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Interactions among genotype, environment and agronomic practices on production and quality of storage onion (*Allium cepa* L.) – A review

Agnieszka Sekara[1], Robert Pokluda[2], Laura Del Vacchio[3], Silvano Somma[3], Gianluca Caruso[3]*

[1]*Department of Vegetable and Medicinal Plants, University of Agriculture, Krakow, Poland*
[2]*Faculty of Horticulture, Mendel University, Brno, Czech Republic*
[3]*Department of Agricultural Sciences, University of Naples "Federico II", Italy*

**Corresponding author: gcaruso@unina.it*

Abstract

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The aim of this review is a wide description of the relationships between growing conditions and bulb yield and quality of onion (*Allium cepa* L.), focused particularly on long-day cultivars suitable for storage. Marketable yield decreases according to the reduction of crop length caused by the increase of growth temperature. The nutritive requirements of storage onion are highest during the vegetative growth. The application of humic substances and the inoculation of mycorrhizae may enhance bulb growth and quality, mainly under stress conditions. Onion is a slow-growth, shallow-rooted crop with non-shading habitus and therefore its productivity is highly dependent on water availability in the soil, proper fertilization and weed control. The shelf-life of onion bulbs is a genetic trait, improvable by efficient crop and post-harvest management, and adequate conditions of bulb storage. The quality of storage onion bulbs is ascribed to several indicators, such as thiosulfonates, pyruvic acid, soluble solids, sugars, and many other biological compounds. This review is also focused on onion quality as affected by the interactions among genotype, environment, farming practices and post-harvest management.

Keywords: bulb yield; farming management; shelf-life; thiosulfonates; antioxidants

Geographical distribution

Onion (*Allium cepa* L.) belongs to the Amaryllidaceae family and originates from western Asia, i.e. Turkestan and Afghanistan. It is among the oldest cultivated species and, according to the Codex Ebers (1550 BC), an Egyptian medical papyrus, ancient Egyptians used several therapeutic formulas based on onion as remedies for a variety of diseases (Block 1985).

Currently, onion is one of the most important crops grown in the world (Kumar et al. 2007b), with total cultivated surface of about 4.4 million ha and 85.8 Mt production in 2013. Asia produces 66.8% of the world onion, China being the major producer with 22.3 Mt, followed by India with 19.3 Mt. Other important producers are United States (3.2 Mt) and Iran (2.4 Mt). European production reaches 9.2 Mt, corresponding to 10.8% of total world production, with the highest value

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of 1.3 Mt in the Netherlands and 1.2 Mt in Spain (FAOSTAT 2013).

Physiological features

Onion is a biennial herbaceous plant, therefore the annual growing is to be accurately planned, in order to prevent bolting. Indeed, onion plants are induced to flowering by low temperatures, ranging from 5°C to 13°C (Thompson, Smith 1938; Woodbury 1950; Aoba 1960; Brewster 1987), provided they have passed through the juvenile phase (Heath, Mathur 1944; Hartsema 1947; Shishido, Saito 1975; Rabinowitch 1990). The juvenile phase is over when the plant has developed 4 to 14 leaves, depending on the genotype (Heath, Mathur 1944). However, temperature over 20°C accelerates the growth of emerged inflorescences compared to 15–20°C (Brewster 1982), whereas inflorescences get suppressed by temperature exceeding 25°C (Heath 1943a,b; Heath, Mathur 1944).

Onion is among the most sensitive crops to salinity, which affects plant growth and productivity particularly at the emergence of seedlings; yield reduction starts over 1.4 dS/m EC and reaches 50% at 4.1 dS/m (Alen et al. 1998). Moreover, the tolerance ranges of other soil parameters are as follows: pH 6.0–6.5; organic matter (OM) 25–35 mg/kg; P 129–168 mg/kg; exchangeable K, Ca and Mg, 0.39–0.50, 5.8–6.7 and 2.1–2.7 $cmol_c$/ kg, respectively (Lee, Lee 2014).

External scales of bulbs represent a protection tool and their number and integrity play an essential role in rating the commercial value of storage onion; their colour is a varietal trait, associated with the presence of pigments even acting as antioxidants (Prakash et al. 2007).

Genotype and environment

Genetic factors affect the variability of many traits marking differences among cultivars: morpho-physiological characteristics; photoperiod requirements, duration of crop cycle and storage ability; bulb yield, size, shape and colour; bulb quality in terms of pungency, dry residue, content of sugars and soluble solids, antioxidant capacity of flavonoids (Randle 1992a,b; Marotti, Piccaglia 2002; Yoo et al. 2006).

The overtime breeding activities have led to a large number of cultivars and ecotypes, identifiable on the basis of morphological, physiological, productive and qualitative features. With this respect, the production of onion hybrid seeds is aided by cytoplasmic male sterility, as maternal transmission of both the mitochondrial and chloroplast DNAs allows for polymorphisms in either genome, which is useful for classifying onion cytoplasms (von Kohn et al. 2013). However, the degree of genetic trait expression depends on the interaction of genotype with environment and farming practices. With this respect, Tsukazaki et al. (2008) constructed a new linkage map on *Allium fistulosum*, the first one mainly based on SSR markers in the genus *Allium*, which will be useful for genetic studies such as QTL analysis of agronomic traits.

Among the genetic features, the induction of bulbification is associated to temperature and photoperiod: onion cultivars are termed as short-day, needing under 12 hours light, middle-day from 13 to 14 hours and long-day between 15 and 16 hours. Environmental limitations may arise from the interaction between temperature and day length, since the warm conditions of late spring hasten bulbing response in short-day cultivars, forcing plants to develop smaller bulbs, but, conversely, colder winter temperatures can induce "bolting" (Gaskell et al. 1998). Moreover, cultivars resistant to bolting require longer exposure to cool temperature than susceptible varieties to be induced to pre-flowering (Shishido, Saito 1975; Bertaud 1988). However, the time interval from planting to inflorescence progressively shortens with increasing day length or temperature up to 24.8°C (Brewster 1982; Gaskell et al. 1998). Notably, in onion the "flowering locus" genes which encode proteins involved in regulating flowering are different from those which regulate bulb formation; the ability of "flowering locus" gene proteins both to repress and promote different developmental transitions highlights the evolutionary versatility of these genes (Lee et al. 2013).

The ability of bulb storage is a cultivar-specific genetic trait relevant to the duration of bulb integrity, after harvest and "cure", before sprouting and/ or rotting. Since it affects the tendency to bolting, it is connected both to planting time and market destination, allowing for distinction between fresh and storage cultivars. The latter are usually long-day cultivars, transplanted in winter or spring and harvested in summer to autumn, and can be

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stored over autumn-winter time. This cultivar type, thanks to the long period of bulb dormancy, can turn to reproductive stage only if undergone vernalisation. On the other hand, fresh onions are usually short-day cultivars, transplanted from late summer to early spring and harvested at different bulb size, according to local climatic conditions and consumers' demand. Notably, fresh onions can be harvested from bulbification beginning, as sets, to the complete development of bulbs; in the latter case, they can just be preserved for some weeks, since they have a short dormancy period. Thus, the cultivar choice is linked to local climatic conditions, precocity requirement, storage expectation, consumer's demand and market destination.

