Phenolic Components and Health Beneficial Properties of Onions †

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Abstract: Onions are a widely cultivated and consumed vegetable, and contain various bioactive components, which possess various health benefits, such as antioxidant, anti-obesity, and anti-diabetic properties. As the major bioactive constituents in onions, it is essential to study phenolic compounds and the health beneficial properties of onion and its by-products. The bioactivity of phenolic components in onions can be affected by many factors, including the genotype, different growing environments and food processing methods. Currently, most reviews have focused on an investigation of the chemical compounds or bioactivity of raw onions, but there is a paucity of studies concerning whether pre-harvest (i.e., genotype and growing environment) and post-harvest (i.e., storage) factors can impact its phenolic compounds. This review provides knowledge and guidance to agricultural production on producing high-quality onions and to the food industry on developing functional foods to reduce some chronic diseases such as diabetes. It also promotes research interest in studying bioactive compounds in fruits and vegetables considering different pre-harvest and post-harvest conditions.

Keywords: onions; pre-harvest treatments; post-harvest treatments; bioactivity of phenolic compounds; storage conditions

1. Introduction

The onion (Allium cepa L.) is a common vegetable and is widely consumed all over the world. It originated in central Asia and is one of the oldest cultivated plants, with cultivation records dating back more than 4000 years [1,2]. Onions are known to contain bioactive compounds related to positive nutritional and health benefits, such as anti-inflammatory, antioxidant, anti-obesity, anti-diabetic, anticancer, anti-allergic, cardiovascular protective, neuroprotective, respiratory protective, and bacteriostatic properties [1,2] (Table 1).

When onions grow to an appropriate stage of maturity, they are harvested. The stage of maturity depends on the planting season, cultivar and conditions of the crop. Before harvest, onion bulbs, along with their tops, are pulled/lifted from the soil in order to stop growth, and are usually kept/cured in the field for a few days to remove excess moisture from the outer skin and neck to avoid excessive shrinkage of the onion, allowing for color development during storage. These fresh onions can then be directly supplied to the market, or further processed into different forms; for example, in dried powders or flakes [3]. It has been reported that the growing international market for onion products has been developed with dehydrated methods such as powder, frozen, or canned onions [4]. One of the drivers to further process fresh onions into other forms was to reduce product loss (20–30%) during storage. Additionally, dehydrated products possess medicinal features, containing higher concentrations of beneficial compounds than fresh onions [5].
The food industry offers commercial onion powder as a nutraceutical or a dietary supplement [5,6]. Onion powders, rich in phenolic compounds, can produce positive effects that combine with other food to improve antioxidant capacity and flavor [5–7].

Although the bioactive compounds and certain bioactivities of onion have been discussed in recent reviews [8–10], this review can provide a more comprehensive understanding about how pre-harvest and post-harvest factors affect the changes of phenolic compounds in onions. The literature summarized in this review was mainly collected from Web of Science and Scopus databases from 1996 to 2021. We hope that this paper can attract a broader attention to those who are interested in studying bioactive compounds in onions and those who are interested in developing functional foods with the extraction of phenolic compounds in reducing the risk of some chronic diseases.

Table 1. Reported bioactivity of phenolics in onions.

| Reported Bioactivities | References |
|------------------------|------------|
| Preventing cardiovascular diseases | [11] |
| Antioxidant | [12] |
| Anti-inflammatory | [13] |
| Anti-proliferative | [14] |
| Anti-angiogenic | [15] |
| Pro-apoptotic | [16] |
| Activating Immune destruction | [17] |
| Tumor promoting inflammation | [18] |
| Senescence induction and telomerase inhibition | [19] |
| Preventing the growth of tumors | [20] |
| Apoptosis autophagy | [21–23] |
| Reducing the risk of death from coronary heart disease | [24–26] |
| Against arteriosclerosis | [27] |
| Antimicrobial activity against fungal, bacterial and viral infections | [28] |
| Anticarcinogenic and antimutagenic activities | [29] |
| Anti-hypertensive effect and reduce blood pressure | [30] |
| Anti-hyperglycemic or anti-diabetic potential and prevention of advanced glycation of collagens, which contributes to the development of cardiovascular complications in diabetic patients | [31,32] |

2. Phenolic Compounds in Onions

Common fruits and vegetables that are abundant in phenolics include most berry crops, many tree fruit crops and onions. Onion was reported to be one of the vegetables that contains the greatest amount of phenolic compounds contributing to the human daily diet [33–35]. Flavonoids are the largest group of phenolic compounds, along with quercetin, and will be summarized and discussed in this section.

