3 Technology and Management of Postharvest Dehydration

Fabio Mencarelli and Andrea Bellincontro

DIBAF, University of Tuscia, Viterbo, Italy

3.1 INTRODUCTION

When a winery decides to start a wine project using the postharvest technique of grape dehydration, the winemaker should have some knowledge of the physiology of grape dehydration and of the fundamentals of water loss. Why? Because 'withering, with the different practices and technologies, produces different grapes and thus different wines' (Di Lorenzo, 2007). Besides this knowledge, it is important for the winemaker to have other practical, tangible, information, by asking some specific questions:

1. What are the weather conditions during the grape dehydration period?
2. What kind of facility is available to carry out dehydration?
3. What financial resources are available?
4. What is the situation in terms of available energy and relative cost?

First of all, we must keep in mind that grape berry is a living tissue which continues to live after harvest, meaning that it breathes, consuming oxygen (O_2) and eliminating carbon dioxide (CO_2) and heat. For the winemaking process, the faster the transfer of the harvested grapes from the vine to the winery, the better, but in the case of wine that requires grape dehydration, the postharvest life of the berry is very important and needs to be managed. But why do we speak about dehydration and not drying? We define *drying* as the rapid process of water removal from items containing water (processing technique), so raisins are dried and wood is dried. *Dehydration* indicates the physical principle by which, depending on the environmental conditions surrounding the item, water vapour is drawn off from that item. Finally, in the wine sector, we speak about *withering* (*appassimento* in Italian), which can be explained as a slow process of water removal from a berry where over-ripening, or even better, senescence, occurs. Thus, dehydration is the correct term to identify water loss from the berry to the surrounding air and thus our objective is to manage the dehydration because it means managing the water loss and, in turn, all the metabolisms affected by water loss, which causes *water stress* in the berry cells.

This is the point: in a living tissue like berry, with dehydration we create water stress and, as described in Chapter 4, dramatic changes occur in the berry cell's metabolism.

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In this chapter we will provide information on the fundamentals of water loss based on environmental conditions and we will explain why the above questions are important.

3.2 BASIC CONCEPT AND PRACTICAL NEEDS

Food drying is based on three main concepts (Rozis, 1997):

- Supply of thermal energy (heat)
- Ability of the air surrounding the commodity to take the water vapour released by the commodity
- Air speed striking the commodity.

Moreover, according to Rozis, drying should not occur either excessively fast or at a high temperature. This suggestion is true because, as Wang and Brennan (1995) discovered, shrinkage occurs first at the surface and then gradually moves to the internal tissue as drying time increases; at a slow drying rate, the moisture content at the centre of a berry is not much higher than at the surface, the internal stresses are minimized, and the material shrinks fully onto a solid core. For commercial reasons, the faster the drying, the more profitable is the process. Raisins are dried quickly, exposed to the sun or kept in commercial ovens, because the process is more profitable (more berries per time unit) and also because there is no interest in having a final aromatic product but just one that is as sweet as possible, and maybe a bit chewy. However, when the final goal is to have not just sugars but a panorama of different characteristics useful for wine quality, then drying must be carefully controlled or, as we say, 'managed'.

The main processes involved in the drying process can be summarized in (1) heat transfer to the liquid, (2) mass transfer as liquid or vapour inside the solid, and (3) as vapour from the solid surface to the outside. So, depending on the drying plant, these processes can proceed faster or slower. Inside the solid, that is, a berry, the driving force which allows the matter (water) transfer is a concentration gradient (mainly sugars) and the movement of the water can occur through diffusion, due to VPD (vapour pressure deficit) or to continuous changes in evaporation and condensation.

If we take into account the water loss during the heating process, first of all water evaporation occurs from the surface due to VPD, and this evaporation cools down the cells; consequently, water vapour moves from the internal layers (cell and intercellular spaces) to the superficial ones, cools down and condenses. To evaporate this water, we must provide further heat. At the same time, the dry matter of superficial cells concentrates, drawing more water from internal layers. Thus, in the cell and in the intercellular spaces of the berry, we will have a continuous concentration gradient and a continuous evaporation–condensation process during dehydration, which in turn will affect the diffusion coefficient of water in the tissue.

The water diffusion inside the tissue is a slow movement whose speed decreases as the relative humidity (RH) of the tissue decreases. The moisture diffusion coefficient D ($m^2\ s^{-1}$) is based on Fick's second law (Barbanti *et al.*, 2008):

$$\ln\left(\frac{M - M_e}{M_o - M_e}\right) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D t}{R^2}\right)$$

Table 3.1 Pick-up efficiency (g water vapour per m^3 of air) of air at different temperatures and relative humidity.

Relative humidity (%) \ Temperature (°C)	10	15	20	25	30	35	40	45
10						8.2	9.2	9.9
20					6.0	7.3	8.0	8.6
30				5.0	5.6	6.2	6.6	6.9
40	2.7	3.2	3.7	4.2	4.6	5.1	5.5	6.1
50	2.2	2.6	3.0	3.4	3.7	3.9	4.1	
60	1.8	2.1	2.3	2.6	2.9	3.1		
70	1.3	1.5	1.7	1.9	2.1			
80	0.9	1.0	1.1	1.2				
90	0.5	0.5	0.7					

where M = moisture content at any time during the berry dehydration process (kg water × kg dry matter^{-1}); Mo = initial moisture content (kg water × kg dry matter^{-1}); Me = equilibrium moisture content (kg water × kg dry matter^{-1}); R = berry radius at time 0 (m); t = withering time (days). Thus, the diffusion coefficient is directly proportional to the berry surface and inversely proportional to the withering (dehydration) time and water content.

Practically speaking, some basic questions on product dehydration are asked and relative answers provided in the drying manual (Rozis, 1997):

1. How much water should be removed from the product? The mass of water (M_w in kg of water per kg of fresh product to be dried) to be extracted during dehydration = (m_i% − m_f%) M_p/(100 − m_f%) where m_i % = percentage of moisture of the product before dehydration; m_f % = percentage of moisture of the product after dehydration; M_p = product mass.
2. How long should the drying last? It depends on the production rhythm given by the quantity of dried product to be processed during each cycle, divided by the length of each cycle; the second factor is how long the product can wait before being dry enough so that pathogen micro-organisms do not develop; the third factor is the pick-up rate which must not be too fast to avoid case hardening.
3. What is the moisture pick-up rate (V_{ap}) in the product? It is the ratio between M_w/T_d where T_d is the ideal drying time for a given product (hours).
4. What is the pick-up efficiency of the air? It is the maximum quantity of moisture that a cubic meter of air can pick up when in contact with the humid product. It depends on the water vapour density, the pressure conditions, and the air temperature.

The ability of air to catch the water vapour is shown in Table 3.1 and is directly proportional to the increase in temperature and to the decrease in RH, as expected. But the table is interesting for grape drying because this ability is similar under different temperature and relative humidity conditions; that is, at 10°C and 40% RH the value is 2.2, similar to 2.1 and 2.3, which we find matching 15 and 20°C and 60% RH or 30°C and 70% RH. If we observe these data mechanically, we conclude that keeping grapes under these conditions, the dehydration time is similar, so the quality of the final product is similar. This is true for non-living material such as a wooden bar, but with harvest grape we are dealing with a living being, so the effect of temperature first and RH second plays an important role in the metabolism.

All of the questions mentioned earlier, together with other basic questions such as the drying temperature to be used, the average moisture pick-up rate and the air flow to be used, are important for an industrial technique or in a natural (sun) drying plant where the final objective is to dry the product completely, in the shortest amount of time but avoiding case hardening when the temperature is adjustable. However, when we speak about grape dehydration for wine production, dehydration management is a complex system in which the operator must have in mind the type of grape (physical and physiological features), the final water percentage in the berry, the time to reach this value and, very important, what kind of dehydrated grape he or she wishes to obtain. In short, the operator must manage water stress and senescence of the berries and thus adapt the dehydration conditions to control these two events.