Farming practices

Ranges of values concerning the indexes of yield and growth as affected by farming practices are reported in Table 1.

Planting time and density. Planting time and density, along with other agronomic practices such as nitrogen fertilization and irrigation, can have a significant impact on the characteristics of onion plants, i.e. biomass, leaf area index, cell turgor and chlorophyll concentration, yield components and bulb quality (Hay, Walker 1989; Dubuis, Mauch 2003; Haneklaus et al. 2003; Pasricha, Abrol 2003; de Santa Olalla et al. 2004; Kumar et al. 2007a).

The choice of planting time is crucial, since each cultivar has its own degree of susceptibility to bolting, whose intensity also depends on seasonal time when the conditions for induction occur.

In southern Italy (Caruso et al. 2014), planting delay of storage cv. 'Ramata di Montoro' from early February to mid-March resulted in remarkable shortening of crop cycles, with smaller leaf area and dry weight of plants in the latest planted crops. In fact, the longer growth season of early-planted crops allows the plants to develop larger leaf area and higher biomass than the late-planted cultivations whose vegetative growth is accelerated by increasing photoperiod, light intensity and air temperature (Khokhar 2008). Planting time also affects the mean weight and grade of bulbs as well as marketable yield: the values of these parameters gradually decrease when the planting is delayed from mid-winter to late-winter, as a consequence of crop length reduction which shortens the time available for synthesis and storage of metabolites into the bulbs (Boyhan et al. 2009a; Caruso et al. 2014). In addition, the increase of growth temperature from 27°C to 32°C results in the reduction of bulb size (Coolong, Randle 2003b) and up to 34°C enhances ripening (Coolong, Randle 2006). Moreover, the dry weight of ripe bulbs may show linear and adverse correlation with temperature (Steer 1982) or just the opposite trend (Coolong, Randle 2003b). Planting time also interacts with plant density, since plant density does not affect yield in early plantings whereas in late crops higher densities result in higher production (Stoffella 1996; Shock et al. 2004; May et al. 2007; Caruso et al. 2014). This is maybe due to the combination of crop cycle shortening and air temperature increase and, however, this correlation may also depend on cultivar (Boyhan et al. 2009b). Moreover, both mean weight and calibre of bulbs decrease with the increase of plant density from 40 to 49 plants/m^2 (Leskovar et al. 2004) or from 60 to 108 plants/m^2 (May et al. 2007), even due to the reduction of intra-row spacing from 25 to 10 cm (Aliyu et al. 2008) or from 15 to 5 cm (Leskovar et al. 2004). This is a consequence of the increased competition among plants for the available resources and of the limited space for bulb expansion.

Table 1. Range of yield and growth indexes values in storage onion (*Allium cepa* L.)

Indicator	Range	References
Bulb yield (t/ha)	27.1–86.5	Drost, Koenig 2002; de Santa Olalla et al. 2004; Ghosheh 2004; Leskovar et al. 2004; Kadayifci et al. 2005; Bolandnazar et al. 2007; Kumar et al. 2007b; Khokhar 2008; Lee et al. 2012; Buckland et al. 2013; Caruso et al. 2014; Sivesind et al. 2012
Mean bulb weight (g)	47.0–643	Hamilton 1998; Kumar et al. 2007b; Khokhar 2008; Lee et al. 2012; Caruso et al. 2014
Total plant dry weight (kg/m^2)	1.0–1.4	Drost, Koening 2001; Caruso et al. 2014
Leaf area index (m^2/m^2)	3.2–5.1	Drost, Koenig 2001; Caruso et al. 2014

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Nutrient requirement and fertilization. Fertilization should aim at enhancing the productivity of onion, in respect of nutrient requirements connected to optimum yield under minimum cost and high use efficiency of fertilizers (Lee, Lee 2014). This can be obtained by choosing the most suitable chemical form and application time, since high rates of fertilizers, especially with leachable nitrogen, may threaten the sustainability of onion systems when applied to short rotations (Buckland 2013). Notably, onion requires high level of N, P, K to attain max. yield of bulbs, compared to other vegetable crops, because the plants have a shallow, sparsely branched root system, resulting in considerable residual nutrients in soil following harvest (Brewster 2008). However, the uptake of plant nutrients depends on several factors, such as cultivar, crop environment, soil fertility, fertilization methods (Zink 1966; Salo et al. 2002; Lee et al. 2009a; Yoldas et al. 2011). According to Fink et al. (1999) and Lee and Lee (2014), production of bulbs as much as 60 t/ha takes up 108 kg/ha of N, 21 kg/ha of P, 120 kg/ha of K and 9 kg/ha of Mg, while 5 t of harvest residues remove 15 kg/ha of N, 1 kg/ha of P, 9 kg/ha of K and 1 kg/ha of Mg. In southern Italy (Caruso et al. 2014), yield of onion bulbs as much as 50 t/ha can be achieved supplying 70 kg/ha of N as ammonium sulphate, 80 kg/ha of P_2O_5 as superphosphate and 130 kg/ha of K_2O as potassium sulphate before transplanting; 130 kg/ha of N and 140 kg/ha of K_2O as calcium nitrate and potassium nitrate on dressing. Moreover, the nutrient ratio of N, P, K, Ca and Mg was 8.0:1.0:9.0:2.0:0.3 in dry matter of bulbs when yield reached 11 to 13 t/ha (Bosch Serra 1999). Notably, the concentration of N and P shows a decrease in leaf tissue but an increase in bulbs from their initial growth stage to harvest, whereas the concentration of Mg, Na and Fe results in the opposite trend (Lee, Lee 2014).

The rate of nutrient uptake changes with phenological stage, as the requirement of nitrogen is high during the vegetative growth; in fact, this nutrient plays an important role in the development of bulbs, primarily by controlling leaf growth (Drost, Koenig 2002), and plants may benefit from increased supply of fertilizer in this stage (Painter 1977; Buwalda, Freeman 1987; Westerveld et al. 2003). Conversely, excessive and late-season application of nitrogen, even during the period of bulbification, increases the growth of leaf blades (Brewster 1994); thus, it delays the ripeness of bulbs (Schwartz, Bartolo 1995) and adversely affects their storability (Brown et al. 1988; Brewster 1994). Indeed, overfertilization with N, P, K or compost causes the drop of bulb yield or the unbalance of nutrient content at harvest (Abdelrazzag 2002; Lee et al. 2012); in addition, the efficiency of fertilizer uptake decreases with the increase of N or K application rates (Lee et al. 2011).

