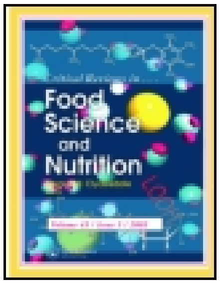

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Increasing the added-value of onions as a source of antioxidant flavonoids: a critical review

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Increasing the added-value of onions as a source of antioxidant flavonoids: a critical review

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Abstract

Flavonoids are a large and diverse group of polyphenolic compounds with antioxidant effects. While the flavonoid content and composition profile clearly reflectsthe genetic background of the cultivar, environmental conditions and agronomic practices are also determinant for the composition of crops at harvest.Considerableresearch has been directed toward understanding the nature ofpolyphenols in different products and the factors influencing their accumulation. This reviewexamines the flavonoids as a class of compounds, the role thesecompounds play in the plant, their contributions to product quality,and recent research on the impacts of environmental factorsand cultural practices on flavonoid content in onions, highlighting how this knowledge may be used to modulatetheir polyphenolic composition at harvest or during post-harvest handling.

Keywords: Polyphenols, plant foods, *Allium cepa*, pre-harvest factors, harvest handling, genotype

CONTENT

ABBREVIATIONS

AOA	Antioxidant activities
C4H	Cinnamate 4-hydroxylase
DW	Dry weight
FOS	Fructo-oligosaccharides
FRSA	Free radical scavenging
FW	Fresh weight
NBT	Nitrobluetetrazolium chloride
PAL	L-phenylalanine ammonia-lyase
POX	Peroxidase
Qag	Quercetin aglycone
Qdg	Quercetin diglucoside
Qmg	Quercetin monoglucoside
ROS	Reactive oxygen species

INTRODUCTION

Phenolic compounds constitute one of the major classes of plant secondary metabolites that, unlike primary metabolites, are not essential for plant survival. They display a large range of structures and they are responsible for the major organoleptic characteristics of plant-derived foods and beverages, particularly color and taste properties and they also contribute to the nutritional qualities of fruits and vegetables (Cheynier, 2005; Parr and Bolwell, 2000).

Over the course of evolution, plants have developed diverse defense mechanisms, including physical and chemical barriers. Phenolic compounds are particularly abundant and play an important role in both strategies, as monomers for the synthesis of lignin and as chemical agents (Fig. 1).

Among them, flavonoids are one of the most prevalent groups, accounting for more than 9000 compounds identified in plants, and the list is constantly growing (Williams and Grayer, 2004). They share a common backbone consisting of two phenyl rings connected through a three-carbon bridge, commonly becoming part of a six-membered oxygenated heterocyle. According to the unsaturation and oxidation degrees of the three-carbon segment, flavonoids can be classified into several families (Table 1) such as flavonols, flavanonols, flavones, flavan-3-ols, flavanones, isoflavones and anthocyanidins (Beecher, 2003; Scalbert and Williamson, 2000). Additionally, each family comprises a wide variety of derivatives according to the number and nature of substituent groups attached to the flavonoid nucleus. Furthermore, most flavonoids are present in nature as glycosides and other conjugates, which contribute to their complexity and the large number of different molecules that have been yet identified.

Flavonoids are synthesized in plants via the flavonoid branch of the phenylpropanoid metabolic pathway, which begins with the deamination of phenylalanine by the enzyme L-phenylalanine ammonia-lyase (PAL). This is enzymatic reaction is considered as a key point to redirect the carbon flux from primary metabolism (Ferrer et al., 2008; Vogt, 2010). The

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metabolic pathway continues through a series of enzymatic modifications to produce the different flavonoid classes.

Genetic factors, environmental conditions and agronomic practices play important roles in the phenolic composition of plants. Crops can be affected by numerous pre-harvest variables, including endogenous factors—genotype (cultivar and variety), maturity at harvest and tissue distribution—as well as exogenous factors—climate, pathogen stress, plant-eating animals or insects, and soil micro-environment (Tomás-Barberán and Espín, 2001; Wang, 2006). This paper reviews recent literature on the main factors affecting the flavonoid content, as well as different approaches aiming to increase the accumulation of these compounds in onions, which provide an added functional value.

Flavonoid roles in plants

Flavonoids play a lot of roles in plant physiology, mainly related to plant resistance (Dixon et al., 2002; Treutter, 2006). They act in defense mechanisms against herbivores or pathogens and also as supporting materials of cell walls against UV radiation and plant-microbe symbiosis. Another significant function of flavonoids, especially the anthocyanins, together with flavones and flavonols as co-pigments, is their contribution to flower and fruit colors (Alén-Ruiz et al., 2008). This is important for attracting pollinators and seed-dispersing animals, influencing the competition among plants, which is known as allelopathy (Peer and Murphy, 2006). Flavonoids have also been shown to modulate transport of the phytohormoneauxin (Peer and Murphy, 2007) as well as the levels of reactive oxygen species (ROS) (Taylor and Grotewold, 2005).

Flavonoid roles in human nutrition and health

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Beside their importance in plant development and adaptation to the environment, these molecules are of major interest for human nutrition and health due to their medicinal, pharmaceutical and nutritional properties, and are thus termed nutraceutical compounds(Hichri et al., 2011; Lin and Weng, 2006; Parr and Bolwell, 2000; Zern and Fernandez, 2005).They have been shown to present antioxidant, anti-inflammatory, anti-proliferative and anti-tumor activities (García-Mediavilla et al., 2007; Middleton et al., 2000; Paredes-López et al., 2010; Sun et al., 2002). These health-promoting properties are currently increasing the demand of both industry and consumers for flavonoid-rich foods.Nevertheless, it should be also taken into account that at excessive doses, flavonoids may be toxic to human health, acting as mutagens, pro-oxidants that generate free radicals, and as inhibitors of key enzymes involved in hormone metabolism. Otherwise, the adverse effects of flavonoids might outweigh their beneficial ones, and caution should be exercised in ingesting them at levels above that which would be obtained from a typical vegetarian diet (Skibola and Smith, 2000).

In this regard, onion (*Allium cepa* L.) is one of the richest sources of dietary flavonoids, contributing to a large extent to the overall intake of flavonoids (Manach et al., 2004; Slimestad et al., 2007). Two flavonoid classes are mainly found in onion, the anthocyanins, which impart a red/purple color to some varieties, and flavonols such as quercetin and its derivatives, responsible for the yellow and brown skins of many other varieties.