2.1. Flavonoids in Onions

Most flavonoids are important polyphenols in foods and they are categorized by their chemical structure, namely: flavonols, flavones, flavanones, isoflavones, flavanols, catechins, flavanonols and anthocyanidins (Figure 1). Many studies have investigated the presence of flavonoids in onions [26,36]. At least 25 different flavonols have been characterized in onions [37]. There are seven major flavonol compounds in onions and they are (i) quercetin aglycone; (ii) quercetin monoglucoside; (iii) quercetin diglucosides; (iv) isorhamnetin, which is a methyl ether of quercetin; (v) isorhamnetin monoglucoside; (vi) rutin; and (vii) kaempferol. Kaempferol is detectable in certain onion varieties but it presents in much smaller quantities than quercetin [38,39].
Even though anthocyanins do not constitute a major flavonoid content in onions, they have frequently been reported to be presented in red onions. Slimestad, Fossen, and Vagen [37] reported that there are at least 25 different anthocyanins in red onions, with the quantitative content being approximately 10% (39–240 mg/kg fresh weight) of the total flavonoid content (TFC). Bystricka et al. [40] also showed that many varieties of red onions contain red anthocyanins in the form of glycosides of cyanidin, peonidin, and pelargonidin. Anthocyanins are also reported to be a source of antioxidant activity [41]. Anthocyanin pigments, concentrated in the outer shell/skin of red onions, are only minor constituents of the edible portion.

However, little is known about the total amount of anthocyanins in red onions. Although some researchers have found about 250 mg/kg (wet weight) anthocyanins in red onions, they did not address which part of the onion they used, the edible part or the whole onion [42,43]. Statistically, the most amount of anthocyanins was found on the dry skin of red onions, ranging from a minimum 109 mg/100 g to a maximum 219 mg/100 g [44].

2.2. Quercetins in Onions

Quercetin is the aglycone form of a number of flavonoid glycosides, such as rutin, found in onions [45,46]. Glycosides can be classified by the type of glycone, by the type of glycosidic bond, or by the aglycone. The aglycone part is the non-sugar part of a glycoside. Quercetin diglucoside (Qdg) and monoglucoside (Qmg) account for up to 93% of the total flavonol content in onions [47]. Sellappan and Akoh [48] also reported that quercetin is the major flavonoid found in onion and is presented in its conjugated form, quercetin 4′ glucoside (4′Qmg), quercetin 3,4′ dioglucoside (3,4′Qdg), and quercetin. Slimestad, Fossen, and Vagen [37] also agreed that quercetin and its derivatives were the most dominant flavonols found in studied onion cultivars. Similarly, Lombard et al. [49] reported that 4′Qmg and 3,4′Qdg are the main flavonols present in onions, accounting for about 80 to 95% of the total flavonol content.
3. Variation of Phenolic Contents in Onions

3.1. Different Onion Cultivars

Onions have the highest quercetin compounds among many other vegetables and fruits [50]. Onions contain 300 mg quercetin/kg fresh weight compared to 100 mg/kg fresh weight in kale, 40 mg/kg fresh weight in blackcurrants, and 30 mg/kg fresh weight in broccoli and apples [51]. Onions provide a good example of the importance of a vegetable genotype on the content of phenolic compounds [52]. Both color and long/short day onion cultivars contribute to the differences in the content of phenolic compounds.