First of all, as mentioned earlier, we need to know the final quality of the dehydrated product that we wish to obtain. In this case, the amount of water loss, the rate of water loss and the temperature are fundamental. We usually calculate the following values, based on our scientific experience, for the amount of weight loss (%) and for the speed of dehydration (days).

$$\begin{aligned} \text{Amount of weight loss (\%)} &= 10\text{–}15\% \\ &= 20\text{–}30\% \\ &= >30\% \end{aligned}$$

We know through experience (Costantini *et al.*, 2006; Chkaiban *et al.*, 2007; Santonico *et al.*, 2010; Mencarelli *et al.*, 2010; Cirilli *et al.*, 2012) that significant change occurs in the grape metabolism with these weight loss percentage values. Regarding the dehydration speed, we list the following:

Very fast = 5–10 days
Fast = 2–3 weeks
Slow = 4–8 weeks
Very slow = >8 weeks

Some important dehydration parameters to check, which are useful for comparison, are given in Table 3.2.

The rate of weight loss (WLR) under carefully controlled atmospheric conditions is one of the more important parameters: Aleatico cultivar loses water rapidly and consequently the sugar content increase rate (SIR) is much higher than in the other cultivars. But if we look at the SIR-to-WLR ratio, Aleatico, Shiraz or Montepulciano cultivars have similar values, meaning that the increase in sugars during dehydration is not merely concentration but events such as sugar respiration (main) and sugar biosynthesis by gluconeogenesis ((sugars can be synthesized from malic acid under stress conditions, as is the case of high sugar concentration (Sweetman *et al.*, 2009)) occur. In contrast, cultivars such as Grechetto rosso (red cv.) and Roscetto (white cv.) have a lower ratio, suggesting that, most likely, the consumption of sugars is greater than their synthesis, partially reducing the concentration effect.

Table 3.2 Wine grape cultivars dehydrated under the same atmospheric conditions (15–17°C and 45–55% RH).

	Aleatico	Grechetto Rosso	Procanico	Roscetto	Montepulciano	Shiraz
Dehydration time (days)	12	12	16	16	33	33
°Brix at harvest	21	21	21	21	24	24
Final weight loss (%)	27	19	20.5	20	40	44
Final °Brix	27	24	25	24	32	34
WLR = rate of weight loss (%/day)	2.25	1.58	1.28	1.25	1.21	1.33
SIR = rate of sugar increase (°Brix/day)	0.50	0.25	0.25	0.19	0.24	0.30
SIR/WLR (°Brix/%)	0.22	0.16	0.19	0.15	0.20	0.23

3.3 ENDOGENOUS AND EXOGENOUS FACTORS AFFECTING WATER LOSS

How does water get transferred from inside to outside the berry? It depends on the environmental conditions and will be dealt with later in this chapter. In any case, with a RH (tissue water content) higher than 27%, first of all, the free water (the water which works like a solvent) evaporates, and subsequently, the osmotic water evaporates when the RH is between 13 and 27%; the evaporation of these two types of water cools down the cells. In the third step, when the RH is between 5 and 13%, the polymolecular water, highly adsorbed on dry matter (matrix), is removed with difficulty and cell heating occurs. Finally, with RH below 5%, water is very strongly bound through van der Waals bonds and is a single monomolecular layer (Rozis, 1997). This water cannot be removed.

The factors affecting the postharvest water loss of berry are *endogenous* (depending genetically on the cultivar and on the physical and biochemical characteristics induced by the climate conditions during berry growth), and *exogenous*, which are related to the environment where the bunch is kept after harvest for the dehydration process. Speaking of endogenous factors, the following are the main physical features which affect water loss:

- ratio of surface to mass or volume (berry size)
- berry size and shape
- berry skin surface
- micropores and cracks
- presence and physical condition of the rachid
- bunch density.

Technically speaking, the main factors for grape dehydration are: initial moisture content, sugar content, berry volume, berry surface area and surface-to-volume ratio (S/V) values (Barbanti *et al.*, 2008).

The ratio of surface to volume is very important for water loss; indeed it is the main factor affecting the vacuum cooling technique, which is based on rapid and controlled water loss to cool down vegetables (Thompson, 2004). In dehydration, we do not want to cool down the berry but we want to have easy water loss. In the same bunch, small berries lose water

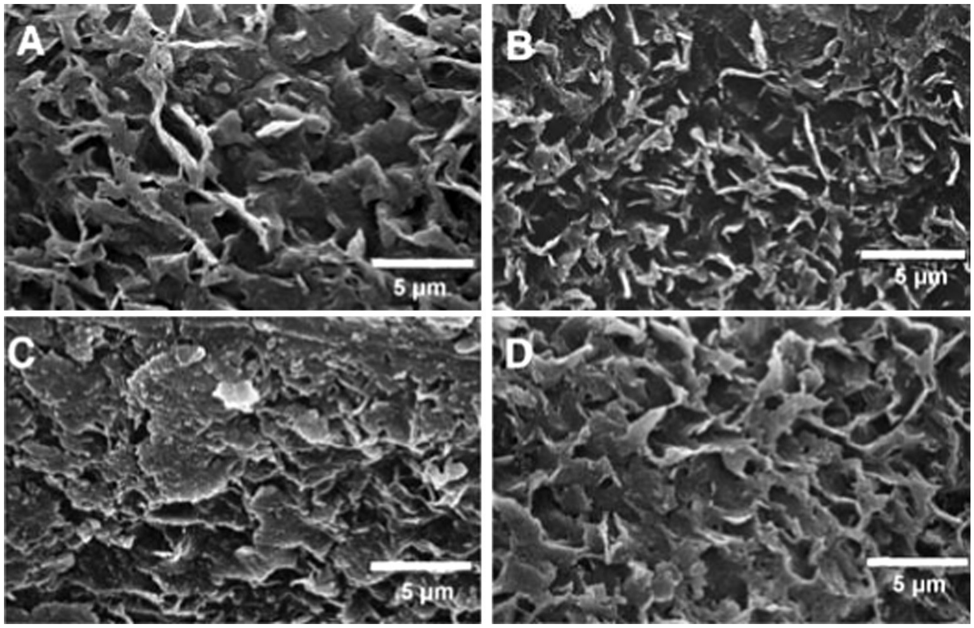

Figure 3.1 Scanning electron micrographs of epicuticular wax on berry surface at harvest. Cultivar Trebbiano Toscano: (A) extra-canopy; (B) intra-canopy; cv. Rossetto: (C) extra-canopy; (D) intra-canopy. Reproduced from Muganu *et al.* (2011), with permission from American Society for Enology and Viticulture.

faster than larger berries because the surface-to-volume ratio is higher; as a matter of fact, if the surface rises two-, three-, fourfold, the volume increases at a lower rate: $2x\sqrt{2}$, $3x\sqrt{3}$, $4x\sqrt{4}$.

Moreover, the shape affects the water loss of berries with the same volume: the spherical berry loses water more slowly than the spheroidal one because the surface-to-volume ratio is higher for the latter than for the former.

Speaking about surface means speaking about the thickness of the wax (pruine), and how the wax is distributed on the surface because, depending on the cultivar, the pruine platelets are different. It is clear that this surface is strongly affected by the growing conditions of the berries in the vineyard, which mainly means sun exposure and irrigation, but also vine nutrition. It has been seen recently (Muganu *et al.*, 2011) that shaded berries (intra-canopy) dehydrate more slowly than berries exposed to the sun (extra-canopy) but the wax platelet content is greater in extra-canopy berries. It is likely that the berry anatomy and morphology characteristics and the morphology of the wax could be the reason (Figure 3.1).