Glycosides of quercetin are more efficiently absorbed than quercetin itself (Hollman et al., 1995). Human absorption of the quercetin glycosides from onions (52%) is far better than that of the pure aglycone (24%) and is up to three times higher than that of apples (only 17%) (Hollman and Katan, 1999). Onion contains only easily absorbable glycosides of quercetin, while in apples quercetin occurs as a mixture including glycosides with lower absorption, i.e., quercetin 3-galactoside, -rhamnoside, -arabinoside, -xyloside and –glucoside (Hollman et al., 1995; Manach et al., 2005).With regards to quercetin aglycone, recent studies obtained inverse results, being quercetin aglycone better absorbed than glycosides. Wiczkowski*et al*. (2008) used plant foods rich in quercetin aglycone instead of quercetin in a purified commercial formula. Therefore, quercetin aglycone seems to be more bioavailable than its glucosides when naturally included in a food matrix. The synergistic and antagonistic effects observed when flavonoids interact may explain the results obtained when measuring the antioxidant effects of whole food extracts (Hidalgo et al., 2010).

OCCURRENCE AND IDENTITY OF FLAVONOIDS IN ONIONS

Onion has been reported as one of the major sources of dietary flavonoids in many countries (Hollman and Katan, 1999; Knekt et al., 1996; Nijveldt et al., 2001; Sampson et al., 2002). Only compounds belonging to the flavonols, the anthocyanidins, and the flavanonols have been reported to occur in onion bulbs.

Flavonols are the most ubiquitous flavonoids in onions. At least 25 different flavonols have been characterized in onion, being quercetin derivatives the most important ones in all onion cultivars (Slimestad et al., 2007). Quercetin 4'-glucoside and quercetin 3,4'-diglucoside are reported as the main flavonols in onions, accounting for about 80 to 95% of total flavonols (Grzelak et al., 2009; Ioku et al., 2001; Lombard et al., 2005; Marotti and Piccaglia, 2002; Moon et al., 2000; Pérez-Gregorio et al., 2011a; Pérez-Gregorio et al., 2011b; Pérez-Gregorio et al., 2011c; Pérez-Gregorio et al., 2010; Price et al., 1997; Price and Rhodes, 1997; Rodrigues et al., 2009; Rodrigues et al., 2010, 2011; Yoo et al., 2010).

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The quantitative content of anthocyanins in some red onion cultivars has been reported to be approximately 10% of the total flavonoid content or 39–240 mg kg-1 FW (Slimestad et al., 2007). In red onions, the cyanidin glucosides acylated with malonic acid or non-acylated, account for >50% of total anthocyanin content. Delphinidin and petunidin, in contrast to cyanidin, do not have malonyl derivatives in detectable amounts, indicating that the presence of malonylated derivatives is an exclusive feature of cyanidin derivatives (Gennaro et al., 2002). Some of these pigments facilitate unique structural features like 4′-glycosylation and unusual substitution patterns of sugar moieties. Altogether at least 25 different anthocyanins have been reported from red onions, including two novel 5-carboxypyranocyanidin-derivatives (Fossen and Andersen, 2003).

Flavonoids comprise a generous portion of the total antioxidant activity in onions (Yang et al., 2004). Elhassaneen and Sanad (2009), in a study with Egyptian onion varieties, concluded that phenolic compounds, particularly the flavonol quercetin, beside other factors including selenium and sulphur-containing amino acids, play the major role in the antioxidant activity of onion bulbs.

APPROACHES FOR THE ACCUMULATION OF ANTIOXIDANT FLAVONOIDS IN ONIONS

As the content of flavonoids in plants is affected by the combination of genetic factors, environmental conditions and agronomic practices (Tomás-Barberán and Espín, 2001), different strategies can be applied in order to obtain foods enriched in these antioxidant compounds, thus increasing their functional value.

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But which approach is more suitable to increase the flavonoid productivity of onions with large-scale, low-cost solutions? Can the phytochemical profile of onions be modulated in order to enhance the accumulation of these valuable constituents? What balance between phytochemical yield and total biomass production can be achieved? Providing a proactive answer to such questions is an extremely hard task, due to the large number of variables involved: intra-specific chemodiversity, plant breeding, ontogenetic stage, post-harvest handling, biotic and abiotic factors.

The first steps to be taken are undoubtedly the evaluation and the organization of scattered data regarding the diverse factors involved in the optimization of plant cultivation, in order to provide an interdisciplinary overview of main possibilities, weaknesses and drawbacks (Bruni and Sacchetti, 2009).

The main route of targeted phytochemical farming (Fig. 2) starts from the environmental factors modified by agricultural technology which must be recognized by the plant. Sensitivity of the respective tissue is a prerequisite. This step must be followed by a metabolic response depending on the expression of related genes which has to be transcribed to functional enzymes. Metabolic channeling may then direct to the accumulation of the target product if not disturbed by feedback mechanisms or by further metabolism or degradation. The farmers' activities and/or changing environments also control growth and differentiation of the plant, thereby modifying precursor pools of the targeted secondary metabolism. The requested bioactive compound may exhibit physiological activity, thus affecting plant development and ecological performance. Increased resistance to biotic and/or abiotic stress situations may crop up as an added-value of accumulating phenolic compounds (Treutter, 2010).

Approaches based on endogenous factors

The role of genetics has received considerable research attention and new crop varieties with enhanced phytochemical concentrations are now available in the market. While the impact of genetics appears greater than the environmental factors, the synergistic effect of genetics with selective agronomic strategies could have a much stronger impact on enhancing certain phytochemicals. However, defining optimum pre-harvest strategies to maximize the biosynthesis of specific phytochemicals is complex and difficult. Progress towards understanding the impact of key strategies will allow their integration into sustainable cropping systems aimed to alter the content and/or profile of phytochemicals in new crop varieties, while preserving water resources and maintaining soil quality (Leskovar et al., 2009). Table 2 summarizes the main endogenous factors affecting the flavonoids content in onions.

Cultivar selection

Onion provides a good example on how the genotype affects the content of phenolic compounds. There are an immense number of onion cultivars, hybrid and open-pollinated, worldwide. The genetic makeup of the onion varieties need to be factored in when differences in flavonoids content and antioxidant activity are considered (Fig. 3). Most variability in flavonoid content in onions is explained by genetic factors (Marotti and Piccaglia, 2002).