Color is a phenotypical attribute and is closely related to the content of flavonols in onions [33]. Total flavonol contents in onions are usually higher in red onions, and lower in yellow or white varieties [54,55]. In a detailed study of 55 onion cultivars, the level of quercetin was found to be the highest in red, pink, and yellow onion varieties (in the range of 54–286 mg/kg fresh weight (FW), whilst white onions contained low levels of quercetin [56]. Similarly, Pérez-Gregorio and colleagues studied two white and three red onion varieties and the results showed that all the red onions contained the highest levels of flavonols and anthocyanins [36]. Marotti and Piccaglia stated that colored onions showed higher TFC than white ones [52,57]. It seems that color plays an important role in determining the content of flavonols. However, Crozier et al. [58] found that red-skinned onion did not contain a higher level of quercetin content than the white-skinned onions. This could be due to different onion varieties and different growing locations.

Long-day onion cultivars and short-day onion cultivars were studied by Okamoto et al. [59], Yoo, Lee, and Patil [60] and Petropoulos et al. [61], who reported the differences in quercetin content in these two cultivars. Lombard, Geoffriau, and Peffley [62] pointed out that the total quercetin content in long-day cultivars was documented to be higher than in short-day cultivars and this difference did not depend on growing locations. The effects of onion bulb size on quercetin content was also investigated by some researchers. Lee et al. [63] reported that small onions had higher flavonoid contents than larger onions. However, Patil, Pike, and Hamilton [64] demonstrated that bulb size did not show any effect on the quercetin level. Mogren, Olsson, and Gertsson [51] also reported that minor or no differences in quercetin glucoside content were observed between small- and large-sized onions.

3.2. Flavonoid Distribution in Onion Tissue

Flavonoids in onions, mainly consisting of quercetins, accumulate to varying degrees in plant tissues and the levels determined in different plant parts are dependent upon environmental conditions [65]. Onion bulb skin (the non-edible dry peel) is richer in total flavonoids compared to the edible pulp. Grzelak et al. [66] determined a three-fold difference in flavonols presented in the fresh outer scales of the studied onion compared to any other onion part. Lee et al. [63] reported a decrease in the content of flavonoids in onion from the first to the seventh scale, i.e, from the onion skin to the onion pulp. Mogren, Olsson, and Gertsson [51] claimed that about 90% of total flavonols was concentrated and confined to epidermal tissue. Nemeth and Piskula [67] and Slimestad and Vagen [68] suggested that higher flavonol contents in the outer bulb scales, compared to the inner scales, is due to cell aging. However, Beesk et al. [69] found that the total flavonoid content in onions ranked as follows: middle layers > outer layers > inner layers.

Anthocyanin contents in onions were also studied and reported to be rich in the dry skin of onion bulbs (particularly in red and pink onion varieties). It is noteworthy that 63% of red onion anthocyanins are presented in the dry skin, which means that, after bulb peeling, only 27% of the total anthocyanins of red onion will be consumed [70].

4. Bioactivity of Phenolic Compounds in Onions

Onion has been reported to have multiple health functions based on in vitro, in vivo, and human studies [71–76] (Table 1). Phenolics, as the major bioactive constituents in onions, not only have strong biological functions such as anti-inflammatory and antioxidant activities [77–86], which are linked to the prevention of a number of degenerative diseases,
but also provide sources for natural food dyes [77]. In this section, antimicrobial activity, antioxidant activity and anticarcinogenic and antimutagenic activities of onion and its by-products are mainly summarized and discussed.

4.1. Antimicrobial Activity of Onions

Pszczola [87] highlighted the fact that onions have been used for centuries against fungal, bacterial and viral infections. Phenolic compounds in onions were reported to contribute to these activities [75]. Due to the great antimicrobial activity that onions appear to possess, it is not surprising that onion-derived phenolic compounds have been investigated for their antimicrobial properties, especially owing to the fact that these compounds appear to be relatively stable. Santas, Almajano and Carbo [88] investigated the antimicrobial activity of flavonol standards and ethyl acetate subfractions of methanolic extracts of three Spanish onion varieties against three different bacterial strains. Among the onion extracts tested, ethyl acetate sub-fractions alone showed microbial inhibition.