The excess of applied fertilizer or nutrient content in the soil does not produce benefits to plants or may even depress the uptake of nutrients as well as crop growth and yield (Lee, Lee 2014), either concerning nitrogen (Boyhan et al. 2007; Halvorson et al. 2008) or phosphorus and potassium (Laughlin 1989; Amin et al. 2007; Boyhan et al. 2007; Lee et al. 2011). According to Lee et al. (2011) no increase of bulb yield is achieved over the range of 7 to 42 mg/kg NO_3-N content in the soil. Moreover, long-term and excessive application of chemical fertilizers causes nutrient accumulation in the soil, which may result in increased susceptibility of onion roots to water saturation or deficiency in the soil (Lee, Lee 2014). In western United States, frequent application of nitrogen rates as high as 450 kg/ha may increase bulb size and market value (Buckland 2013), but may also enhance both nitrogen concentration in onion tissues and crop susceptibility to pests (White 1984). Conversely, lowering nitrogen supply from 402 kg/ha to 134 kg/ha N produces a 23% reduction of thrips population, slightly decreasing both bulb size and yield under cold and rainy spring season, due to leaching and denitrification (Buckland 2013). Moreover, halving the application of non-coated urea from 224 to 112 kg/ha does not cause the decrease of bulb yield, whereas production drop occurs when the same procedure is applied to coated urea (Brown et al. 1988; Drost, Koenig 2002). The application of coated urea also improves the use efficiency of nitrogen, which is better retained in onion beds than non-coated urea formulate. Moreover, fertilizers of slow release nitrogen may produce optimal yield and size of onion bulbs; in addition, these formulates can match the application of nitrogen to the actual requirement of plants at each growth stage, thus allowing for best valorisation of this nutrient (Ells et al. 1993; Drost et al. 1997; Bar-Yosef 1999; Hochmuth 2003). With this regard, fertigation is a strategy for maximizing the efficiency of fertilizer application and for minimizing leaching losses (Ajdary et al. 2007); in this way, the prevention of nitrate pollution can be

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achieved in both ground and surface water due to excessive or inappropriate supply of nitrogen (Haynens 1985; Waskom 1994), even associated with significant health risks (Doran, Zeiss 2000). Notably, under fertigation the nutrient solution can be: easily adjusted in terms of concentration; correctly balanced as for macro and micronutrients content, using solid or liquid fertilizers; automatically delivered to crops through different methods of distribution. Among the latter, drip system is the most efficient for the nutrient absorption by roots (Liptay et al. 1997; Battilani 2008) and offers some advantages such as: reduction of salinization and groundwater pollution; decrease of nutrient fluctuation in the soil during the crop growing season; prevention of foliage wetting and pathogen infection of crops (Yarwood 1978). However, even when watering does not exceed the evapotranspiration rate, the leaching of water and nitrate may occur (Gardenas et al. 2005), depending on soil properties, crop species, management practices, climatic parameters and drip fertigation design (Ajdary et al. 2007). Notably, significant differences in nitrogen concentration and leaching among different soil textures can be detected at 10–15 cm depth, classified as the active root zone revealing the highest concentration of nitrogen. Since soil type is an uncontrollable factor affecting nitrogen leaching, fertigation can even minimize this phenomenon; for this purpose, appropriate rate of emitter discharge, duration and interval of irrigation have to be selected for shallow rooted crops, such as onion, unable to extract nutrients from deeper layers of soil (Ajdary et al. 2007).

Humic substances and arbuscular mycorrhizal fungi. Application of humic substances (HS) and inoculation of arbuscular mycorrhizal fungi (AMF) are practices aimed at strengthening the growth of seedlings by enhancing metabolism in vegetable crops, such as onion (Bettoni et al. 2014). Indeed, the seedling vigour plays a crucial role in the development and quality of bulbs, whose size depends on the number and expansion of green leaves at bulb maturity time (Addai et al. 2014; Bettoni et al. 2014). In onion seedlings supplied with humic substances, higher amounts of chlorophyll a, chlorophyll b and total chlorophyll can be found than in non-HS amended ones (Bettoni et al. 2014). This means that the improvement of photosynthetic rate has occurred (Sánchez-Díaz et al. 1990) and, accordingly, higher concentration of non-structural sugars (starch and soluble sugars) in the leaves of seedlings fertilized with HS has been detected (Baslam et al. 2011a, 2012; Bettoni et al. 2014). Moreover, onion association with AMF can enhance plant height, expansion of leaf area, chlorophyll content, plant biomass as well as dry mass and diameter of bulbs (Bolandnazar et al. 2007). In addition, mycorrhizal symbiosis can improve the defences of plants against bacterial and fungal pathogens due to increased activity of chitinase (Dumas-Gaudot et al. 1992), higher antimicrobial activity and enhanced concentration of phenolic compounds in roots (Lokhandwala et al. 2014). Moreover, mycorrhizal association in onion can also increase both the uptake of nutrients in dry soils (Azcón, Tobar 1998) and yield, whose magnitude depend on the type of fungus inoculated to plants (Afek et al. 1990). Notably, onion plants inoculated with *Glomus versiforme* contain more nitrogen, phosphorus and zinc than those colonized by *Rhizophagus intraradices* (Charron et al. 2001a,b). The interaction between AMF and phosphorus fertilization even enhances the concentration of anthocyanins, carotenoids and phenolics in lettuce plants (Baslam et al. 2011b). The mycorrhizal infected plants also show a significant ability in the uptake of nutrients and water as well as in resistance to biotic and abiotic stresses (Smith et al. 2003), due to the adaptation to a wide range of water regimes in the soil (Mosse et al. 1981). Notably, *Glomus versiforme* is very efficient in enhancing the water use of onion plants, under water deficit conditions (Bolandnazar et al. 2007), since it allows the roots for exploring greater reservoirs of available water in the soil (Fitter 1985; Koide 1993). Accordingly, the plants result in higher evapotranspiration in comparison to non-mycorrhizal infected ones, due to the increase of leaf area and biomass, and attain higher yield (Bolandnazar et al. 2007).

The humic substances applied and the mycorrhizal fungi inoculated synergistically interact in onion plants, by enhancing the growth (Linderman, Davis 2001; Bettoni et al. 2014) and the concentrations of proteins (Bettoni et al. 2014), as a consequence of the accumulation of nitrogen and phosphorous in the tissues (Xu et al. 2012; Azcón et al. 2008). The interaction between HS and AMF also has beneficial effects on growth and quality of bulbs, since it induces the highest leaf accumulation of soluble sugars and proteins, which are subsequently translocated into bulbs (Bettoni et al. 2014).

doi: 10.17221/92/2015-HORTSCI

Water management. Onion is a shallow-rooted crop, sensitive to water stress (Koriem et al. 1994), and therefore the production of bulbs and dry matter are highly dependent on the availability of soil water (Imtiyaz, Singh 1990; de Santa Olalla et al. 1994; Koriem et al. 1994; Martin et al. 1994; Prashar et al. 1994; Sharma et al. 1994; Thabet et al. 1994; Saha et al. 1997; Shock et al. 2000). This species is cultivated both under irrigated and non-irrigated conditions (Kadayifci et al. 2005) and, in order to avoid water deficiency, it should be taken into account that the decrease of water uptake occurs when about 25% available water in the soil has been depleted (Doorenbos, Kassam 1979). Further, 50% replenishment of crop water requirement results in reduced yield of marketable bulbs, due to earlier ripening and the development of either immature or partially matured bulbs, suffering from early rotting during storage (Kumar et al. 2007a). Moreover, since onion shows the reduction of both evapotranspiration rate and yield under water deficit, irrigation is necessary to obtain the optimum size and weight of bulbs, especially during the stage of bulb development (Chung 1989; Kadayifci et al. 2005). However, when water sources are limited, onion plants can benefit from practices of crop management that enhance the resistance to water stress, in order to improve the efficiency of growth and water use (Abdul-Baki et al. 1992; Egilla et al. 2001). Notably, this species appears to be less sensitive to water deficit during either vegetative or ripening stage and therefore, under water shortage, irrigation deficit should be applied to the crop in these phenological phases (Kadayifci et al. 2005).