Lee and Mitchell(2011) found that the quercetin content ranged up to 18-fold between six commercially onion varieties (93-1703 mg/100 g DW).Milestone, a storage onion, had the highest levels of quercetin flavonoids as compared with the other varieties evaluated.

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Color is a phenotypical attribute that is closely related to the content in flavonoids in onions. Red cultivars generally contain higher flavonoid quantities than the white cultivars (Elhassaneen and Sanad, 2009; Kaur et al., 2009; Lachman et al., 2003; Lako et al., 2008; Pérez-Gregorio et al., 2010; Slimestad et al., 2007).Red onions are not only richer in flavonols, but they also contain anthocyanins. In an evaluation of 34 genotypes, Dalamu*et al*.(2010) verified that mean total phenolic content was 867.8, 702.0 and 165.0 mg kg^{-1} in red, pink and white genotype respectively. This depicted an overall 5-fold variation. The antioxidant activity in red genotype with highest levels of phenolics was roughly three times higher than commercial white genotype. The quercetin content inthese 34genotypes ranges from 22.0 to 890.5 mg kg^{-1}. The yellow cultivars, reveals the largest variation, as contents vary from very low to very high (Slimestad et al., 2007). Patil*et al*. (1995b) in a study with 55 cultivars of yellow onions, the total quercetin content varied from 54-286 mg kg^{-1} FW. Grzelak*et al*. (2009) also reported differences in flavonols glucosides and total flavonols content between three yellow onion varieties but no statistically significant differences have been found in the content within a given variety from the two harvest seasons.

The compilation of quantitative data (Table 2) indicates a great diversity in flavonoid content among the cultivars surveyed. Total phenolic content in onion genotype seems present a definite hierarchy, highest in red, to lowest in white. In contrast, Crozier *et al*.(1997) reported the opposite, but only for quercetin, found only 201 $mgkg^{-1}$ of quercetin in edible parts of red onion but much higher quercetin amount in white onions (185–634 mg kg^{-1}). Also Marotti and Piccaglia(2002) found higher levels of total flavonoids in “Dorata Density”, a golden variety, compared with other color varieties (including red colors).

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There are many reports in the scientific literature on how resistant cultivars of different crops contained more phenolic compounds than susceptible ones suggesting that these compounds play an important role in the defense mechanism (Cherif et al., 2007; Kavousi et al., 2009). Similar profiles in polyphenol content between resistant and susceptible onion cultivars have also been found by Lachman*et al.*(1999).

Yang *et al*.(2004) concluded that onion varieties, which have high sugar contents and strong, pungent, and bitter flavors, exhibited higher antioxidant and antiproliferative activities. The most pungent cultivars also contained the highest amounts of fructo-oligosaccharides (FOS) and flavonols, and gave the highest Trolox equivalent antioxidant capacity (TEAC) values among the 15 cultivars studied (Vågen and Slimestad, 2008).

Okamoto and co-workers(2006) reported on the differences in quercetin content between long-day cultivars and short-day onion cultivars. The long-day cultivars from Northern Europe and their close relatives contain higher concentrations of quercetin glucosides than those of Japanese and North American origins. Total quercetin content in long-day cultivars was higher than in short-day cultivars and this does not depend on the growing origin (Lombard et al., 2004; Okamoto et al., 2006).

Tissue selection

Although flavonoids are derived from the same biosynthetic pathway, they accumulate differentially in plant tissues, depending on the developmental stage and the environmental conditions, since they fulfill different physiological functions (Hichri et al., 2011).Higher concentrations of total phenolics in young than in mature leaves could be interpreted as an allocation strategy to prioritize defense of the most valuable tissues. Similarly, ontogenetic changes in defensive allocation in seedling and juvenile plants may also be an evolutionary response to herbivore at this particularly vulnerable stage of a plant's life history (Cella Pizarro and Bisigato, 2010). In tissues with protective function, such as skin scales, there seems to be also the same strategy.

Although the onion bulb grows under the soil at least partly, its skin—the non-edible dry peel, is richer in total flavonoids compared to the edible flesh (Bilyk et al., 1984; Gennaro et al., 2002; Nemeth and Piskula, 2007). Hirota and co-workers (1998) found that 4'-Qmg and 3,4'-Qdg, and Qag were higher in outer scales and at the upper portions of the scales compared to the lower portion of them.

The flavonoids present in the peel are mainly aglycones due to flavonol glucoside hydrolysis during the peel formation (Price and Rhodes, 1997; Takahama and Hirota, 2000). Quercetin is concentrated in the dry skin of most onions where its oxidation products, 3,4-dihydroxybenzoic acid, and 2,4,6-trihydroxyphenylglycosilic acid imparts the brown color and provides the onion bulbs protection from the soil microbial infection (Takahama and Hirota, 2000; Takahama et al., 2001). Bilyk*et al*.(1984) observed a strong difference between dry skin and the other bulb scales and that as much as 53% of the total quercetin in onion skin was present as the aglycon. The dry skin of onion bulbs is quite rich in both anthocyanins (in red and pink onion varieties) and flavonols, with a high percentage of aglycon forms. It is noteworthy that ~63% of the red onion anthocyanins are present in the dry skin. This means that, after bulb peeling, only 27% of the total anthocyanins of red onion will be consumed (Gennaro et al., 2002).

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Slimestad and Vågen (2009) found that, considering only edible portion,theouter fresh onion scales contain the highest amounts of fructose and flavonols, and have the highest antioxidant capacities. An abrupt drop in flavonol concentrations occurred from the first to the second scale, followed by a slight decrease further inwards. Grzelak *et al*. (2009) also reported that there is,on average,3-fold of mono-, diglucosides of quercetin and isorhamnetinin the outer fresh scales of the bulb edible portion. The content of triglycosides is ca.1.5-fold greater in the outer than in the middle scales.A graduated decrease was also observed in the distribution of the flavonoids across an onion bulb from the first to the seventh scale (Lee et al., 2008). Beesk *et al*.(2010), inversely to other authors, verified that distribution of the total flavonoid content in the different parts of the onion bulb showed the following order: middle layers > outer scales > inner layers. In the inner layers Qdg was the major flavonoid, while in the middle layers Qdg and Qmg were in equal amounts. In the outer scales quercetin was the major flavonoid prior to Qmg.