It was reported that the major onion flavonoids possessed antiviral activity and enhanced the bioavailability of some antiviral drugs [89]. Chen et al. [90] found that shallots presented the highest antiviral activities, followed by onions. Given the high content of quercetin in onion, it was suspected that quercetin and its derivatives affected antiviral action.

Zohri, Abdel-Gawad, and Saber [91] reported that onion extracts are effective against many yeast species, and their essential oils inhibit dermatophytic fungi. De Souza et al. [92] demonstrated a relationship between the levels of total phenolics in onion and the antifungal activity tested against Rhizopus oryzae.

In sum, accumulated studies have demonstrated that onion inhibits the growth of microbes, showing great potential to be used as a natural preservative in the food industry to maintain food quality.

4.2. Antioxidant Activity of Onions

Onions have shown antioxidant properties due to the presence of polyphenols [93–95]. Some research has highlighted the variation that occurs in antioxidant activity in onions, owing to the fluctuation in onion total phenolic content [96,97]. Gokce et al. [98] suggested that red onions had higher antioxidant activities than yellow and white onions. Bora and Sharma [38] indicated that the dry outer layers of onion contained large amounts of quercetin, quercetin glycoside and their oxidative products, which are effective antioxidants against non-enzymatic lipid peroxidation and oxidation of low-density lipoproteins.

A good source of antioxidant polyphenols can be found in onion waste (i.e., residues and surpluses of onion) and by-products [99]. Singh et al. [29] pointed out that extracts from red onion peel contained large amounts of antioxidant polyphenols. Benite et al. [100] reported a higher content of total phenolics and flavonoids from brown skin and top-bottoms of industrial onion wastes had a high antioxidant activity compared with other bioactive compounds, and hence the wastes could be used as functional ingredients. A by-product developed by Roldan et al. [101] derived from two Spanish onion cultivars that were stabilised by thermal treatments are shown to possess good antioxidant activities measured by the DPPH (2,2′-diphenyl-1-picrylhydrazyl radical) assay.

In addition to onion varieties, processing treatments and extraction methods could also affect the antioxidant activities of onion extracts. Widely employed food processing methods on the antioxidant activity of onions include drying [102,103], heating [104], and high-pressure processing [105], which showed a decrease in the antioxidant activity of onions [104].

Singh et al. [29] used several methods to extract polyphenols and found that ethyl acetate (EA) extract obtained large amounts of polyphenols, and hence displayed a stronger antioxidant capacity. Roldan et al. [101] found that obtaining the onion paste from processing the onion wastes, followed by applying mild pasteurization, were the best approach to obtain an increasing stabilized onion by-product with good antioxidant activities. Ac-
According to Lee et al. [106], onion samples were heated and juiced and the levels of active compounds in onions increased after heating, since the antioxidant activities of the ethyl acetate fraction were higher in onions heated at 120 °C, 130 °C or 140 °C for 2 h than in raw onions, and the higher the processing temperature employed, the greater were the radical and nitrite scavenging activities observed. Similar results were found by Woo et al. [107], who indicated that the optimal heating time and temperature were 2 h at 130 °C. In contrast, Khaki et al. [108] employed acidified water/ethanol-based solvent extraction systems and reported that optimal extraction yields occurred at 6 h, whereas an increasing temperature from 40 °C to 60 °C had a negative effect on yields. Different processing conditions (e.g., temperature, time) may affect the antioxidant activity in onions. The bioactivity of phenolic compounds in onion was reduced by thermal processing, but the use of extraction solvents or extraction techniques could improve the bioactivity of its phenolic compounds under optimal conditions (i.e., temperature and time).

4.3. Anticarcinogenic and Antimutagenic Activities

As highlighted previously, quercetin and its derivatives have been shown to exhibit anticancer properties, including activity against prostate, breast, skin, lung and liver cancers [109]. Jeong et al. [110] reported different anticancer activities from extracts from pulp and peel of white, yellow and red onion. In general, onion peel with the highest amounts of total phenolics and flavonoids inhibited the growth of several human cancer cell lines, including cells from both the stomach and colon, breast and prostate [110], more efficiently than fresh onion pulp. Likewise, several studies have reported that quercetin enhanced the bioavailability of some anticancer drugs, such as Tamoxifen, a non-steroidal antiestrogen for the treatment and prevention of breast cancer, by promoting its intestinal absorption and reducing their metabolism [89].