According to Kumar et al. (2007a), irrigation has a significant effect on the growth parameters of onion, such as plant height, leaves number, neck thickness, and dry weight of plant biomass, which are significantly affected by the volume of water supplied. With this respect, Baslam and Goicoechea (2012) observed a significant interaction between water regime and inoculation of arbuscular mycorrhizal fungi in lettuce, as the inoculated plants grown under 33% water deficit showed similar dry matter of shoots compared to optimally watered control plants. In addition, size and weight of bulbs are positively correlated to the amount of water applied (de Santa Olalla et al. 1994, 2004; Kumar et al. 2007a). Notably, the highest yield of onion bulbs occurs when the soil is constantly kept moist but the irrigation is performed until two weeks before harvest, which also prevents rot and sprouting during storage (Chopade et al. 1998; Shock et al. 2000, 2004; de Santa Olalla et al. 2004). However, excessive irrigation during the vegetative period may lead to a delayed and attenuated development of bulbs (Doorenbos, Kassam 1979). In fact, the performance of onion improves with increasing irrigation until the overall water supply reaches the threshold for the optimal production of bulbs; over this threshold yield begins dropping (Orta, Ener 2001; Kumar et al. 2007a).

As for bulb quality, total soluble solids significantly increase with the increase of soil moisture, maybe due to both the fulfilment of crop water demand and the use of nutrients under optimum availability of soil moisture (Chopade et al. 1998; Kumar et al. 2007a); protein content shows the opposite trend (El-Gizawy et al. 1993; Kumar et al. 2007a).

Weed and parasite control.

Weed control. Both onion and other species of bulb crops are weak competitors for weeds emerging along the rows (Bleasdale 1959; Wicks et al. 1973; Menges, Tamez 1981; Boydston, Seymour 2002), even more when they start from seeds instead of bulbs or seedlings (Trunkenboltz, Prin 1977). Notably, onion plants are poor competitors with weeds because of their slow growth, small stature, shallow roots, and thin cylindrical upright leaves not able to suppress weed growth by shading. Therefore, weeds cause a reduction of soil moisture, nutrients, sunlight and growing space to onion plants, which may result in the reduction of plant growth, yield and quality of bulbs (Ghosheh 2004), up to 62% and 71% in terms of seedlings number and production of bulbs, respectively (Qasem 2006). According to Ghosheh and Al-Shannag (2000) weed occurrence is even more devastating to yield of onion bulbs than the *Thrips tabaci* insect infestation. Moreover, weeds germinating later in the season can interfere with the equipment for mechanical harvesting, but they have little impact on yield (Ashton, Monaco 1991).

Although early growing season is generally regarded the critical period for weed control (Ashton, Monaco 1991; Radosevich et al. 1997), it is also deemed that the optimum weeding time ranges from 21 to 56 days after the emergence of onion seedlings (Bond, Burston 1996) and the weed control in late season also plays a significant role in weed management (Ghosheh 2004). Indeed, the long growing season of storage onion

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allows for periodic flushes of weeds, therefore the crop must be kept weed-free for a relatively long term after planting to avoid yield loss (Dunan et al. 1996; Sivesind et al. 2012).

The partial phytotoxic effect of some herbicides to onion plants raises the issue of the integrated control of weeds, combining soil tillage, herbicide treatment and hand weeding, in order to achieve the most effective control of weeds (Qasem 2006). However, within conventional systems, soil tillage has a multi-purpose use, herbicide is diffusely practised, whereas hand weeding is quite neglected.

In direct-seeded onion, effective pre-emergence weeding can be performed with herbicides, such as glyphosate for non-specific weed control, oxyfluorfen for broadleaved weeds and fluazifop-butyl for wild oat (Ghosheh 2004).

In transplanted onion crops, herbicides can be applied before or after planting, at appropriate growth stages in order to avoid crop injuries (Ashton, Monaco 1991). Pre-planting application of residual herbicides into the soil, such as metribuzin, oxadiazon, oxyfluorfen, or pendimethalin, shows effective weed control in different environments, resulting in increased yield even in cabbage-onion rotation (Amrutkar et al. 2002; Sanjeev et al. 2003). Notably, oxadiazon and oxyfluorfen achieve effective weeding of both narrow and broad-leaved weeds (Qasem 2006) and, in particular, dominant broadleaved weeds are appropriately controlled by oxyfluorfen at 1.2 kg/ha a.i. and oxadiazon at 3 kg/ha a.i., both of them applied two weeks to two months after crop emergence. Oxadiazon activity shows a shorter effect than the oxyfluorfen one, but the latter may result in leaf necrosis caused by phytotoxicity (Ghosheh 2004), even in the early phenological phases under rates as low as 68 g/ha (Warholic 1982). Crop injuries may also occur later in the season, probably due to active herbicide residues that are absorbed by the roots from deeper layers of soil (Ghosheh 2004). However, onion plants show a positive vegetative reaction (Warholic 1982; Ghosheh 2004) and therefore, post-emergence treatments result in higher yield of bulbs than the pre-emergence applications (Ghosheh 2004).

Because of the concerns upon herbicide effects on human health and environment, flame weeding has become more common as weeding practice in southern Europe, especially in organic crop production (Sivesind et al. 2012). It is being effectively used for weed control in onion, either prior to planting or before crop emergence (Ascard 1995), even in combination with other weeding strategies (Ascard 1989; Melander, Rasmussen 2001; Ascard, Fogelberg 2008). Flame weeding is viable for weed control along plant rows in onion, where mechanical tillage is ineffective or causes unacceptable crop damage, and can reduce or eliminate the hand-weeding cost, while inter-row weeds can be effectively controlled through mechanical tillage (Melander, Rasmussen 2001).

The flame weeding is more effective to broadleaf weeds than to grass species (Ascard 1995; Knezevic et al. 2008; Ulloa et al. 2010; Sivesind et al. 2012), but its success also depends on propane dose and plant development. According to Ascard (1989), three sequential flaming treatments result in comparable yield of bulbs to mechanical and chemical weeding in onion. Notably, the density and biomass of broadleaf weeds decline with the increase of flame treatments number from one to six and of propane dose from 45 to 72 kg/ha (Sivesind et al. 2012); flame treatments performed in the early growing season show better effects than those done later, though flame weeding may cause damage to onion canopy and, accordingly, lead to a delay of crop maturity.

However, hand weeding represents a necessary post-planting tool within eco-compatible productive systems such as organic farming.