The intactness of the berry surface is another important characteristic affecting the rate of water loss. It is very important not only to avoid micro-organism contamination but to manage water loss. The presence of microcracks alters the natural permeability of berry skin; abrasion due to vine stem or leaves favours water loss, removing pruine and causing microcracks. The grapes are harvested carefully (by hand) and plastic boxes are used for grape bunches intended for dehydration.

Grape berry is unusual compared to other fruits because the surface does not have stomatas but only a few lenticels and tiny micropores which are covered by a thick layer of pruine, a wax formed by oleanolic acid (2/3) and the rest by alcohols, esters, and long-chain fatty acids, which are produced by epidermal cells. Thus, apparently the flesh of the grape berry is almost completely isolated from the external environment, and the berry is similar to a controlled atmosphere room, gas-tight, where apples or kiwifruits are commercially stored for long-term use. This means that the gas concentration inside the berry is not the same as the outside air, and O_2 will be reduced and CO_2 increased. There are no data about this on grape berry due to the difficulty in measuring, but there are interesting findings on pears by Franck *et al.* (2007), who measured a concentration of 17.2% O_2 and 0.76% CO_2 in the pear core. Taking into account that pear peel is rich in stomata and lenticels, we can assume that the O_2 in the berry core (seed area) is much lower and CO_2 much higher than is found in pear, and this would explain the high ADH (alcohol dehydrogenase) activity found during berry ripening (Tesniere *et al.*, 1993). The concept of aerobic fermentation is today accepted as a way for the cell to find other sources of energy when the main pathway (Kreb's cycle) is blocked, as in the case of high sugar content of dehydrated berry, before the cell dies. In this case, even under normal atmospheric conditions, glycolysis goes fast while the Krebs cycle is blocked, thus pyruvic acid is converted to ethanol, completely modifying the aromatic panorama of the berry (Cirilli *et al.*, 2012).

Despite this apparently impermeable surface, grape berry loses water if it is kept under atmospheric conditions of low RH or high air flow. Becker and Knoche (2011) have shown that for transpiration, the berry surface contribution went from 58% between 26 and 59 DAFB (days after full blooming) to an average of 77% between 73 and 129 DAFB in cv. Riesling, and similar data was found in cv. Chardonnay and cv. Muller-Thurgau. Moreover, transpiration through the berry surface occurred at a higher rate at the stylar end (+44%) as compared to the cheek. No relationship was found between stylar scar area and transpiration rates and neither the rusty area nor the number of lenticels had a significant effect on transpiration rates. Thus, berry transpiration occurs mainly through the surface. The same authors showed that the permeability of the berry cuticle decreased throughout berry development. Thus, diffusion is the primary mechanism for water movement through the berry surface during transpiration. As explained by Schönherr (2006), diffusion occurs along a lipophilic and/or polar pathway; the former is formed by the amorphous wax fraction within the cuticle and the latter is formed by the orientation, clustering and hydration of polar functional groups within the cuticle, clusters forming an aqueous continuum such as micropores (not detectable under the microscope), which allow viscous water flow.

In addition, the berry is attached to the stem through a pedicel, so the bunch is a complex system of stems and pedicels. This green structure is rich in stomatas and lenticels, and does not have a thick cuticle like the berry. The periderm of the receptacle where the berry is joined to the pedicel, together with the pedicel, has a high permeability rate of 376.1 nm s^{-1} versus 6.7 nm s^{-1} (Becker and Knocke, 2011). Generally speaking, water loss from the green parts of the bunch is reduced by the presence of the boundary layer, but under postharvest environmental conditions when the RH is low and air flow is present, the high permeability of the rachid, therefore its high water loss, induces a pressure differential that draws water from the berry to the rachid, causing water loss from the berry, even though limited. This process continues until the pedicel is completely dry, an event that usually occurs at between 5 and 10% of water loss from the bunch of grapes. This is why, in Figure 3.2, berries detached from the rachid with 2 mm of pedicel lose less water than the whole bunch. To confirm this behaviour, the hypothesis for the mechanism of berry weight loss on vine proposed by Tilbrook and Tyerman (2008), that is that the membranes of the pericarp cells begin to lose semi-permeability at the same time as weight loss begins, so the large negative osmotic potential of the berry sap is no longer effective in opposing the xylem tensions developed by

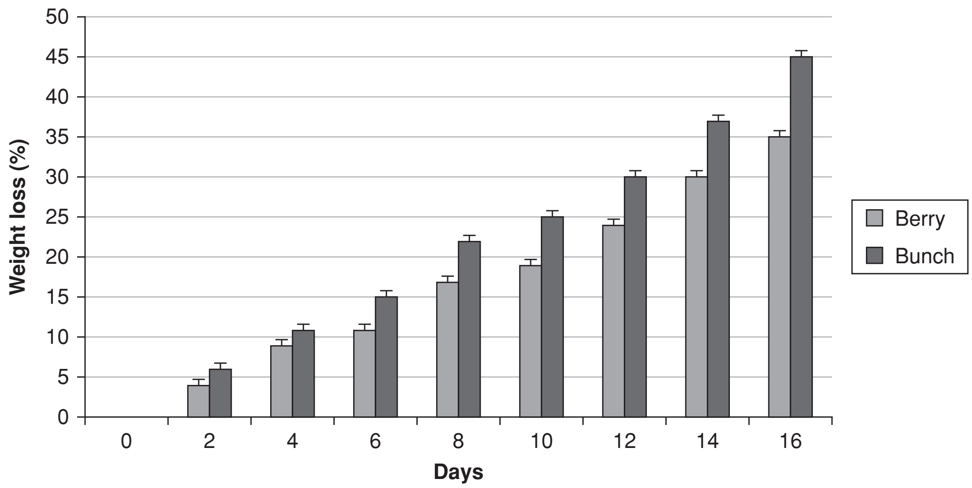

Figure 3.2 Weight loss of a sample of berries (cv. Aleatico) detached with 2 mm of pedicel (20 berries) or of the whole bunch (3 bunches), both kept in air flow of 1.5 m s^{-1}, 50% RH, and 20°C. Vertical bar indicates standard deviation. Reproduced with permission from Mencarelli *et al.* (2006).

leaves. Those cultivars that maintain higher xylem-to-berry hydraulic conductance, such as Shiraz, are therefore more vulnerable to backflow via the xylem.

If the environmental conditions change and the rate of weight loss (weight loss per day) is very low, this difference is not so significant.

Beyond the physical features, respiration affects water loss by heating the tissue, favouring water evaporation, and, in turn, dehydration affects the respiration rate. Furthermore, ethylene production, as a consequence of water stress, may affect the water loss and the respiration rate of the berry cells (Botondi *et al.*, 2011). Figure 3.3 shows the respiration rate of some wine grape cultivars during dehydration.