4.4. Hypotensive and Bradycardic Effects

A study with several rat models of hypertension has indicated that quercetin and its methylated metabolite isorhamnetin can reduce blood pressure [30]. Moreover, Edwards et al. [111] investigated the efficacy of supplementation of quercetin on lowering blood pressure in hypertensive humans and demonstrated that 730 mg of quercetin per day could reduce systolic blood pressure by 7 mm Hg, diastolic blood pressure by 5 mm Hg, and mean arterial pressure by 5 mm Hg in hypertensive patients. Egert, Bosy-Westphal, and Plachta-Danielzik [112] also found that quercetin reduced systolic blood pressure and plasma oxidized low-density lipoproteins concentrations in overweight subjects with a high cardiovascular disease (CVD) risk phenotype. It is believed that more animal studies and clinical trials are required for a better understanding of the cardiovascular protective effects of onion and its phenolic compounds.

4.5. Anti-Hyperglycemic and Anti-Diabetic Potential

An investigation into the effects of quercetin on human diabetic lymphocytes showed an association between an increase in the protection against DNA damage from hydrogen peroxide at the tissue level and the number of consumed flavonols (mostly quercetin) from onions [113]. Likewise, it has been reported that long-term absorption of quercetin could be useful to prevent advanced glycation of collagen, which contributes to the development of cardiovascular complications in diabetic patients [31].

4.6. Anti-Platelet Effect

Quercetin and its derivative showed their beneficial effects on cardiovascular health because of their antioxidant and anti-inflammatory activities [114], through the inhibition of lipid peroxidation and endothelial cell damage, which are involved in the early development of atherosclerosis [115]. An in vitro study carried out by Janssen et al. [116] showed that 2500 µmol/L quercetin isolated from onions inhibited platelet aggregation by 95–97%. However, an in vivo assay from the same authors with 18 human subjects ingesting 114 mg
quercetin/day showed no significant effects. They concluded that necessary concentration levels of quercetin for the beneficial effects were too high to be obtained in daily dietary.

5. Pre-Harvest Treatments Influencing the Phenolic Compounds in Onions

Besides intrinsic characteristics such as different onion varieties, many other factors influence the level of phenolic compounds in onions, for example environmental conditions (e.g., soil type, sun exposure, and rainfall) and agronomic conditions (e.g., culture in greenhouses or fields, biological culture, and hydroponic culture) [117,118]. Table 2 lists the pre-harvest factors and their effects on the quercetin content of onions during growing and storage.

| Factors                        | Effect on Quercetins Content                                                                 | References        |
|--------------------------------|------------------------------------------------------------------------------------------------|-------------------|
| Variety of onion               | Rank of quercetins content: Red > Yellow > White                                              | [49,53,60,119-124]|
| Bulb parts                     | Rank of quercetins content: small > large                                                     | [31,63]           |
| Organic/Conventional varieties | Rank of quercetins content: dry outer skins > inner skins                                     | [37]              |
| Light                          | Rank of quercetins content: after curing > at lifting                                        | [125,126]         |
| Curing                         | Exposure to sun light during production period > less sun light during production period of onion | [63,127,128]     |
| Lifting                        | UV light lamps after harvest > no UV treated onion                                             |                   |
|                                | Fluorescent light after harvest > no UV treated onion                                         | [63]              |
|                                | Rank of quercetins content: field curing > dark environment                                  | [51,129]          |
|                                | Rank of quercetins content: late lifting time > early lifting time                           | [130,131]         |

Patil, Pike, and Hamilton [64] showed that meteorological factors (including temperature and rainfall patterns) had a stronger influence on quercetin concentration in onion cultivars than soil factors or plant maturity. Mogren, Olsson, and Gertsson [126,130] indicated a strong correlation between total radiation during lifting stages and the quercetin glucoside content of onions. However, Patil, Pike, and Hamilton [64] reported no correlation between onion growth stage and quercetin content in onions. On the other hand, they showed a relationship between the quercetin content of onions and environmental factors such as location and soil type, which played a major role in affecting the levels of quercetins.