Trammell and Peterson(1976) found that the flavonol content in onion in general increased from bottom to top (vertical distribution) of the bulbs by less than a factor of 2. The horizontal distribution showed a 2- to 3-fold increase in concentration from the center of the bulb outward. The least pigmented line showed a 17-fold increase, and had 56% of its total flavonols in the outermost scale compared with about 30% for the other lines. Similar gradient in total quercetin content in the edible onion parts has recently been reported by Mogren *et al.*(2006, 2007b) and Lee and co-workers(2008). About 90% of total flavonols has been confined to epidermal tissue. Parenchymous storage tissue, which makes up the bulk of a bulb, contains only about 10% of the total pigment. It follows that scale thickness or any other factors which alter the ratio of epidermal to storage tissue could indirectly affect gross flavonol concentration.

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In onion, it has been reported that size and bulb weight are not correlated with quercetin concentration and that small bulbs contain the same concentration of quercetin as larger bulbs (Patil et al., 1995b). Mogren *et al.* (2006) obtained results that showed minor or no differences in quercetin glucoside content amongst small-, medium- or large-sized onions. Although, Lee *et al.* (2008) and Pérez-Gregorio *et al.* (2010) reported that small onions had higher flavonoid content than large ones.

Approaches based on exogenous factors

Numerous factors other than genetic may affect the flavonoid content of onions, including environmental conditions, agronomic practices, post-harvest treatments, processing and storage. If one consider secondary metabolism as an integral part of the plant capacity to modify its metabolic processes in order to achieve a better adaptation to the surrounding environment, it comes as no surprise that all these factors can lead to variations in its phytochemical profile.

As polyphenolic compounds are part of a complex defense mechanism against stress, plant interaction with environmental stress factors such as herbivores, pathogens, metal ions and excessive UV light, among others, can induce their biosynthesis (Dixon and Paiva, 1995; Harborne and Williams, 2000). This fact provides an opportunity to enhance the flavonoid content of plants by using regulated environmental stresses.However, such an approach should be considered with some caution because of their potential adverse effects on crop growth and yield.

A survey of agricultural technologies influencing the biosynthesis and accumulation of phenolic compounds in crop plants was presented by Treuter (2010), including observations on the effects of light, temperature, mineral nutrition, water management, grafting, elevated atmospheric CO_2, growth and differentiation of the plant and application of elicitors, stimulating agents and plant activators.

Table 3 summarizes the main exogenous factors affecting the flavonoid content in onions, as well as diverse strategies aiming to increase their accumulation.

Soil nutrient status

Mineral nutrition can have a major effect on the accumulation of phenolic compounds, being a limited nitrogen supply typically associated with higher levels of phenolic compounds in the plant (Manach et al., 2004). This higher content under nitrogen stress conditions can be explained by the increased activity of PAL enzyme in order to obtain ammonia from phenylalanine, as source of nitrogen for amino-acid metabolism. As a result of the deamination process, cinamic acid is also released and further incorporated into the phenylpropanoid synthetic pathway, increasing the phenolic production (Stewart et al., 2001). Alternatively, nitrogen limitation will affect photosynthesis by decreasing available chlorophyll and disrupting photosynthetic membranes due to starch accumulation. This may lead to increased sensitivity to high light levels. The production of photoprotective pigments such as anthocyanins and flavonols may afford protection against light-induced oxidative damage (Guidi et al., 1997).

Patil*et al.*,(1995a) observed higher amounts of quercetin in onions growing under nitrogen limitation in both clay and sandy loam soils. However, correlation between nitrogen stress and flavonols synthesis could not be verified due to the different growth stages of onions during experiments. Moreover, it was concluded that the site of growth, more than growth stage and soil type is a major environmental factor in determining quercetin concentration in onion.

Mogren *et al*.(2006, 2007a, b) compared different ways of applying organic fertilizer and it was confirmed that placement of the nitrogen fertilizer did not affect either yield or quercetin glucoside content in onion. Additionally, no significant difference in quercetin glucoside content could be found between unfertilized onions and onions that received nitrogen fertilizers. The higher level of nitrogen (80 kg ha^{-1}), did not affect the yield or the content of quercetin glucosides in the onions after curing any of the years, or at later stages during storage. Thus, minimized split application of nitrogen fertilizers reduced the risk of mineral nutrient leaching without lowering the yield or quercetin content.

The effect of different ammonium:nitrate ratios as nitrogen source and mycorrhizal colonization on onion growth and nutritional characteristics were evaluated. It was concluded that the plant antioxidant activity, quercetin glycosides and organosulfur compounds can be increased in sufficiently supplied onion plants by dominant nitrate supply (Perner et al., 2008). Furthermore, mycorrhizal colonization increased the antioxidant activity and also concentrations of the major quercetin glycosides. This was probably due to increased precursor production and induced defense mechanisms.

Water availability can also considerably affect plant phenolic composition in fruits and vegetables (Tomás-Barberán and Espín, 2001). As these compounds are produced as part of plant defense mechanisms against stress factors, regulated deficit irrigation might modulate their metabolic pathway. Nevertheless, to the best of our knowledge no studies have directly addressed the effect of irrigation on the flavonoid content in onions.

Light

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One of the major environmental factors affecting the flavonoid synthesis is light, where its intensity, quality and photoperiod contribute to the overall effect.

Light is involved in the regulation of the expression of several genes that encode the activity of enzymes participating in the phenylpropanoid pathway, such as PAL or cinnamate 4-hydroxylase (C4H). Thus, light conditions during plant development and/or storage (in light or darkness) could play an important role in the polyphenol content.

From the standpoint of evolution, the protective property that flavonoids display against UV-radiation has been suggested to be among the oldest functions of flavonoids in plants. Flavonoids are strongly UV-absorbing compounds, and accumulate mainly in the epidermal cells of plant tissues after UV-induction (Jaakola et al., 2004).