Parasite control. As far as onion parasites are concerned, the control strategies of the major diseases, pests and viruses are reported. In this frame, the integrated management is essential and it consists of the combination of genetic, agronomic, chemical and biological tools. Notably, the genetic and agronomic tools are applicable as a general rule for preventing the parasite occurrence; they are represented by resistant cultivars, crop rotation, disposal of onion waste, appropriate planting time and density, correct management of water and nutrients, removal of weeds and onion volunteers (Gent et al. 2006; Brewster 2008). The chemical and biological strategies are referred to as associated to each parasite species or homogeneous group of species, instead.

Among the major leaf diseases, there are: the downy mildew and the white tip, caused by *Peronospora destructor* and *Phytophthora porri,* respectively, resulting in pale green oval patches on leaves; *Botrytis* leaf blight (BLB), caused by *Botrytis squamosa* and

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whose symptoms are small, white spots with a light green halo; rust, caused by *Puccinia allii*, identifiable by rust brown clusters of spores (pustules) over the leaf, surrounded by pale yellow tissues; *Stemphylium* and purple blotch, caused by *Stemphylium vesicarium* and *Alternaria porri*, respectively, resulting in leaf lesions with brownish purple rings, which can merge with each other causing the leaf death.

The downy mildew (*Peronospora destructor*) and the white tip (*Phytophthora porri*) can be chemically controlled by choosing among the following active ingredients: copper-based formulations, azoxystrobin, chlorothalonil, cymoxanil, mandipropamid, metalaxyl, dimethomorph, dodina, folpet, benthiavalicarb, iprovalicarb, mancozeb, metiram, pyraclostrobin, systemic acquired resistance (SAR) inducers and K phosphate (Survilienė et al. 2008; Romanazzi et al. 2012). Moreover, molecular diagnostic methods are important tools in detecting and exactly recognizing a pathogen in plant tissues with no symptoms (Mancini et al. 2012).

The chemical control of *Botrytis* leaf blight (*Botrytis squamosa*) is achievable by using the following active ingredients: boscalid, chlorthalonil, dithiocarbamate, mancozeb, pyraclostrobin, fluopyram, metconazole, cyprodinil, fludioxonil, iprodione, vinclozolin. Moreover, the use of *Bacillus subtilis* and *Microsphaeropsis ochracea* represents an alternative or additional biological strategy (Carisse et al. 2015).

As for rust (*Puccinia allii*), several active ingredients are available for the chemical control: benzothiadiazole, propiconazole, tebuconazole, mancozeb, maneb, manzate, chlorthalonil, azoxystrobin, metalaxyl, myclobutanil, iprodione, sulphur, copper hydroxide (Koike et al. 2001).

The control management of *Stemphylium* (*Stemphylium vesicarium*) and purple blotch (*Alternaria porri*) can be achieved both by chemical treatment with mefenoxam and copper, or by the application of biological agents such as *Bacillus subtilis*, *Pseudomonas fluorescens*, *Saccharomyces cerevisiae*; the use of resistance inducers, i.e. Bion, K_2HPO_4 and salicylic acid, is also effective (Hussein et al. 2007).

Among the soil-borne diseases, the most spread in onion are: white rot caused by *Sclerotium cepivorum*, which results in damages to roots and bulb base; pink root caused by *Pyrenochaeta terrestris*, which leads to roots and sometimes outer skins of bulb changing from pink to deep purple colour before dying; *Fusarium* basal rot caused by *Fusarium oxysporum* f. sp. *cepae*, is identifiable by yellowing, twisted leaves, then dying, by roots turning dark brown, then rotting, and the entire plant wilting during the early stages of infection. The soil-borne diseases can be mainly controlled by performing seed disinfection, soil fumigation or solarization and biological control (Lane, Bowen 2005; Mancini, Romanazzi 2014). Moreover, real-time qPCR using primer pair P1 may be useful to differentiate between onion cultivars that are susceptible or resistant to *Fusarium* basal rot (Sasaki et al. 2015).

Among the major insects in onion crops, there are *Thrips tabaci*, *Delia antiqua,* and *Liriomyza cepae.*

Thrips tabaci causes damage by feeding on leaf tissue and by transmitting other parasites, including Iris yellow spot virus (Gent et al. 2006). The control strategies consist of: applications of predators of the genera *Aeolothrips*, *Toxomerus*, *Sphaerophoria*, *Orius*, *Coleomegilla*, *Hippodamia* (Fok et al. 2014); chemical treatments with azadirachtin, spinosad, deltamethrin, methomyl, acephate and chlorpyrifos (Jensen 2005).

Onion maggot (*Delia antiqua*) damages are caused by larvae that feed on developing epicotyls and roots of young onion plants often resulting in seedling mortality. Among the available chemical ingredients, spinosad, clothianidin, imidacloprid, thiamethoxam, and chlorpyrifos show effectiveness (Wilson et al. 2015).

Onion leaf miner (*Liriomyza cepae*) burrows tunnels in the leaves and it can be chemically controlled by dimethoate, chlorpyrifos, phoxim and imidacloprid (Mešić et al. 2008).

The main parasite nematodes in onion are *Ditylenchus dipsaci* and *Pratylenchus penetrans*, causing the stem nematode and the root lesion nematode, respectively. These affections result in twisted and deformed leaves, root rot, soft and swelled bulbs, stunted and rotting plants. They can be controlled by soil fumigation or solarization, and chemical treatments (Brewster 2008).

Viruses affecting onion are transmitted by *Thrips tabaci* and the main ones are Iris yellow spot virus (IYSV), genus *Tospovirus*, and Onion yellow dwarf virus (OYDV), genus *Potyvirus*. They can be preventively controlled by using meristem culture on symptomless plants and by preserving genetic material with virus resistance. Moreover, a clear and rapid diagnosis of these viruses is needed, as well as a control of *Thrips* and of imported materials (Gent et al. 2006).

doi: 10.17221/92/2015-HORTSCI

Bulb storability

Shelf-life of onion bulb is a genetic trait, but it is also correlated with size, dry matter content, maturity degree at harvest, and storage conditions of bulbs (Shalunkhe, Kadam 1998). This feature can be enhanced under adequate management of crop water and nutrients (Kumar et al. 2007a) as well as under controlled post-harvest conditions (Palta et al. 1976). Indeed, bulbs grown under low moisture regime in the soil are usually smaller and tend to get dried earlier than large-sized bulbs during storage (Narang, Dastane 1972), because either they have higher overall surface area or losses of water vapour occur lengthwise from the sides of bulbs (Kumar et al. 2007a). Moreover, crops grown under water stress show high incidence of neck rot as well as early rot of bulbs (Ali, Shabrawy 1971) and produce early, immature or partially mature bulbs, which start sprouting after 75 days storage (Narang, Dastane 1972). Conversely, shifting the irrigation regime from 0.60 to 1.20 replenishment of pan evaporation better meets the requirements of storage onion, although the physiological loss of bulb weight increases during 45 days storage (Kumar et al. 2007a), due to both higher moisture loss and bulb rotting.

Under 200 kg/ha nitrogen supply through fertigation, during the first 45 days storage lower physiological loss of weight occurs in larger bulbs (Thambizarsi, Narasimhan 1988); the latter show further loss in the following 45 days, primarily due to rotting and sprouting of bulbs, presumably caused by higher application of nutrients than that required by the crop (Kumar 2007a). In fact, excessive availability of nitrogen causes an adverse effect on onion storability, since bulbs tend to rot and sprout earlier during storage than those grown under optimal doses (Rao, Srinivas 1990; Kumar et al. 2007a).