Furthermore, there is increasing evidence indicating an impact of genotype, growing environment including the production year, and interactions between the genotype and growing conditions on variations in the bioactive compositions and contents of onion [117,118]. Others have also reported the effect of genotype and environment interaction on the total phenolic contents and antioxidant properties of wheat [114], but little is known about such interactions in onions.

5.1. Light

Light can influence genetic expression that is relevant to enzymes participating in the phenylpropanoid pathway [129]. Light conditions during plant development and/or storage (in light or darkness) could play an important role in the total phenolic content [129]. Quercetins are strong UV-absorbing compounds, and can be accumulated mainly in the epidermal cells of plant tissues after UV-induction [132]. Light stimulates the synthesis of quercetins, and L-phenylalanine ammonia-lyase (PAL) is the major inducible enzyme [133]. The formation of the quercetin glucoside (QG) is normally induced by UV light, which induces PAL activity up to 30-fold [71]. Yoo, Lee, and Patil [134] exposed onions under different lights, and found that the synthesis of QG compounds is enhanced by UV light and, to a lesser extent, by visible light. In the sprouting leaves, 4′Qmg and 3,4′Qdg concentrations increased most when exposed to UV light and, to a lesser extent, when
exposed to visible light; however, even the samples in dark conditions showed a slight increase in QG compounds.

Onions grown in full sunlight have been reported to contain higher levels of flavonoids [135]. A five-year study which examined the effect of climatic conditions on flavonoid contents in two Portuguese landrace onion varieties, total quercetin levels varied significantly between years, with the highest quercetin levels observed in dry years [131].

Mogren, Olsson, and Gertsson [51] proposed that global radiation rather than temperature is the determining factor for quercetin glucoside biosynthesis in onions. Rodrigues et al. [127] pointed out that global radiation at the end of the onion production period seemed to be one of the major determinants of annual quercetin glucoside content in the onions. Mogren, Olsson, and Gertsson [51] reported that, during a four-year study, the month with the lowest global radiation corresponded to the lowest levels of quercetin glucosides. Higashio et al. [128] found that quercetin content in onion could be doubled after harvest using UV light lamps to irradiate the onion. Lee et al. [63] conducted a similar study where they exposed onions to fluorescent light for 24 and 48 h and showed that this induced time-dependent increases in quercetin content.

Light can also cause a stress signal, enhancing flavonoid synthesis in some fresh cut foods [129]. Under the light, an increase of flavonols [63] and quercetin has also been found in fresh-cut onions [130]. Pérez-Gregorio et al. [131] also found that, with the light, total flavonoids in fresh-cut onions were increased by 58% and anthocyanins were increased by 39%.

5.2. Soil Status

Patil, Pike, and Hamilton [64] observed higher amounts of quercetin in onions grown in both clay and sandy loam soils with nitrogen limitation. However, the correlation between nitrogen stress and flavonol synthesis could not be verified due to the different growth stages of onions during experiments. On the other hand, they concluded that the site of growth, more so than the growth stage and soil type, is a major environmental factor in determining quercetin concentration in onion.

Application of fertilizer is one of the most dominant factors affecting the level of quercetin in onions [132]. Nitrogen, phosphorus, and potassium are the three major fertilizers required for the optimum growth of plants; however, the amount and the method of fertilizer application also influences the level of quercetins. A decrease in soil nitrogen concentration may be associated with an increase in total quercetin concentration [133], and a limited nitrogen supply was also reported to be associated with higher levels of phenolics in plants [71]. However, either high or low levels of nitrogen fertilizers during the growth of onions did not result in differences in quercetin content after field curing [132].