It is evident that the response of various plant species to UV radiation can differ considerably in terms of flavonoid synthesis (Harborne and Williams, 2000). Interesting questions in this area are how the synthesis of specific flavonoids and other phenolics is regulated in response to UV light in different plant species, how do the flavonoids compare to other phenolics in contributing to UV stress protection, and do the flavonoids have other roles in UV protection beyond the absorption of UV radiation (Winkel-Shirley, 2002). In general, light stimulates the synthesis of flavonoids, especially anthocyanins and flavones, being PAL the major inducible enzyme (Dixon and Paiva, 1995; Macheix et al., 1990)

Content of quercetin glucosides and their distribution in onions are influenced by the accessibility of light (Patil and Pike, 1995). The levels of these compounds in the dry outer skins, exposed to light, are less than 10% of the levels in fleshy and partly dried scales. The probable mechanism is that quercetin is formed by deglucosidation of quercetin glucosides on the border between drying and dried brown areas on individual scales (Takahama and Hirota, 2000).

Global radiation in the end of production period seemed to be one of the major determinants of mean annual quercetin glucoside content in the onions (Pérez-Gregorio et al., 2011a; Pérez-Gregorio et al., 2011b; Pérez-Gregorio et al., 2011c; Pérez-Gregorio et al., 2010; Rodrigues et al., 2009; Rodrigues et al., 2010, 2011). Mogren *et al.*(2006) observed that the least amount of global radiation of all four years studied in the last month of onion growing, resulting in the lowest levels of quercetin glucosides of all years at the end of the growing period. Quercetin content in onion can be doubled after harvest using UV light lamps (Higashio et al., 2005). Exposure onion bulbs to fluorescent light for 24 and 48 h induced time-dependent increases in the flavonoid content (Lee et al., 2008).

Organic vs. conventional production

Regarding the differences between organic and conventional production systems, Manach *et al.*(2004) suggest that the polyphenol content of vegetables produced by organic or sustainable agriculture is higher than that of vegetables grown in conventional or hydroponic conditions. Two major hypotheses explaining the possible increases in organic acids and polyphenolic compounds in organic versus conventional foods have been proposed. One hypothesis considers the impacts of different fertilization practices on plant metabolism. In conventional agriculture, synthetic fertilizers frequently make nitrogen more available for the plants than do the organic fertilizers and may accelerate plant growth and development. Therefore, plant resources are allocated for growth purposes, resulting in a decrease in the production of plant secondary metabolites such as organic acids, polyphenolics, chlorophyll, and amino acids. The second hypothesis considers the responses of plants to stressful environments such as attacks from insects, weeds, and plant pathogens. It has been argued that organic production methods—which are limited in the use of insecticides, herbicides, and fungicides to control plant pests—may put greater stresses on plants and may require plants to devote greater resources toward the synthesis of their own chemical defense mechanisms.

Organically grown cabbage, spinach, Welsh onion, green pepper generally had higher levels of flavonoids and antioxidant activity than conventional. Among all green vegetables tested for flavonoid composition, quercitrin, caffeic acid and baicalein in organic vegetables were detected in concentrations 1.3–10.4 times higher than those found in conventional vegetables, suggesting the influence of different cultivation practices (Ren et al., 2001).

Grinder-Pedersen *et al*. (2003) found differences in quercetin content between conventionally and organically grown onions, but different cultivars were studied in the two different cultivation systems, so the possibility could not be excluded that the difference were due to cultivar differences.

Mogren *et al*.(2008) found no significant effects on quercetin glucoside levels between onions that received organic fertilizers, and no chemical herbicides or fungicides, or inorganic fertilizers. One conclusion could be that the form of nitrogen, organic or inorganic, seemed to have no effect on quercetin synthesis. Another conclusion could be that the extra stress that could be expected from the absence of chemical fungicides did not seem to induce extra quercetin biosynthesis. Differences were observed in the effect of organic and inorganic fertilizers on the yield and size of onions, probably due to the differences in time and amount of release during the season.

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The results obtained by Faller and Fialho (2010) suggests that the effect of organic practices results in different effect patterns according to the plant species analyzed, with fruits being more susceptible to the induction of polyphenol synthesis than vegetables.Organic onion pulp had higher antioxidant capacity than conventional (Faller and Fialho, 2010).

Søltoft *et al.*(2010) found no significant differences between the conventionally and the organically grown onions in the content of flavonoids. However, the harvest yield was significantly affected by the different amounts of fertilizer and fertilizer types used for onions in the growth systems in their study. Thus, the application of high amounts of inorganic fertilizer in the conventional growth system resulted in the highest harvest yield.

Chemical treatments

The synthesis of phenolic compounds in plants can also be modulated by the application of herbicides and, to a lesser extent, insecticides and fungicides. Diphenyl ethers (e.g., acifluorfen) exert herbicidal effects mainly by oxidative damages (singlet oxygen of protoporphyrin). Possibly as a protective reaction to the oxidative damages, plants increase the PAL synthesis and synthesize more flavonoids when treated with herbicides. But, the effects of these treatments on ecosystem functioning and human health are complex and cannot be predicted with great certainty. The consequences of the combined natural and pesticide-induced modulating effects for ecologic functions and human health should be further evaluated (Daniel et al., 1999).

Kamal *et al.*(2008) observed that onion plants treated with benzothiadiazole (Bion) and di-potassium phosphate showed significantly higher PAL activity, PO activity, and phenolic contents than the untreated ones. It was concluded that application of simple chemical solutions such as benzothiadiazole and di-potassium phosphate can be applied for disease control and enhancing phenolic compounds in onion plants (Kamal et al., 2008).

Harvest time and post-harvest treatments

Many phytochemicals are synthesized in parallel with the overall development and maturation of fruits and vegetables. Therefore, their content in plants can considerably vary with different stages of maturity (Manach et al., 2004).

Total flavonols content increased as spring onion plants matured (226–538 mg/100 g at 14 and 77 days, respectively) (Thompson et al., 2005). In bulbs, harvest date has been reported to have almost no effect onion bulbs (Patil et al., 1995a).

Mogren *et al.* (2007a)found that the later the lifting time, the higher the quercetin content in the fresh onions at lifting. Thus, late lifting of onions (80% fallen leaves) resulted in up to 45% higher concentrations of quercetin glucosides compared with early lifting (50% fallen leaves)).