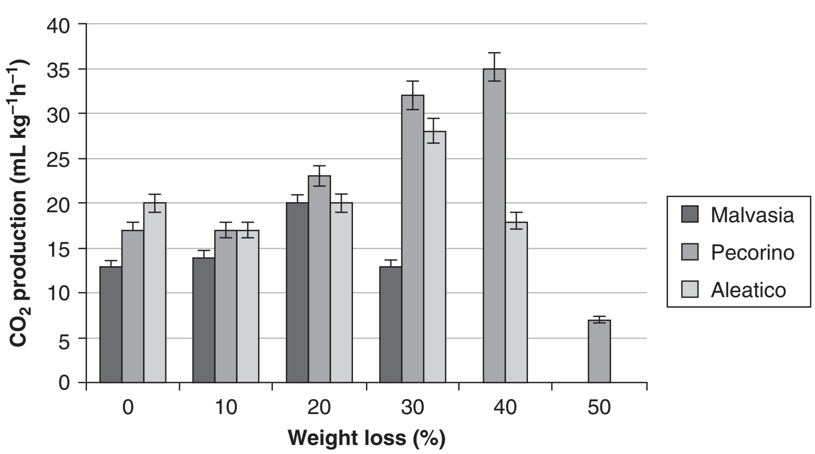

Figure 3.3 CO_2 production of three cultivars during dehydration in the same environmental conditions (20°C; 45% RH; 1.5 m s^{-1}).

The environmental factors affecting water loss are mainly temperature, RH, and air flow. Sunlight can be another factor for dehydration in open air but its role is a combination of infrared and UV radiation, which are not studied at all.

As mentioned beforehand, providing heat is the first factor affecting water loss. Thus temperature plays an important role. Until recently, no one paid attention to carefully controlling the temperature during grape dehydration. This lack of interest is based on the concept that, as in an industrial drying process, it is important to remove water quickly, adding to the use of high temperature, ventilation and/or removal of water vapour or, more simply, leaving the grape in the sun. This is a mechanical view of the dehydration process, which does not take into account that the berry cells are living, as we emphasized earlier.

What is the best temperature for the dehydration of grapes to produce wine? It depends on what we want to obtain from the grape metabolism. Bellincontro *et al.* (2009) have shown that the lower the temperature (with fixed RH and air flow), the better the grape structure during dehydration, and it is known that fruit pigment is more likely to remain intact with a lower dehydration temperature (Del Caro *et al.*, 2004). This is very important because the water loss must occur slowly, by transfer from cell to cell and to cell interspace. Speaking of low temperature, we mean temperatures between 5 and 10°C. These temperatures can be found naturally in the Verona area, where Amarone and Recioto wines are produced and where the dehydration facilities are built in such a way that when the outside air conditions are optimal for dehydration, the outside air is pulled inside the facility (see Chapter 13 ‘Amarone’). In a closed, insulated facility where all the ambient parameters can be carefully controlled, the temperature can be maintained at 10°C. If the cellular structure of the berry is maintained, we obtain the following advantages: first, water stress can be postponed and be less traumatic; second, the secondary metabolism for the production of polyphenols (Mencarelli *et al.*, 2010) and volatile compounds can proceed slowly (Santonico *et al.*, 2010), releasing important compounds into the cell sap; third, less oxidation occurs; and fourth, slower aerobic fermentation takes place with lesser formation of metabolites dangerous for berry quality such as ethanol, acetaldehyde and acetic acid (Cirilli *et al.*, 2012). These advantages do not mean that the grape is guaranteed to be better because there may even be a reason to use temperatures of 20 or 30°C, but we know that the higher the temperature, the more oxidation of compounds occurs. High temperature is a determining factor for sun-drying as in Pantelleria or the Aeolian Islands or in Andalusia (Malaga, Jerez, Montilla-Moriles). The must from such dried grapes mainly has the aroma of over-ripe or dried fruit with some toasty notes, due to the Maillard reaction (Franco *et al.*, 2004). An interesting paper by Piombino *et al.* (2010) on the processing of wine grape cv. Malvasia carried out in the Aeolian Islands to produce the Passito wine Malvasia delle Lipari, showed that the off-vine bunches dried under shaded conditions significantly affected the volatiles of Malvasia delle Lipari wine traditionally produced by sun-dried grapes. The wine coming from shaded dried berries was richest (67%) in free volatiles with 20% higher total bound terpenoids. It is interesting to note the high content of alcohols derived from amino acid catabolism in wine coming from shaded dried berries, probably due, as the authors suggest, to the lesser availability of free amino acids (less degradation due to the lower temperature) and even to the higher concentration of volatile phenols likely due to light degradation of the precursors in the sun-dried berries. Speaking of sun-drying, the effect of temperature and light is combined and there are no papers which discriminate between the two factors. When we speak of closed facilities for dehydration, as explained later, the light effect disappears and only the temperature effect becomes important. However, if we wish to study the effect of temperature on metabolism during dehydration, the closed system is the best. Sun radiation

Table 3.3 Changes in volatile terpene compounds (μg 100 g^{-1}) in Muscat of Alexandria (Zibibbo) on Pantelleria island.

	Before dehydration	After sun dehydration (40% weight loss)	After sun dehydration in plastic tunnel (40% weight loss)
Free terpenes	1285 ± 518	1246 ± 40	352 ± 21
Glycosylated terpenes	3814 ± 1607	2450 ± 1119	1840 ± 607
Free linalol	1192	392	158
Glycosylated OH-linanol	386	295	164

Source: Modified from Di Lorenzo (2007).

(UV and infrared) plays an important role in polyphenol biosynthesis (Rustioni *et al.*, 2007) and in the anthocyanin fraction (Tarara *et al.*, 2008) during berry growth. Most compounds important for flavour, such as methoxypyrazines, accumulate during the green stages of berry development and are gradually metabolized during maturation; the extent of this is dependent upon sun exposure and other microclimate factors (Lund and Bohlman, 2006). Since grape berry cells continue to live after harvest, the possibility of having the biosynthesis of important compounds for final wine quality will depend on the dehydration rate and on the amount of weight loss during sun exposure for drying. Sun exposure, however, is both complex and difficult (but not impossible) to control, and the need to attain a high sugar content as a unique quality parameter for dried grapes, results in no one taking care to manage the dehydration process during sun-drying, which cancels out the differences in the quality of different varieties of grapes, especially in terms of primary aroma. In particular, under high temperature conditions, strong oxidation occurs and the majority of the primary volatiles are oxidized with the formation of hydroxylated compounds such as the large increase in OH-geraniol, OH-linalool, OH-citronellol, and the consequent decrease in linalool, geraniol and citronellol (Di Lorenzo, 2007) in Muscat grape sun-dried on Pantelleria island. In Table 3.3 we can observe the great drop in free and glycosylated terpenes and linalool during sun dehydration under plastic tunnel and between sun dehydration in air or under plastic tunnel.

For this reason we believe that the use of high temperature has a negative impact on grapes and cancels their amazing aromatic diversity, giving sweet wines a similar aroma. This is why we have changed Rozis' first rule for food drying, reported earlier; instead of supplying thermal energy, we must remove thermal energy (heat), reducing the dehydration temperature. Figure 3.4 shows what happens in different aromatic and non-aromatic cultivars during dehydration at three different dehydration temperatures.

Aromatic cultivars (Muscat, Aleatico, Malvasia, etc.) dehydrated at 10°C keep the varietal aroma, but dehydrating them at high temperature causes them to lose the varietal aroma and shift to the aroma of Vinsanto and Passito wines from hot regions, because oxidative aroma becomes predominant. Vice versa, non-aromatic cultivars such as Trebbiano, Cesanese and Sagrantino can emphasize their own weak primary aroma if they are dehydrated at low temperature. This is only a general assessment to give an idea of how the management of dehydration can change the aroma profile, but the following vinification process plays an important role in guaranteeing the maintenance of the varietal volatile compounds.