Fertilizer application methods and nitrogen source (organic and conventional fertilizers) can significantly affect bulb size, without affecting total yield and the quercetin content of dry bulbs [132].

5.3. Agronomic Conditions

Agronomic practices, such as sowing date, fertilization, irrigation, and subsequent harvesting, would affect quercetins content in onions. Previous studies showed that organically grown onions had higher levels of flavonols and antioxidant capacity than conventionally grown onions [126]. However, Solloft et al. [134] found no significant differences between the conventionally and the organically grown onions in terms of quercetin content.

6. Changes in Content of the Phenolic Compounds in Onions during Post-Harvest

Onion bulbs are normally sown in March and are generally mechanically harvested from late August to mid-September. Before harvest, they are lifted to stop their growth and are cured by air drying at 25–28 °C and 65–75% RH for ten days to six weeks in the UK and Ireland [135] (Figure 2).
Figure 2. Post-harvest factor changes in the contents of the phenolic compounds in onions.

Onion bulbs are ready for harvest as soon as the leaves of the plants (‘top’) start to recline (‘fall’). The usual practice is to harvest when 25–80% of tops have fallen, with a consequently significant effect on storage susceptibility and quality of the bulbs. Harvest stage can be essential for sprout incidence, since early lifting can result in a lower sprouting percentage and better storage without negative effects on the initial quercetin content, which remains unchanged during storage [51].

Quercetin content in onions increases after lifting and the lifting time would affect the increase. Mogren, Olsson, and Gertsson [136] pointed out that an early lifting time of onions resulted in a reduced level of quercetin content in onions, probably due to low sprouting and a lighter color in the early lifted onions. On the other hand, late lifting (80% fallen leaves) resulted in up to 45% higher concentrations of quercetin glucosides compared to early lifting (50% fallen leaves).

6.1. Effect of Curing on the Phenolic Compounds

Straight after harvest, bulbs have to be subjected to a drying process (‘curing’) in order to have their outer scales hardened and to reduce skin cracks, and allow the necks to become narrower, thus inhibiting pathogen infections. Curing method (field curing or forced air curing) and conditions (temperature and relative humidity), as well as growing conditions and harvest stage, can be of major importance for maximum quality in dry bulbs and minimum losses due to water losses and pathogen infections [137].

Curing may result in an increase of flavonols in onions, although this phenomenon depends on the year and cultivars [138]. Patil, Pike, and Hamilton [64] indicated that onions cured in the field could accumulate more flavonols. Traditionally, in hot dry climates, onions can be left to cure in the field in windrows or mesh bags and this has been reported to be associated with an increase in quercetin content [51]. Rodrigues et al. [125,129] also reported that field curing increased 4′Qmg and 3,4′Qdg (33–40%) content compared to levels at lifting, particularly when the flavonol concentrations were low at lifting. Light conditions (light or dark condition) during curing, however, did not affect flavonol and anthocyanin contents, regardless of skin color and cultivar.

The effect of cold storage combined with curing or post-curing treatment was studied by many researchers. Downes, Chope, and Terry [131] cured two types of yellow onion and one kind of red onion at 20 °C, 24 °C or 28 °C for six weeks and then stored the onions at 1 °C for seven months. They found that levels of flavonols in red onions cured at 20 °C decreased during cold storage for seven months.

The evolution of onion flavonols during storage after post-curing heat treatment at 36 °C for 24 or 96 h was studied by Olsson, Gustavsson, and Vagen [139]. Three onion va-
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...rieties were cured in the field for two weeks and then heat treated, followed by subsequent cold storage at 2 °C for up to eight months. The levels of Q 3,4′D increased in the 24-h. A lower content of total flavonols was found in the three onion varieties after eight months of cold storage following the 96-h heat treatment, possibly due to negative effects of heat treatment on onion metabolism.

Price and Rhodes [133] investigated the levels of flavonols of two onion varieties (‘Red Baron’ and ‘Crossbow’) cured at 28 °C for ten days and stored for six months at ≤ 4 °C in dark, and found no change in the flavonol levels for the two varieties after storage.

