*
5	1	4			*											*	*				–	–	*					*	*				*	*	*	*	*	*
5	1	7														*	*				–	–	*				*	*	*	*			*	*	*	*	*	*
5	4	7																			–	–						*	*				*	*	*	*	*	*

A: Weight cleaned, B: Firmness, C: Total sucrose, D: α-amino N, E: Potassium, F: Sodium, G: Dry matter, H: Dirt-tare, I: Washed roots weight, J: Soil weight, K: CMTC-direct, L: CMTC-S-R-S.

Table A2
Statistical analysis results for pair-wise comparison of Days, within Run and Air, by parameter. Air shown on second row of header. Parameter indicated by letter, with key at bottom of table, also in Tables 3 and 4 * indicates p-value <0.05. - indicates no contrast possible.

Run	Days A	Days B	A				B				C				D				E				F				G				H				I				J				K				L			
			0	1	4	7	0	1	4	7	0	1	4	7	0	1	4	7	0	1	4	7	0	1	4	7	0	1	4	7	0	1	4	7	0	1	4	7	0	1	4	7	0	1	4	7	0	1	4	7
1	1	4																									–	–	–	–	*					*	*	*		*	*									
1	1	7																									–	–	–	–	*					*	*	*		*	*									
1	4	7																									–	–	–	–						*	*	*												
2	1	4																		*							–	–	–	–						*	*	*												
2	1	7																									–	–	–	–					*	*	*	*			*	*								
2	4	7																		*				*	*		–	–	–	–					*	*	*	*												
3	1	4																							*		–	–	–	–						*	*	*		*						*				
3	1	7																*		*	*	*					–	–	–	–						*	*	*		*						*				
3	4	7																		*	*	*					–	–	–	–						*	*	*												
4	1	4																									–	–	–	–						*	*	*		*	*	*								
4	1	7																		*	*	*					–	–	–	–						*	*	*		*	*	*				*				
4	4	7																		*							–	–	–	–						*	*	*												
5	1	4																			*	*					–	–	–	–						*	*	*		*					*	*				
5	1	7																		*	*	*					–	–	–	–				*		*	*	*		*					*	*				
5	4	7																		*	*	*					–	–	–	–						*	*	*								*				

A: Weight cleaned, B: Firmness, C: Total sucrose, D: α-amino N, E: Potassium, F: Sodium, G: Dry matter, H: Dirt-tare, I: Washed roots weight, J: Soil weight, K: CMTC-direct, L: CMTC-S-R-S.

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