In conclusion, as regards temperature, we can state that keeping the dehydration temperature at 10°C or lower, first of all, slows down the water stress response, then reduces the

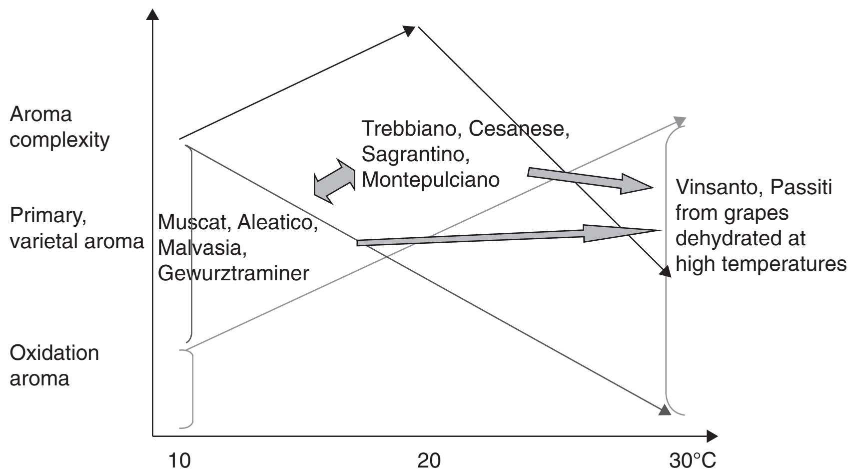

Figure 3.4 Changes of aromatic panorama of different grapes cultivars during dehydration (40% weight loss) at different temperatures based on experimental and commercial data (Mencarelli, unpublished data).

formation of oxidative compounds, maintains the varietal volatile compounds and delays the formation of volatile acidity; whereas, using a temperature of 20°C favours aroma complexity, increases volatile acidity and increases the phenolic fractions.

Besides temperature, the other very important factor for grape dehydration is the RH of the environment. The formula for RH is:

$$\text{(vapour pressure of air} \times 100)/\text{vapour pressure at saturation point.}$$

For all practical purposes, it gives an indication of the capacity of air to pick up water. The lower the RH of the environment, the faster the weight loss from the grapes, whatever temperature is used. We have already spoken about VPD as the driving force of weight loss: this factor increases when the RH decreases, keeping the temperature constant. Thus, maintaining a low RH is one of the goals of the dehydration process, but there are physiological and technical limitations.

Physiological limitation is related to the need to slow the dehydration process down. We saw earlier that the dehydration rate decreases when low temperature is used and this is very important for obtaining good grape characteristics. As we have already discussed, the water loss process must occur slowly to have continuous diffusion of water vapour from cell to intercellular space and to prevent the superficial cells of the berry from squeezing each other, making a continuous barrier against water loss. The interesting paper published by Barbanti *et al.* (2008), where different temperatures (10, 15, 20 and 25°C) and different relative humidities (53, 75, 95%) were used to follow the dehydration of Corvina, Corvinone and Rondinella grape cultivars, reported the withering kinetic rates. They increased with increasing temperature and decreasing RH (both above and below the critical moisture value). Moisture diffusion coefficients, calculated for each trial condition by solving a simplified equation based on Fick's second law, varied from 1.63×10^{-13} to 6.34×10^{-12} m^2 s^{-1}. Withering kinetic rates showed an opposite dependence on temperature and RH, as shown by multiple linear regression analysis results. The grape surface-to-volume ratio affected the withering kinetic rates for values above 3.8 and at low RH (53%). Chkaiban *et al.* (2007) showed that when the dehydration environment is not hygrothermally controlled, such as for the traditional dehydration of grapes for making Vinsanto wine in Tuscany, the continuous change in VPD causes a fluctuating change in relative weight loss. This behaviour causes an acceleration of water stress and a rapid rise in volatile acidity in the berry. As a comparison, they show that the maintenance of a hygrothermally controlled environment postpones water stress. Careful control of the environment plays an important role even in the evolution of volatile compounds in grape berry. In a study carried out on white wine cv. Pecorino, dehydrated under controlled or uncontrolled conditions, up to 25 and 45% weight loss, it was shown that the volatile compound panorama is quite different with similar percentages of groups of volatile compounds at 25% weight loss and with a significant prevalence of alcohols, mainly fuel alcohols, in berries from uncontrolled conditions at 45% weight loss (Figure 3.5).

On the other hand, if the low RH speeds the dehydration process up too quickly, the high RH during grape dehydration is extremely detrimental, especially if an efficient ventilation system is not used, as is the case in the traditional dehydration technique (*fruttaio*). High RH

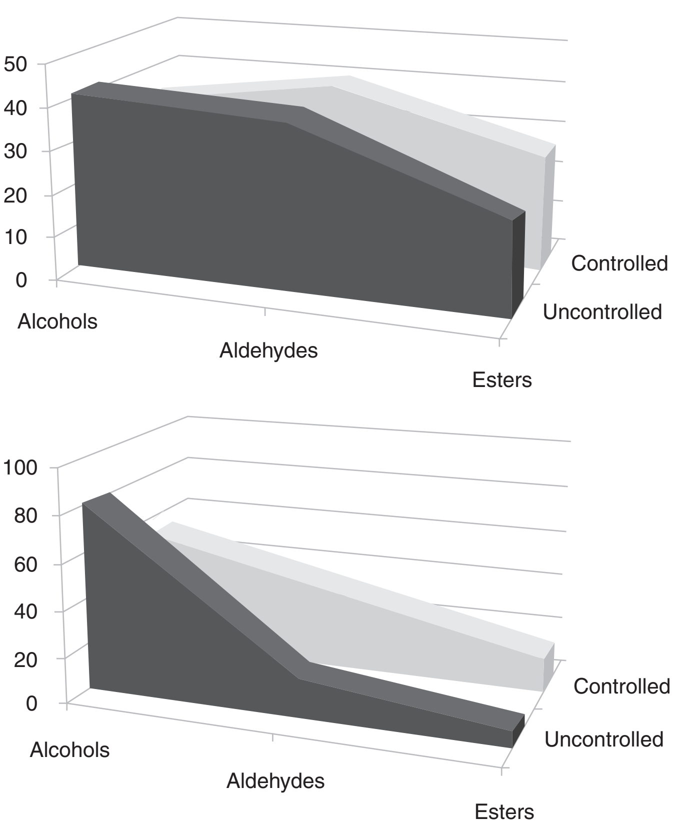

Figure 3.5 Total alcohols, aldehydes and esters in Pecorino grape berries dehydrated in uncontrolled or controlled conditions (10°C, 45% RH) up to 25% (up) and 45% (down) weight loss. Reproduced with permission from Prosperi (2007).

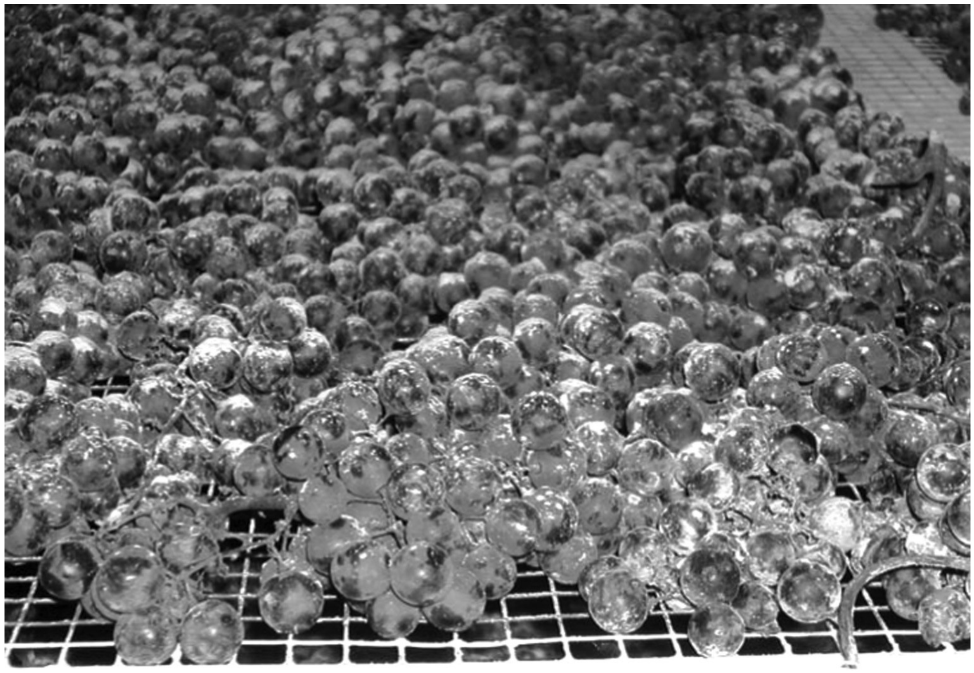

Figure 3.6 Excess of sulfur bentonite on grapes cv. Sagrantino placed over a metallic net for dehydration. (For a colour version of this figure, please see the colour plate section.)