Onions left in the field after harvest accumulate more flavonols (Patil et al., 1995a). Mogren *et al*. (2006) also detected a dramatic increase increase in quercetin glucoside content during field curing (between 100-300%, during the 10-14 days of curing). Price *et al*. (1997) demonstrated a 50% loss in quercetin monoglucoside during de initial curing process. Mogren *et al*. (2006) observed that quercetin content increased significantly less in dark environments compared to field curing, but some quercetin synthesis occurred regardless of light. Field curing with or without foliage still attached did not affect quercetin content, suggesting that no transportation from the foliage to the scales occurred. Field curing resulted in increases in quercetin content compared to levels at lifting; particularly when the flavonol concentrations were low at lifting the observed increases during curing were higher (Rodrigues et al., 2009). In the years with high flavonol content at lifting, almost no increase in flavonol levels occurred during curing. This behavior could explain the different response of red onions, with higher flavonoid content at lifting, increase their levels to a lower extent during curing than white onion. Flavonol and anthocyanin levels in onions cured in the dark were similar to those obtained in bulbs cured in the light.

VALORISATION OF ONION BY-PRODUCTS

In the recent years, the increasing demand for processed plant foods has led to a parallel increase in agro-industrial waste production. Since onion is one of the most cultivated horticultural crops worldwide, the resulting wastes and by-products have become a major problem for the concerned industry (Schieber et al., 2001). These residues mainly include onion skins, the outer two fleshy scales and roots generated during industrial peeling. Moreover, the current quality levels demanded by customers lead to discard worthless onions, i.e. undersized, malformed or damaged onion bulbs.

These products are not particularly suitable as fodder because of their strong characteristic aroma, and neither as an organic fertilizer due to the rapid development of phytopathogenic agents such as *Sclerotium cepivorum* (Coventry et al., 2002). Therefore, their disposal commonly involves landfill which results in high economical costs, as well as an important environmental impact (González-Sáiz et al., 2008).

One of the best options for agro-food residues is the recovery of valuable phytochemicals with high potential for the pharmaceutical, food and cosmetics manufacturing (Laufenberg et al., 2003; Schieber et al., 2001). In this regard, several studies have reported the valorisation of onion by-products as an important source of natural antioxidants (Khiari et al., 2008; Ly et al., 2005; Roldán et al., 2008).

Aiming to develop sustainable processes, approaches using ethanol/water mixtures have been evaluated for the extraction of flavonoids from onion solid wastes (Khiari et al., 2008, 2009; Kiassos et al., 2009). The use of subcritical water as extraction solvent, at temperatures above 100 ºC, has also been proposed as an environmental friendly alternative to organic solvent-based extractions (Ko et al., 2011; Turner et al., 2006).

Notwithstanding, it should be highlighted that most of these studies have been carried out at a laboratory scale, so further research is necessary in order to scale-up these processes to the industry requirements, assessing their economical viability.

To the extent that the retrieved substances are proven safe, they could be useful as functional ingredients due to the increasing demand of consumers for substituting synthetic compounds by natural substances (Khiari et al., 2008; Roldán et al., 2008).

FUTURE CHALLENGES FOR PLANT SCIENTISTS AND GROWERS

Additionally, the improvement of vegetable quality require knowledge of consumer needs and desires: consumer quality can include such attributes as nutritional and functional value, flavor, texture, color, appearance and price.It is essential that studies, carried out to enhance the content of phenolic compounds, take into account the effect on other quality parameters, as it is known that these compounds can for example affect the sensory attributes such as color, flavor, bitterness and texture affecting the consumer assessment (Robards and Antolovich, 1997).

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Many studies demonstrate that onions have functional properties with high antioxidant properties and the ability to modify lipid metabolism and stimulate the immune system. However, the differences in the responses observed in some the studies demonstrate the complex interaction between the onion dose and type of onion, which may be due to the differences in the amount of active compounds. The identification of specific compounds in different onion cultivars and agronomic practices would lead to a better understanding of the physiological responses to onion consumption. This would aid the development of onion production systems that provide an increased health benefit and the development of guidelines for the consumption of these compounds (Ostrowska et al., 2004).

In this regard, it is necessary to increase our knowledge on optimization and influencing the composition and enhancement of “bioactive” metabolites in onions. An interesting and challenging aspect for future research is to clarify the interactions between genotype and agro-environmental factors on the flavonoid composition in onions.

This review summarizes the current state of knowledge on the main factors affecting the flavonoid content in onions, as well as different approaches that can be applied to increase the accumulation of these compounds. Thus, selection of a suitable variety isdeterminant to obtain flavonoid-rich onions. In general, red cultivars contain higher flavonoid quantities than yellow and white cultivars, whereas resistant onion cultivars present higher flavonoid contents than susceptible ones.Among the different tissues, the non-edible dry skin is richer in total flavonoids compared to the edible flesh, whichmight be used to obtain natural antioxidants from these agro-food residues. Considering only the edible portion, a decrease is observed in the distribution of the flavonoids across an onion bulb from the outer fresh onion scales to the inner scales.

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Regarding the exogenous factors, the content of flavonols in onions is not affected by a higher level of nitrogen in soil. Thus, the nitrogen fertilizer levels may be minimized if given at the appropriate time and in the correct amounts, without negative effect either on yield or quercetin glucoside content. Moreover, organically grown onions have been shown to present higher levels of flavonoids and antioxidant activity than conventional.Late lifting of onions generally results in higher concentrations of quercetin glucosides compared with early lifting.

At the moment, it may not be recommended starting the production of plant foods with an attributed enhanced nutritional quality for a common market. However, the production of fresh "functional food" with defined health claims may be favorable for a premium market segment. In future, it may be expected for the global market that minimum quality of plant foods will be defined on the base of their content of bioactive components.

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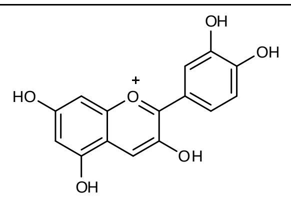
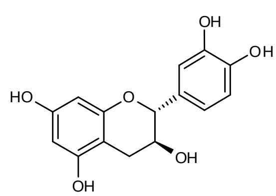
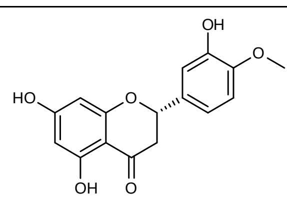
Table 1