Stored bulbs show increasing percentage of visible roots with increasing air humidity (5%, 40%, 90%, 100%), under controlled temperature (3 ± 1°C), thus revealing a direct correlation between root growth and humidity rate (Palta et al. 1976); in addition, rotten bulbs increase from 3 to 83% in coincidence with the 5 to 90% increase of relative humidity. However, since the increase of air relative humidity causes lower drop of bulb weight but higher occurrence of rotten onion, the most effective environmental conditions for storage of onion bulbs are 0°C temperature and <40% air relative humidity (Palta et al. 1976). Moreover, the use of controlled atmosphere produces further improvement of bulb storage. In fact, bulb sprouting and rooting are reportedly reduced during storage under controlled atmosphere with the ultra-low oxygen concentration of 0.5% to 2.0% and the 3% of CO_2 (Adamicki 2004). Additionally, onion bulbs stored for 36 weeks at 2°C in controlled atmosphere with 1% O_2 show lower loss of weight and respiration intensity as well as inhibited sprouting than in natural air with 21% O_2; dropping the O_2 concentration from 1% to 0.5% causes the acceleration of weight loss during the last period of storage. Moreover, lower reduction in water-soluble carbohydrates, i.e. fructans, occurs in 0.5% oxygen than in 21% O_2, due to the reduced breakdown of fructans during storage under low oxygen concentration (Ernst et al. 2003; Praeger et al. 2003). According to Yoo et al. (2012, 2013), onion bulbs stored for five months under controlled atmosphere at 5°C with 1% O_2 and 99% N_2 maintain better quality than bulbs kept in natural air conditions. In fact, slight decreases are recorded in the concentration of flavour precursors, glucose and fructose, whereas no changes occur in pungency as well as in the concentration of sucrose and quercetin.

During storage, onion bulbs can be affected by rot, caused by different pathogens belonging to genera *Aspergillus*, *Alternaria*, *Botrytis*, *Colletotrichum*, *Erwinia*, *Fusarium*, *Lactobacillus*, *Penicillium*, *Pseudomonas*, *Rhizopus*, causing economic loss and being harmful for human health due to production of pathogen toxins (Fink-Grernmels 1999). The chemical control can be achieved by using the following active ingredients: mancozeb, carbendazim, benomyl, bronopol, salicylic acid, and sulphur. Moreover, natural bio-fungicides such as *Trichoderma* can implement the effect of the synthetic fungicides and new perspectives are represented by the use of silver, copper, sulphur and zinc oxide nanoparticles (Kumar et al. 2015).

Bulb quality and biological properties

Ranges of values concerning indicators of bulb quality are reported in Table 2.

The quality of storage onion bulbs is ascribed to several indicators, such as thiosulfonates, pyruvic acid, dry residue, soluble solids, sugars, amino acids, lectins, saponins, mineral nutrients, vitamins C and E, polyphenols (Fenwick, Hanley 1985). Most

doi: 10.17221/92/2015-HORTSCI

Table 2. Range of quality indicators values in the bulbs of storage onion (*Allium cepa* L.)

Indicator	Range	References
Dry residue (g/100 g FW)	7.0–14.3	Hamilton et al. 1998; Kumar et al. 2007a; Caruso et al. 2014
Soluble solids (°Brix)	6.2–13.3	Kumar et al. 2007c; Lee et al. 2009a,b; Caruso et al. 2014
Proteins (g/100 g DW)	7.0–13.2	Kumar et al. 2007c; Caruso et al. 2014
Sulphur content (g/100 g DW)	0.15–1.00	Jones et al. 1991; Randle, Bussard 1993; Hamilton et al. 1998; Lee et al. 2009a,b; Caruso et al. 2014
Pyruvic acid (µM/ml FW)	1.9–8.3	Hamilton et al. 1997; Hamilton et al. 1998; Yoo et al. 2006; Lee et al. 2009a;
Total ACSOs (mg/g FW)	0.33–4.6	Lancaster, Kelly 1983; Thomas, Parkin 1994; Yoo, Pike 1998; Hovius et al. 2005; Lee et al. 2009b
Quercetin (mg/kg FW)	36–1778	Price, Rhodes 1997; Miean, Mohamed 2001; Marotti, Piccaglia 2002

of these substances show biological and pharmacological activities, such as antifungal, antibacterial, antitumor, anti-inflammatory, antithrombotic and hypocholesterolemic properties (Tansey, Appleton 1975; Tsao, Yin 2001; Rose et al. 2005; Lanzotti 2006). Notably, thiosulfonates are organosulphur volatile compounds responsible for bulb pungency, originating from S-alk(en)yl-L-cysteine-sulfoxides (ACSOs); they are located in the cytoplasm and serve as flavour precursors, through an enzymatic reaction catalyzed by alliinase, a C-S lyase present in the vacuoles, giving initially sulfenic acids (Block 1985, 1992; Rose et al. 2005). As for sulfenic acids, they are highly reactive intermediates, which immediately produce thiosulfinates by reaction of condensation (Lanzotti 2006); the thiosulfinates are also very unstable and give rise to several volatile organo-sulphur compounds along with pyruvic acid and ammonia (Lancaster, Boland 1990; Coolong, Randle 2003a). ACSOs are mainly represented by disulfides and trisulfides, among which S-methyl-L-cysteine-sulfoxide (MCSO) and S-1-propenyl-L-cysteine-sulfoxide (1-PeCSO) are major compounds (Lee et al. 2009b; Yoo, Pike 1999). Leaves are the major site of synthesis of ACSOs precursors, which are produced at higher extent under short-day conditions and are then transported to the bulb scales during bulb development under long-day conditions. Therefore, manipulating environmental and genetic factors which control the transition from the growth of foliage leaf to the development of bulbs may offer novel approaches for optimising flavour quality for different end-uses in onion (Mallor, Thomas 2008).

The lachrymatory factor (thiopropanal S-oxide) is the primary compound responsible for onion pungency, although many other volatile compounds of sulphur contribute to pungency (Lancaster, Boland 1990), but it is difficult to be analytically assessed. Therefore, the concentration of pyruvic acid in onion juice (µM/ml) is used as a pungency indicator (Schwimmer, Weston 1961). Onions with 3.5 µM/ml pyruvic acid or below are generally regarded mild and sweet, and those with over 5 µM/ml are considered pungent, but there is no absolute scale of pungency expressed by the content of pyruvic acid (Lee et al. 2009b). Indeed, pungency greatly varies among the genotypes and, notably, bulbs containing 1.9 µM/ml of pyruvic acid may taste low-flavoured, whereas those with 8.3 µM/ml extremely hot (Lee et al. 2009b).