not only prevents water loss but favours fungal attack, mainly by *Botrytis cinerea,* but also by other fungi like the *Aspergillus* family, which can produce ochratoxins.

As we mentioned earlier, besides the physiological limitation, there is a technological constraint. The reduction of RH in the environment where the grapes are placed for dehydration requires a great input of energy for the dehumidification apparatus, thus it represents one of the main costs of the dehydration process. For this reason the RH is often kept around 70–75% in the dehydration facility; this value is not always associated with temperatures below 10°C, and together with inadequate ventilation, makes the berry susceptible to fungal attack. To prevent this infestation and the development of mould, the operators spread sulfur-bentonite over the grape bunches, which results in a white, powdery blanket. This powder absorbs the water vapour from the surface of the berry, facilitating water loss but, at the same time, when the absorbent capacity is finished, it creates a barrier to prevent water vapour from escaping (Figure 3.6).

Rapid water loss and contact between sulfur and berry peel induces cell death, compromising the useful pool of secondary metabolites located in the berry peel, with loss of volatiles, browning of white grapes and bleaching of red grapes. In conclusion, keeping RH low (40–60%) during dehydration of the grapes is as important as keeping the temperature low, and the investment is repaid by the quality of the final grapes.

The last but not least factor affecting dehydration is ventilation, air flow. Fluid dynamics is a subdiscipline of fluid mechanics that deals with fluid flow, the natural science of fluids (liquids and gases) in motion. In traditional dehydration techniques, the air flow is natural

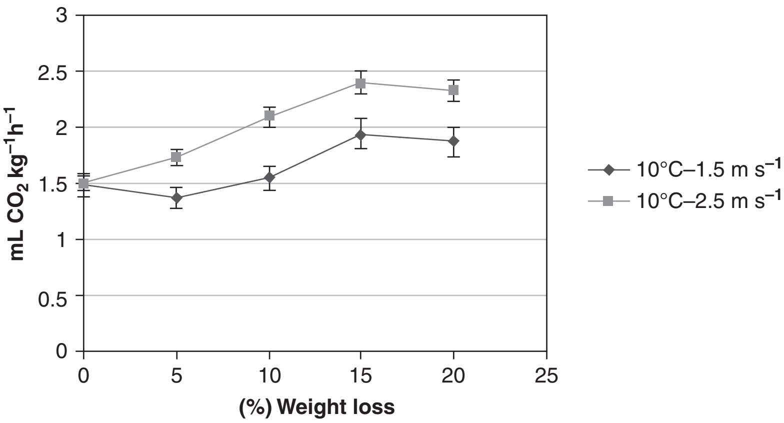

Figure 3.7 Respiration rate of grape cv. Pecorino during dehydration at different air flow. Reproduced with permission from Prosperi (2007).

and conditioned by the arrangement of windows and doors in the room where the grapes are placed to dehydrate. In a facility where the dehydration environment is hygrothermally controlled, the air flow is often insufficient, meaning that it does not reach and 'envelop' the berries, or it is too fast, causing rapid dehydration, or in other cases the air flow is not properly channelled and thus the grapes bunches do not receive the same amount of air. The effect on berry structure of different dehydration air speeds has been clearly shown through magnetic resonance imaging (MRI) by Bellincontro *et al.* (2009). They demonstrated that the faster the air flow at 10°C, the more decompartmentalized the texture of the berry, and the texture is similar to that of a berry kept at a higher temperature.

The effect of air flow on the main metabolism is emphasized by the influence on the respiration rate of the berries during dehydration (Figure 3.7).

Besides the effect on the main metabolism, the air flow affects the secondary metabolism. In Cesanese grape cultivar, dehydration with an air flow of 2.4 m sec^{-1} caused a loss of 30% of total polyphenols whereas, with an air flow of 1.2 m sec^{-1}, the loss is only 17%; no difference was observed for total anthocyanins (Tiberi *et al.*, 2008, unpublished data). It is clear that the effect is not related to the air flow but to the rapid water loss induced by higher air flow. We have observed that in detached berries placed in a dehydration environment, if the RH of the environment is 60%, an air speed of 3 m sec^{-1} accelerates the weight loss of the berries compared with the use of an air speed of 1.5 m sec^{-1}; in contrast, using an RH of 40%, the effect of the speed of the air flow is not noteworthy. By using whole bunches instead of detached berries, the difference observed at 60% of RH between the two air flows was not seen. Why this different response? The reason is found in fluid dynamics and, particularly, in the Reynolds number (RN), which points out when an air flow goes from laminar (the flow moves straight in one direction) to turbulent (the flow draws different paths but always in the same direction).

$$\text{RN} = (\text{humid air density} \times \text{air speed} \times \text{product diameter})/\text{viscosity coefficient}.$$

At 20°C the viscosity coefficient is 1×10^{-3} and 1.8×10^{-5} for water and air, respectively. For water, reducing the environmental temperature to 0°C, this coefficient increases

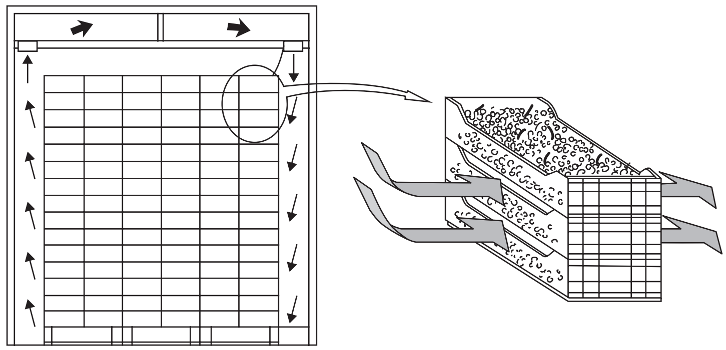

Figure 3.8 Drawing of a cross-section of a new tunnel for grape dehydration with air flow path. Image courtesy of Mercadini, Marvil Eng., Bozen, Italy (2004).

to 1.8, while for air it decreases to 1.7. Thus, the greatest change in the viscosity coefficient with modification of the environmental temperature is due to the water vapour content in the environment.

The higher the RN, the more turbulent the air flow. Being directly correlated with air speed, if the air speed is high, the air flow is more turbulent and strikes a compact bunch (greater mass than single berries), the turbulence increases further, flowing around the bunch and creating vortices in the face opposite to the one struck by the flow. This is not a good way to sweep water vapour off the berry surface. In contrast, if the air speed is lower, the RN becomes smaller and the flow becomes laminar, flowing into the bunch, through the berries, enveloping them.