Common dietary antioxidant flavonoids

Flavonoid subclass	Representativechemical estructure	Prominent Flavonoids	Common Food Sources
Anthocyanidins		Cyanidin, Delphinidin, Malvidin, Pelargonidin, Peonidin, Petunidin	Red, blue, and purple berries, red and purple grapes, red wine
Flavan-3-ols		<u>Monomers (Catechins)</u>: Catechin, Epicatechin, Epigallocatechin Epicatechin gallate, Epigallocatechin gallate <u>Dimers and Polymers</u>: Theaflavins, Thearubigins, Proanthocyanidins	<u>Catechins</u>: Teas (particularly green and white), chocolate, grapes, berries, apples <u>Theaflavins, Thearubigins</u>: Teas (particularly black and oolong) <u>Proanthocyanidins</u>: Chocolate, apples, berries, red grapes, red wine
Flavanones		Hesperetin, Naringenin, Eriodictyol	Citrus fruits and juices, e.g. oranges, grapefruits, lemons

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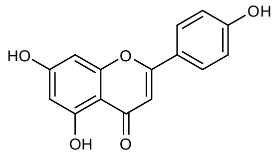
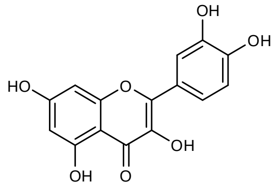
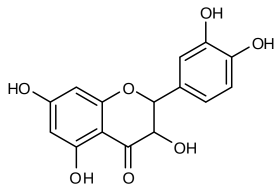
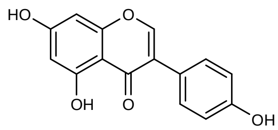
Flavones		Apigenin, Luteolin	Parsley, thyme, celery, hot peppers
Flavonols		Quercetin, Kaempferol, Myricetin, Isorhamnetin	Widely distributed: yellow **onions**, scallions, kale, broccoli, apples, berries, teas
Flavanonols		Taxifolin	Citrus fruits, red onions
Isoflavones		Daidzein, Genistein, Glycitein	Soybeans, soy foods, legumes

Table 2

Endogenous factors affecting the accumulation of flavonoid in onions

Factor	**Evaluated parameters**	**Effect on flavonoids**	**References**
Varietal differences	Different bulb colors	Red>yellow>gold *Exception	(Crozier et al., 1997)* (Lachman et al., 1999) (Lachman et al., 2003) (Marotti and Piccaglia, 2002)* (Slimestad et al., 2007) (Lako et al., 2008) (Kaur et al., 2009) (Elhassaneen and Sanad, 2009) (Dalamu et al., 2010) (Pérez-Gregorio et al., 2010)
	Yellow varieties		(Patil et al., 1995b) (Slimestad et al., 2007) (Grzelak et al., 2009)

	Resistant and susceptible onion cultivars	Resistant > susceptible	(Lachman et al., 1999)
	Long-day and short-day onion cultivars	Long-day > short-day	(Okamoto et al., 2006) (Lombard et al., 2004)
Size and bulb weight		No differences *Small > large	(Patil et al., 1995b) (Mogren et al., 2006) (Lee et al., 2008)* (Pérez-Gregorio et al., 2010) *
Bulb parts	Scales	Dry outer skins > outer edible > middle edible > inner edible *Exception: middle layers > outer scales > inner layers	(Trammell and Peterson, 1976) (Bilyk et al., 1984) (Hirota et al., 1998) (Gennaro et al., 2002) (Mogren et al., 2006, 2007) (Lee et al., 2008) (Nemeth and Piskula, 2007) (Grzelak et al., 2009) (Slimestad and Vågen, 2009) (Beesk et al., 2010)*
	Top to bottom	Top > bottom	(Trammell and Peterson, 1976) (Hirota et al., 1998) (Pérez-Gregorio et al., 2010)

Table3

Exogenous factors affecting the accumulation of flavonoid in onions

Factor	Evaluated parameters	Effect on flavonoids	References
Soil type		Clay > sandy loam	(Patil et al., 1995a)
Fertilization	N levels	No differences in quercetin	(Mogren et al., 2008)
	NH_4^+:NO_3^- ratios	> dominant nitrate supply	(Perner et al., 2008)
	Varieties Kamal and Robin (N and S)	Positive correlation with N and S fertilization	(Golisová et al., 2008)

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	White variety of Pueblo and yellow variety of Mundo were the most efficient when fertilized by nitrogen and sulphur in combination with iron	Positive correlation with N, S and Fe fertilization	(Golisová et al., 2009)
Mycorrhizal colonization/inoculation		>quercetin	(Perner et al., 2008)
		No effects	(Mogren et al., 2006)
Organic vs. conventional		Organic > conventional	(Ren et al., 2001) (Faller and Fialho, 2010)
	Organic fertilizers, and no chemical herbicides or fungicides, or inorganic fertilizers	No differences	(Mogren et al., 2006) (Mogren et al., 2008)
Chemical treatments	Benzothiadiazole and K_2HPO_4 to control *Stemphylium*	>phenolic	(Kamal et al., 2008)
Yearly variation			(Mogren et al., 2006) (Mogren et al., 2008) (Rodrigues et al., 2011)
Light	Global radiation in the end of production period	>radiation > flavonoids	(Mogren et al., 2006)
	Total Global radiation during production period	>radiation > flavonoids	(Rodrigues et al., 2011)
	UV light lamps after harvest	>quercetin	(Higashio et al., 2005)
	fluorescent light after harvest	>flavonoid	(Lee et al., 2008)

Table 3 (continued)

Factor	Evaluated parameters	Effect on flavonoids	References
Lifting	Lifting time	Late lifting > early lifting	(Mogren et al., 2007a)
Curing			(Downes et al., 2009)

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Evolution in relation of levels at harvest	After curing>at lifting	(Patil et al., 1995a) (Mogren et al., 2006) (Rodrigues et al., 2009)
	Field>dark environment *Field curing: dark similar to light exposed	(Mogren et al., 2006) (Rodrigues et al., 2009)

Figure 1

Multifunctionality of phenolic compounds (Treutter, 2010)

Figure 2

Route of targeted phytochemical farmingindicating constraints and physiological feedback (Treutter, 2010)

Figure3

Total flavonoid content of 11 onion varieties and shallots (Yang et al., 2004)

Figure 1

Multifunctionality of phenolic compounds (Treutter, 2010)