The composition of pungency precursors and the accumulation of sulphur compounds in onion bulbs can be greatly affected by interactions among genotype, environment and farming practices, such as cultivar, growth temperature, type and fertility of soil, water supply (Lancaster, Boland 1990; Randle 1996; Hamilton et al. 1997). In fact, the ability in sulphate absorption from the soil as well as in synthesizing flavour precursors differs among onion cultivars and the genetic heritability of the trait associated to enzymatic production of pyruvic acid ranges from 48% to 53% (Lin et al. 1995). Interestingly, pungent onions may have a genetic trait resulting in the synthesis of greater amounts

doi: 10.17221/92/2015-HORTSCI

of ACSOs from the same content of sulphur compounds in the tissues (Lee et al. 2009b).

The content of total ACSOs in onion bulbs varies between 0.12 and 4.60 mg/g FW (Lancaster, Kelly 1983; Thomas, Parkin 1994; Yoo, Pike 1998; Hovius et al. 2005; Lee et al. 2009b). Moreover, the content of major flavour precursors in bulbs increases linearly with the increase of pungency level: the most pungent cultivars can contain about eightfold more 1-PeCSO (0.07 to 0.65 mg/g FW) and threefold more MCSO (0.03 to 0.16 mg/g FW) than the least pungent onions (Lee et al. 2009b).

Moreover, sulphur content in the soil has a great influence on the accumulation of ACSOs, directly affecting flavour and pungency of onion (Randle 1992a,b; Hamilton et al. 1997; McCallum et al. 2005; Guo et al. 2007). Notably, the concentration and lachrymatory factor of thiosulfonates linearly increases as the S content in the soil increases (Randle 1992a; Randle, Bussard 1993; Randle et al. 1994), but pungency is not affected by high sulphur content in the soil (Hamilton et al. 1997; Lee et al. 2009b) and it is not correlated with S level from 16 to 97 p.m. (Yoo et al. 2006). Moreover, the transcript levels of the gene associated to ferredoxin-sulphite reductase in plant roots are enhanced under sulphur sufficiency in pungent cultivars but not in the less pungent ones; moreover, the activity of ferredoxin-sulphite reductase significantly increases in response to sulphur fertilization, in the leaves of pungent cultivars but not in less pungent cultivars (McManus et al. 2012).

Sulphur absorption by onion plants and, accordingly, the intensity of bulb flavour are enhanced by the increase of growing temperatures (Randle 1996). In particular, sulphur is absorbed by the plant as sulphate, successively reduced and incorporated into cysteine, which is used for the synthesis of methionine and glutathione in the pathway of flavour biosynthesis (Anderson 1990; Randle, Lancaster 2002). Glutathione is the key metabolite for the biosynthesis of all ACSOs, starting from cysteine, glutamic acid, and glycine (Lancaster, Shaw 1989), and it serves as sulphur vehicle through several peptide pathways terminating in the synthesis of any flavour precursors (Randle, Lancaster 2002). Notably, amino acids are also included in the flavour determinants and during maturation they are translocated from the senescing foliage to the bulb (Nilsson 1980); arginine and glutamine are the most abundant in onions (Hansen 2001), accounting for over 40% of the total free amino acids. A correlation between amino acid content and pungency degree does not necessarily exist, however cysteine content may be connected to pungency, since the ACSOs are cysteine derivatives (Lee et al. 2009b).

Sulphur content in onion bulbs, on dry weight basis, may range from 0.15 to 0.40% (Lee et al. 2009b), from 0.20% to 0.60% when irrigated with 0.1 to 4.0 meq/l sulphur (Randle, Bussard 1993), from 0.44% to 0.48% when soil texture changes from loam to clay (Hamilton et al. 1998). Sulphur content in leaves increases from 0.5% to 1.0% while crop progresses to maturity, even under deficiency of sulphur in the soil (Jones et al. 1991). Similar values of sulphur content in bulbs produced in different growing conditions result in the absence of correlation between the S content in bulbs and in the soil, possibly due to sufficient level of available sulphur in the soil; the same reason could explain why pungent onion plants do not take up more S than mild onion plants from soils with approximately 110 ppm sulphur (Lee et al. 2009b). Notably, 16 ppm (Hamilton et al. 1997) or 31.7 ppm sulphur in the soil (Lee et al. 2009b) were shown to be sufficient for normal production of onion, while higher concentrations provide higher supply of sulphur than that required by plants (Hamilton et al. 1998). The concentration of pyruvic acid also increases during maturity of bulbs and it is not enhanced by the application of S (Hamilton et al. 1998; Lee et al. 2009b).

Weight, dry matter, soluble solids and sugar content in onion bulbs do not show any correlations with the sulphur content in the soil (Hamilton et al. 1998; Lee et al. 2009b). In addition, bulb weight is not closely related to pungency level (Lee et al. 2009b) and may even be adversely correlated to this attribute of quality (Yoo et al. 2006). Conversely, the interaction between cultivar and sulphur supply may significantly affect the sugar concentration of onion bulbs (Randle 1992b; Randle, Bussard 1993). Moreover, bulbs with low or high pungency may show similar values of soluble solids (6.2°Brix to 9.0°Brix), the latter being a poor indicator of total sugars, since the content of total sugars decreases with the increase of soluble solids (Lee et al. 2009b). Notably during the first phases of bulb growth, the content of total sugars decreases, probably due to dilution effect exerted by the fast intake of water (Smittle, Maw 1988); thereafter it gradu-

doi: 10.17221/92/2015-HORTSCI

ally increases until the final maturity (Hamilton et al. 1998). Carbohydrates are translocated from the senescing leaves to the bulbs (Nagai 1967), so as it happens for sulphur and nitrogen (Mallor, Thomas 2008). Moreover, the content of total sugars in the bulbs may be higher in onions grown in loam soil than in those produced in clay soil (Hamilton et al. 1998) and it is also affected by the growing location (Lancaster et al. 1988). In contrast to pungency variability, the content of total sugars does not show wide differences among the cultivars (8% to 10%), with glucose in the highest amount, followed by fructose and sucrose (Lee et al. 2009b). With this respect, McCallum et al. (2006) identified a locus accounting for the major differences in the content of reducing sugars and fructans in onion bulbs between storage varieties with high dry matter and sweet varieties with low dry matter. Although no correlation is observed between pyruvic acid and carbohydrate concentration (Randle, Bussard 1993), sugars affect the sweetness of bulbs and the ratio of sugars to pungency determines the overall flavour in onion (Vavrina, Smittle 1993). Therefore, the reduction of flavour compounds responsible for bulb pungency could allow for fully tasting the sweetness caused by sugars. Accordingly, sweetness is more perceivable in low pungency bulbs than in hot onions (Lee et al. 2009b). With this respect, chromosomes from *Allium fistulosum* may contribute to modify the quality of shallot bulbs, i.e. increasing the production of highly polymerized fructans and inhibiting the synthesis of ACSOs (Yaguchi et al. 2009).