Finally, besides the care that should be taken when choosing the air flow, which should be between 0.2 and 0.5 m sec^{-1} among the bunches in a box (meaning that the air flow striking the box should have a speed of 1.5–3 m sec^{-1}), it is important to take the following points into account:

- fill the box (or straw) with the bunches in a single layer;
- place the bunches close to each other without leaving empty spaces if using a new dehydration tunnel (Figure 3.8) where boxes with bunches create a double wall and the fans pull the air through the bunches into the double wall, such as a serpentine cooling system (Thompson, 2004); in the case of the traditional technique, the bunches must be placed far apart;
- if plastic boxes are used, use those made specifically for grape dehydration, perforated, with solid plastic, not flexible, with no sharp edges (Figure 3.9);
- stacking of boxes in closed ventilated facilities is very important; air must pass through the bunches; if it finds an open space, it flows into the open space and does not strike the bunches;
- if big fans (7–8000 m^3 h^{-1}) are used, their arrangement is very important to avoid air crossing or too strong a flow against one stack and no flow to another; for these kinds of fans it is better to leave a channel between two stacks of boxes that is as wide as the fan diameter, by creating a Venturi effect, which allows ventilation of the boxes by means of a negative pressure; furthermore, it is important to take into account the air arrow, meaning the distance reached by the air flow leaving the fan, which should be as straight as possible for the length of the stacking channel.

Figure 3.9 Perforated box unsuitable for grape dehydration: berries are pressed in the holes with sharp edges.

Some new grape dehydration facilities have an air flow that is carefully arranged through fan adjustment. The following is a list of the requirements to be considered when dimensioning a dehydration room (Accordini, 2009).

1. Technology employed: natural-traditional, integrated or with total control of the thermohygrometric conditions
2. Perforated plastic boxes of 4–5 kg or 9–10 kg capacity
3. Quantity of grapes to dehydrate
4. Duration of the dehydration
5. Stacking of the grapes in the dehydration room
6. Available electric power (kW)
7. Number of recirculations of room air volume
8. Air flow speed
9. Temperature to be used
10. RH to be used.

3.4 GRAPE DEHYDRATION/WITHERING TECHNIQUES

As mentioned earlier, the term withering is frequently and commercially used especially in the case of the process carried out under uncontrolled environmental conditions. Apparently, the withering process appears to be a more complex event of metabolic evolution (water stress and over-ripening or senescence) and modification of the grape berry as well as the cluster, which are significantly affected by the process. Zironi and Ferrarini (1987) suggested that wine-grape drying (withering) is a special application of the over-ripening processes that is prevalently characterized by water removal from the grape berry. This process, which can last from three weeks to up to four months, allows a sugar concentration of about 30–40% to be achieved, and a final product that is richer in aroma and glycerol and thus characterized by more structure and full of aromatic complexity. In this context, it is obvious how different methods for removing water from grapes greatly affect the dried grapes obtained at the end of the treatment.

As explained at the beginning of this chapter, the term which we use is dehydration and not drying. The grape dehydration techniques currently employed are varied; some of them are based on the oldest wine traditions and are closely related to the characteristic soil and climate environment in which the grapes are grown, others are the result of the latest technologies in this field. Fregoni (2005) suggested that the grape dehydration techniques used in Italy can be grouped into three different types: natural withering, on-vine withering, and forced withering. This breakdown can more or less be applied to all the grape dehydration techniques used throughout the world. As has been explained earlier in this chapter, withered grapes come from a natural process without controlled environmental conditions, very slow, such as for the production of Vinsanto or in the case of Sfursat in Valtellina. In contrast, when the process is fast, as in sun-dried, no over-ripening process occurs, the berries are intensely dried, and so we speak of a drying process (raisins). In the case of environmentally controlled conditions where we can go quickly or slowly through the process, the final product can be dry grapes or withered grapes, so the technique is a dehydration technique. Within each single class of this general grouping it is possible to include specific methods referring to the grape dehydration. Natural withering methods of dehydration include grapes exposed to the sun, placed on mats, on rush matting, on rocks, on roofs, and hanging in bunches. In contrast, late harvest, stem cutting, torsion of the stem, and application of dipping products are methods belonging to on-vine withering. Forced withering (dehydration) is usually obtained using ventilated (naturally or artificially) rooms called ‘fruttai’, or thermo-hygro conditioned rooms, together with forced ventilation. Another type of classification has been proposed by Valero *et al.* (2008) where a breakdown is reported in terms of grapes dehydrated by: sun-drying, warm chamber, fresh chamber, noble rot and ice.

It is particular and curious that the authors attributed the definition of ‘warm chamber’ to grape dehydration processes that take place in closed environments under uncontrolled conditions, and the definition of ‘fresh chamber’ to dehydration always conducted in controlled environments but under the control of the technological parameters affecting the drying process (e.g. temperature, RH and air ventilation).

3.4.1 On-vine withering

In regard to on-vine withering, all the practices adopted have the purpose, directly or indirectly, of delaying the harvest of wine grapes. In Italy, which is the country with the most varied typology of grape drying processes, on-vine withering is used for 17% of the total grapes treated (Fregoni, 2005). This technique is widespread and consists of leaving the grapes on the vine beyond the regular stage of technological ripening.

During the process it is usually possible to observe an increase in sugar content as a consequence of water loss and a decrease in acidity, due to the degradation processes mainly on the part of malic acid. However, the procedure of leaving the grapes on the vine after the optimal ripening stage by inducing an over-ripening effect is just one of the possible on-vine withering techniques. In fact, the producer can choose the option for grape drying directly on the vine employing technical tools capable of interrupting the natural evolution of the physiological ripening. The practices used for on-vine grape withering, such as engraved ring, torsion of the pedicle, double reasoned maturation (Cargnello *et al.*, 2006), are all techniques that partially or completely interrupt sieve vessel continuity and inhibit water flow to the bunches; these effects can induce an acceleration of regular grape dehydration. Another example of on-vine grape withering is represented by the method used for Eiswein or Ice wine production. The drying processes caused by the presence of *Botrytis cinerea* in the form of noble rot can also be counted among the processes belonging to the on-wine withering methods; in this case, the drying effect is strictly related to the fungal metabolism.

3.4.2 Natural withering

The general term of natural withering describes all the procedures of wine grape dehydration that are based on the favourable actions of the environmental conditions like direct grape exposure to the sun or to wind, together with the use of house garrets and house floors arranged for grape drying. In Italy, natural withering covers 78% of the total drying procedures for grapes destined for wine production (Fregoni, 2006), considering that the specific techniques employed differ from country to country and from vineyard to vineyard. In Italy, when grape withering is still carried out in closed and ventilated rooms, these environments are typically called fruttai, and this is probably the most common method for natural grape drying (Amati *et al.*, 1983). Grape bunches collected and suitably selected are placed in a single layer on specific supports, which in most cases are made of wood, at least as regards the frame, and are usually called ‘graticci’ (Figure 3.10). These structures can be stacked or not and left in ventilated rooms or in external environments for the withering processes. The specific base on which the grapes are placed for dehydration can differ in terms of structure and construction materials. For instance, it is possible to find dehydration procedures obtained by leaving grape bunches on straw mats (like for Vinsanto or other types of Vino Passito produced in Italy) or on iron wires. In both of these methods the grape bunches are turned over many times during the withering process.

Another commonly used technique is to hang the grape bunches; the bunches can be suspended in different ways from supports made of different materials. In the Italian Picolit wine production area (the Friuli–Venezia Giulia region), producers hang the grape bunches, still with their branch, from vertical mesh nets. In other cases, the bunches are twisted around strings (Torcolato wine), or around wires, as in the case of some grape varieties destined for the production of Vinsanto. It is also possible to find horizontal wires used, to which the bunches are suspended from ‘S’-shaped hooks, as in grape withering for the production of Erbaluce wine or for Vinsanto in Tuscany (Figure 3.11).