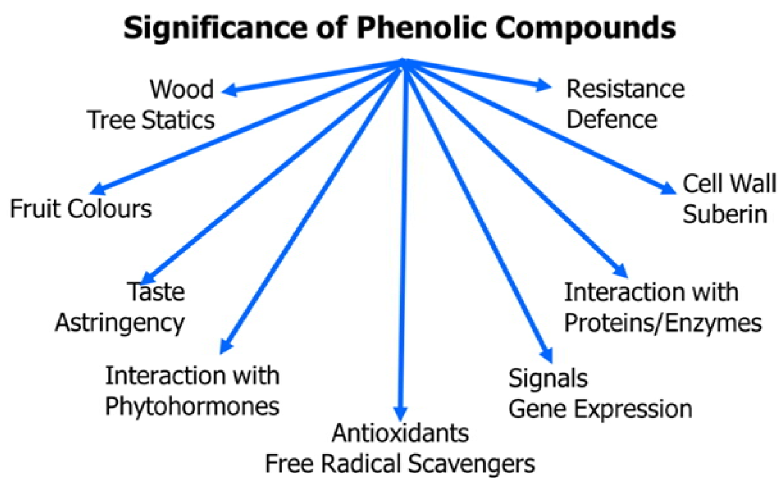

Figure 2

Route of targeted phytochemical farmingindicating constraints and physiological feedback

(Treutter, 2010)

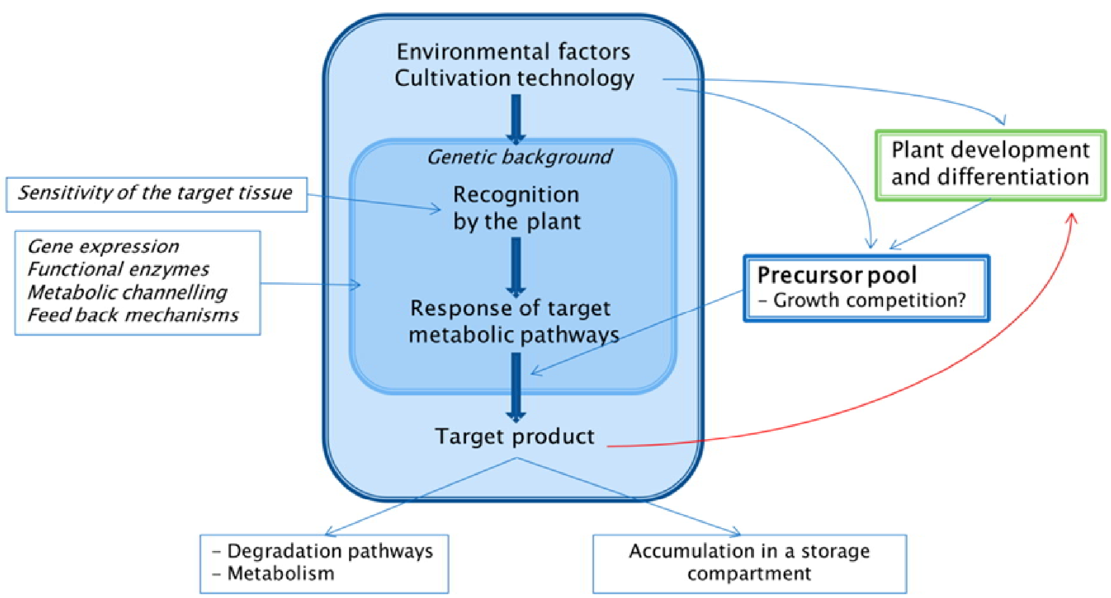

Figure3

Total flavonoid content of 11 onion varieties and shallots (Yang et al., 2004)

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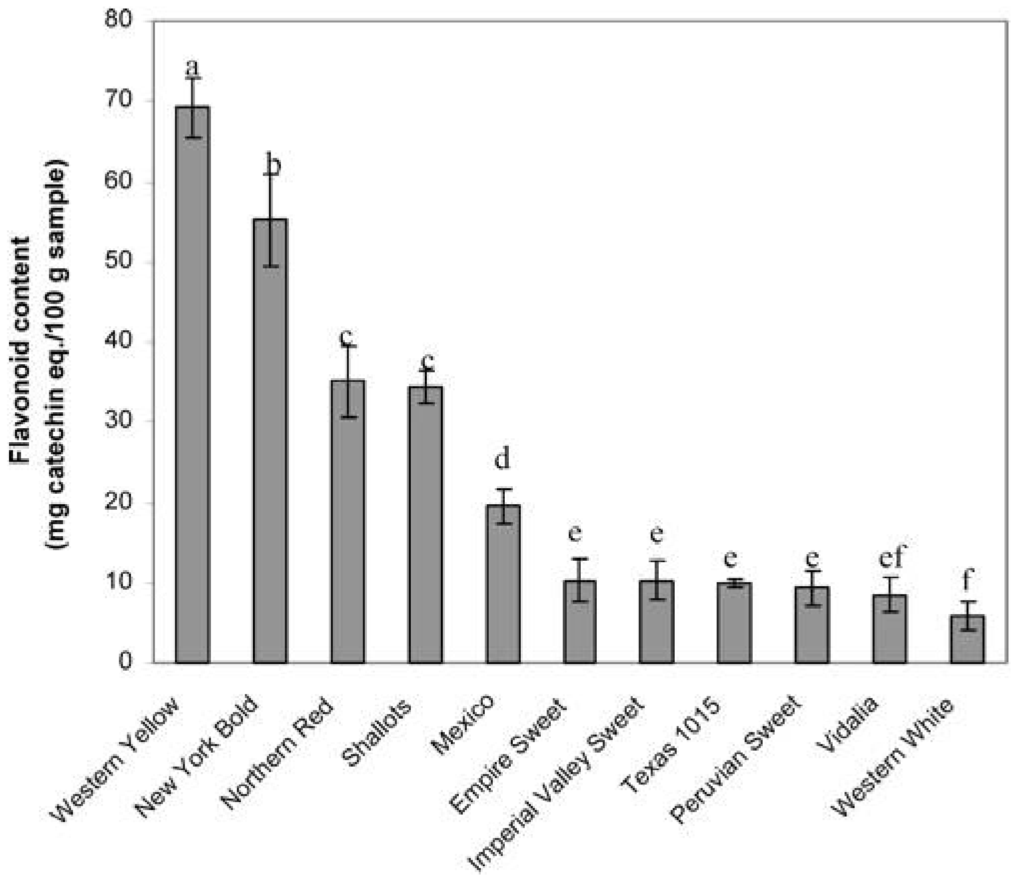

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