As regards the biological properties of onion bulbs, the main active antimicrobial, antifungal and antibacterial agents are represented by thiosulfonates (Tansey, Appleton 1975; Tsao, Yin 2001; Rose et al. 2005), the peptide allicepin (Wang, Ng 2004) and quercetin oxidation products also showing activity against *Helicobacter pylori* and multidrug-resistant MRSA (Methicillin-resistant *Staphylococcus aureus*) (Ramos et al. 2006). Moreover, lectins, i.e. glycoproteins with the ability to recognize and specifically bind to carbohydrate ligands, have a pronounced anti-HIV activity (Van Damme et al. 1993). Recently, attention has also been focused on the polar compounds of onion plants, such as saponins and flavonoids, which are fairly stable at cooking as well as at storage. They are named "nutraceutical" or "phytochemicals", classified as non-essential micronutrients, and they are able to contribute to human homeostasis, playing a significant role in health maintenance (Henry 1999; Zeisel 1999). Moreover, saponins are involved in important biological processes and they show antifungal, anticancer, anticoagulant, anti-spasmodic and anticholesterol activities (Matsuura 2001; Corea et al. 2005). Notably, the anti-spasmodic effect might contribute to explaining the traditional use of onion in the treatment of gastrointestinal tract disturbance (Lanzotti 2006).

Onion bulbs are among the main sources of dietary polyphenols in many countries (Hertog, Hollman 1996; Knekt et al. 1996) and their consumption contributes to DNA protection against oxidation. Polyphenols include a great range of molecular structures and they show important antioxidant activities in dietary plants (Rice et al. 1997; Paganga et al. 1999; Boyle et al. 2000; Kim et al. 2005): in fact, they protect human organism against cellular damage (Dimitrios 2006) and, accordingly, they prevent chronic diseases (Block et al. 1992; Hertog, Hollman 1996; Diplock et al. 1998; Lampe 1999). Notably, oxidation of DNA, proteins and lipids by reactive oxygen species (ROS) play an important role in aging and in a wide range of common diseases, including cancer and cardiovascular, inflammatory and neurodegenerative diseases, such as Alzheimer's, and other age-related degenerative conditions (Borek 1997; Richardson 1993). In fact, when in vitro cell cultures derived from animal (non-neoplastic) and human cell lines (neoplastic) are challenged with specific products, chemical markers or cytological changes are assessed such as oxidative DNA damage, apoptosis markers (such as DNA laddering) or increased production of free radical scavenging enzymes (Griffiths et al. 2002).

Among polyphenols, quercetin glycosides are usually predominant, but glycosides of kaempferol, luteolin and apigenin are also present (Hertog, Hollman 1996). Recent studies (Miean, Mohamed 2001) have shown that onion leaves are characterized by the highest content of total flavonoids in comparison to the leaves of other 62 common vegetable species. Moreover, Masuzaki et al. (2006) localized the genes associated to the synthesis of both flavonoid 3c-hydroxylase and flavonol synthase in the scaly leaf of shallot (*Allium cepa* L., Aggregatum Group), through direct comparisons between the chromosomal constitution and the flavonoid contents, supplemented with SCAR analyses by using genomic DNAs.

doi: 10.17221/92/2015-HORTSCI

Though onion exhibits remarkable antioxidant functions (Cao et al. 1996; Gazzani et al. 1998), among which the effective action exerted by flavonoids on multiple cancer-related biological pathways, epidemiological data relating flavonoids with cancer are still limited (Lanzotti 2006). However, it has been shown that the intake of onion reduces cancer risk in different tissues and organs, such as stomach, colon, oesophagus, prostate, bladder, liver, lungs, mammas, skin and brain (You et al. 1989; Hu et al. 1999; Le Marchand et al. 2000; Le Marchand 2002).

Among the polyphenols detected in onion, the quercetin concentration ranges from 185 to 634 mg/kg on fresh weight basis (Crozier et al. 1997), even reaching about 1500 mg/kg, and it is the most abundant flavonoid followed by kaempferol (832 mg/kg) (Leighton et al. 1992; Miean, Mohamed 2001). Notably, quercetin monoglucoside and quercetin diglucoside are two major components of flavonoids, accounting for 80–93% of the total flavonoids (Rhodes, Price 1996; Price, Rhodes 1997; Sellappan, Akoh 2002), with quercetin diglucoside ranging from 50 to 1,300 mg/kg of fresh onion tissue and quercetin monoglucoside from 36 to 394 mg/kg (Price, Rhodes 1997). The remaining flavonoid fractions (approximately 15%) include at least 17 more components. Among the flavonoids, quercetin and its dimerized compound show the highest antioxidant activities, which are similar to those displayed by α-tocopherol: antiulcer, antispasmodic, antidiarrheal (Corea et al. 2005), anti-HIV (Gupta et al. 2003), anticholesterolic, against cardiovascular diseases (Wang, Ng 1999; Fahs, Faucher 2002). Quercetin also shows antiviral activity and enhances the bioavailability of some antiviral drugs (Wu et al. 2005).

Anthocyanins are only minor components of flavonoid spectrum, detectable in red bulbs of onion.

The polyphenol content of plant extracts is positively correlated with radical scavenging activities, which are more intense in red onion than in yellow ones, with the skin extracts showing the highest activities (Nuutila et al. 2003). Moreover, total phenols and flavonoids are strongly correlated with total antioxidant activity (Yang et al. 2004).

High content of flavonoids is shown by bulbs with coloured skins: 557.8 mg/kg of free quercetin in 'Tropea' and 979.1 mg/kg of quercetin plus isorhamnetin in 'Dorata di Parma' (Marotti, Piccaglia 2002).

In onion bulbs the highest quercetin amounts are located below the surface (Patil, Pike 1995), whereas the dry outer layers, wasted before food processing such as cooking, have large content of total polyphenols (Caruso et al. 2014), mainly quercetin, quercetin glycoside and their oxidative products (Gülşen et al. 2007), therefore potentially serving as a resource of food ingredients (Ly et al. 2005).

The quality of onion bulbs changes during storage and, notably, six weeks storage results in a decrease of total anthocyanins (64–73%), total antioxidant activity (29–36%), glucose, fructose and anthocyanins (Gennaro et al. 2002).

Domestic use of onion bulbs also causes variations of quality, as chopping bulbs results in reduced content of total flavonols as well as cooking lowers the content of antioxidants (Rhodes, Price 1996). Among the cooking methods, both microwave treatment without water and frying do not affect flavonoids and ascorbic acid in bulbs, while boiling leads to 30% loss of quercetin glycosides. Moreover, quercetin monoglucoside and diglucoside in onion are quite stable both under common boiling and heating at 100°C in oven, but they are considerably degraded under heating at 200°C in oven (Takenaka et al. 2004). The use of additives also affects quercetin, since glutamic acid enhances hydrolysis of quercetin glycosides and ferrous ions increase the loss of total flavonoids (Ioku et al. 2001).

With regard to bioavailability, quercetin is indeed absorbed by human organism (Hollman et al. 1995) and quercetin glycosides are even more efficiently taken in than quercetin itself (Graefe et al. 2001), though its absorption is low in comparison to other antioxidants such as vitamins C and E (Lotito, Frei 2006). However, high interindividual variability occurs in the absorption of quercetin, possibly due to the dependence on intestinal enzymes or transporters (Graefe et al. 2001; Moon et al. 2000).

The consumption of red bulbs of onion turns out into twenty-three flavonols in human plasma and urine excreted in the four hours following the ingestion, represented by a range of mixed sulphates, methyl, glucuronide and glucoside derivatives of quercetin (Mullen et al. 2004).

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