In all these cases the reason for suspending the bunches is both to achieve a healthy air flow passing through them and to facilitate the selection operations with the elimination of damaged and/or mouldy bunches. However, despite the care taken in grape bunch management, it is not unusual to find the development of moulds during withering under natural conditions, when environmental parameters (temperature, RH and ventilation) are not properly controlled.

Figure 3.10 Fruttaia of Avignonesi winery in Tuscany for the production of Vinsanto. Picture by Mencarelli with permission of the owner (2005). (For a colour version of this figure, please see the colour plate section.)

Figure 3.11 Erbaluce (left) and Trebbiano and Malvasia (right) bunches dried for Passito in Piedmont (picture by Mencarelli, with permission of the owner, Ciek winery, 2010) and Tuscany (picture by Mencarelli with permission of the owner, Frescobaldi Winery, Pomino, 2006), respectively, hung on wires or on a wooden frame. (For a colour version of this figure, please see the colour plate section.)

Figure 3.12 Muscat of Alexandria (Zibibbo) bunches dried in the sun in a yard on Pantelleria island. (For a colour version of this figure, please see the colour plate section.)

If climatic conditions are favourable, grape withering is carried out with grapes exposed to the sun, as is the case of Passito di Pantelleria in Sicily (Italy) and Pedro Ximénez in Andalusia (Spain). In the drying procedure used for Muscat of Alexandria (Zibibbo), which is the grape variety used for the production of Passito di Pantelleria, or Malvasia delle Lipari in the Aeolian Islands, the grapes are usually harvested slightly over-ripe. The grapes bunches are then quality selected and placed over plastic nets laid on the ground between the vines or over the house roof or in the yard (Figure 3.12); sometimes wooden frames with metal net or plastic boxes are used, as is the case of Salina island (Figure 3.13).

Figure 3.13 Malvasia bunches drying in the sun on the Aeolian Islands. (For a colour version of this figure, please see the colour plate section.)

Figure 3.14 Zibibbo grapes drying in plastic tunnel on Pantelleria island. (For a colour version of this figure, please see the colour plate section.)

In this way the grapes are subjected to sun exposure for the dehydration process, which lasts approximately 10–15 days, obviously depending on the environmental conditions. It depends on the specific area of production and on the weather conditions, especially overnight; the grapes may be covered in order to prevent negative effects caused by high humidity or possible rainfall. To avoid the problem of rainfall, tunnels covered with polyethylene film have recently been used (Figure 3.14). Unfortunately, this method leads to a huge increase in berry temperature, significantly compromising the primary aroma of the grapes.

In Spain, as a result of the dry weather, the grape bunches are placed in a single layer on sheets which are laid directly on the ground. The sheets arranged in this way, one next to the other, can cover entire fields, which are typically called *pasera* in Spanish. Because of the high temperature, the dry climate and the strong sun exposure, the drying procedures generally last 7–10 days. When natural withering processes are carried out under external conditions and, in particular, by exposing grapes to the sun, a possible negative effect, which is also favoured by the high RH and good temperature conditions, is the spreading of fungi and the possible consequent contamination of the grapes by ochratoxins (Valero *et al.*, 2008).

3.4.3 Forced withering

The definition of forced withering is usually used to describe the grape drying procedures that take place in closed environments which frequently have technology installed for the partial or total control of air ventilation, RH and temperature (Fregoni, 2006).

Indeed, the term 'forced' does not seem to be totally appropriate to define the process, as total control of the environmental parameters might not necessarily favour acceleration of the drying effect on grapes but could be aimed solely at control of the process. As explained in the first part of this chapter, the possible modulation of the parameters affecting dehydration could also be used for the control or slowing-down of the drying event (e.g. the use of low temperature, or high humidity or low ventilation, alone or combined). On the basis of this consideration, the definition of 'controlled withering' might be more appropriate to describe this kind of wine grape dehydration. The use of technologies for controlling environmental conditions is not only aimed at modulation of the grape dehydration process, with important consequences on the formation of useful metabolites for wine (Chkaiban *et al.*, 2007; Mencarelli *et al.*, 2010; DeSanctis *et al.*, 2012), but is also aimed at preventing pathogen attacks, rot diffusion and consequentially, possible mycotoxin contamination. Technologies for the partial control of environmental conditions were proposed based mainly on high ventilation and relatively high humidity (Amati *et al.*, 1983; Corte *et al.*, 2001). The production of Amarone (dry) and Recioto (sweet) wines, which are famous Italian wines obtained from the same dehydrated grape varieties, is also based on grape dehydration that takes place in closed environments (fruttai) where, however, there is a combination of forced ventilation and more or less dry air (Paronetto and Dellaglio, 2011). When the climate is quite hot and dry, the windows of the fruttaio are opened and the dry air from outside is ventilated into the room, to favour grape dehydration and the partial control of mould spreading. Vice versa, when the external air is humid, the windows are closed. It is obvious that such techniques do not guarantee accurate control of grape dehydration and grape sanitation. Temperature, as well as RH, can be more or less controlled by artificial systems, but in some case the large size of the dehydration facilities, such as for Amarone wine, and the large amount of grapes to be dehydrated, in addition to the need to save energy for the environmental control of the facility, makes these systems not perfectly suited to obtaining an excellent final dehydrated product. As regards ventilation, large fans (1.5 m in diameter) with a delivery capacity of around 3000 m^3 and 0.75 kW h^{-1} of electricity consumption, are used in these facilities. The spatial distribution on the floor of these fans among the stacks of pallets with grapes inside the large facilities is done with the objective of removing as much air as possible. Unfortunately, when the ceiling of the facility is very high (5–10 m), the air flow of the fans placed on the floor is unable to remove the air over the fans and under the ceiling, with consequent non-uniformity in temperature and RH. A new technology for guaranteeing uniform air distribution has been developed by an Italian company, Antonelli, with a vertical stack of fans which moves forward and backward through the pallet stacks (Figure 3.15). This guarantees a more uniform temperature and RH in the dehydration environment.

Recently, even traditional producers of Amarone and Recioto wines have started to use dehydration systems in which environmental parameters are totally under control. Studies conducted over the last 10 years proposed and demonstrated the effectiveness of controlled dehydration in terms of possible modulation of the dehydration process (Bellincontro *et al.*, 2006). For instance, the possible use of different temperature conditions (low or relatively high) together with a lengthening or shortening of the duration of the process, can have a significant effect on the quality attributes of the grapes destined for wine production (Bellincontro *et al.*, 2004; Pietromarchi *et al.*, 2007; Botondi *et al.*, 2008; Bellincontro *et al.*, 2009). New facilities by Italian Companies, built as cold storage rooms but with a combination of coil and condenser inside the dehydration room, have the aim of reducing

Figure 3.15 New technology for air ventilation in a grapes dehydration facility. (For a colour version of this figure, please see the colour plate section.)

temperature and, at the same time, RH, and are becoming widespread in Italy (Figure 3.16). These rooms provide very accurate control of the environment climate by allowing the use of a wide range of dehydration temperatures (5–30°C) and relative humidities (15–95%), as well as the possibility of managing air speed. This room can even be used for controlled botrytization treatment on grapes (Guenzi *et al.*, 2011).

Figure 3.16 Dehydration rooms for grapes with accurate control of the environmental parameters. Pictures by Mencarelli (2008–2009). (For a colour version of this figure, please see the colour plate section.)

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