6.2. Evolution of the Phenolic Compounds When Sprouting during Storage

Post-harvest sprouting in onions would occur after long-term storage. Onions may be kept in cold storage at around 1–4 °C in the dark to induce dormancy and prevent sprouting; however, sprouting commonly initiates within one to three weeks after removal from cold storage [140]. Benkeblia and Shiomi [141] indicated that total phenolics content (TPC) in onions began to reduce when internal sprouting began, which can be caused by the temperature change (from cold to room temperature) during storage. In their study, the reduction also happened to onions stored in control conditions (in refrigerators) when internal sprouting began, after seven weeks of storage. Benkeblia et al. [142] also reported that there was an inverse relationship between total phenolic content and sprout development.

However, conflicting results were reported by Sharma et al. [143], who investigated the evolution of total flavonoid content (TFC) of onions during storage (post-storage) at room temperature and relative humidity (RH) 60–80%, subsequent to a cold storage for eight months. They found that internal sprouting began within the 1st week post-storage, but TFC increased during the post-storage time, and reached a maximum between the 4th and 8th weeks.

6.3. Evolution of the Phenolic Compounds during Storage

Phenolic contents can be changed during storage. Kevers et al. [144] argued that, 23 days after purchasing, both antioxidant activity and the total flavonols of onions increased during storage and became 10 times higher than on purchase from the market. Sharma et al. [143] also reported increased TPC and TFC during storage at room temperature after cold storage. However, due to sprouting and decay after four weeks post-storage, they suggested that the onions thereafter should be used only for, e.g., extraction of nutraceuticals. Rodrigue et al. [145] stored Portuguese red and white onions after harvest for seven months under refrigeration (at 2 °C and 65% relative humidity) or under traditional bulk storage in the field. TFC in both of the two varieties increased up to 64% after six or seven months of storage, especially in the first three months (58% increase), irrespective of the storage temperature. Regarding anthocyanins, after seven months in both conditions (refrigeration and traditional treatment), the anthocyanin content was reduced by more than 40%. Elhassanneen and Sanad [146] reported significant differences in flavonol content between white and red Egyptian onion varieties, with red varieties having a higher content of total flavonols, quercetin and quercetin glucosides after storage for a three-month period. Quercetin glycosides are not significantly affected by storage; however, the fact that these compounds are present mostly in the outer scales, which are severely affected by storage and are usually discarded after the peeling of bulbs, could affect nutritional values and their intake on a daily basis [147].

It is believed that the phenolic compounds in onions could be influenced by storage conditions [35]. Storage conditions, like storage time, temperature and light, have effects on the synthesis, retention or breakdown of quercetins. Sharma et al. [148] examined the effect of storage under aerobic and anaerobic conditions at ambient temperatures, reporting that quercetin content increased significantly during anaerobic condition and that total phenolic and flavonoid contents were positively correlated with antioxidant activity. Light conditions and light quality during storage may affect quercetin and quercetin glucoside profiles. Ko et al. [149] examined the effect of five light wavelengths (dark, white, red,
blue and UV-A light) for three days as a post-harvest treatment and found that white light treatment significantly increased quercetin glucoside content in peeled onion bulbs, as well as in bulb skins.

7. Storage Technologies

Storage technologies are employed to prolong onions or its product shelf life. Some studies have been carried out to investigate the effects of these technologies on the levels of phenolics, mainly flavonoid compounds, in onions during storage [150,151].

Drying technological developments are driven by consumers who demand a healthy, fresh, and convenient food. Hence, the effect of dehydration on onion quality was studied [3,152]. Drying can prolong the shelf life of onions, and onions can be marketed as dried powder intended for culinary uses, by applying various drying processes [153,154]. Pérez-Gregorio et al. [131] pointed out that freeze-drying, as an innovative drying technique, used to dry chopped onions could prolong the shelf life of dried powder at room temperature for up to six months without significant quality losses in terms of antioxidant compounds (flavonols and anthocyanins), provided that they are stored under dark conditions and within air-tight containers. The freeze-drying process produces the highest-quality dried food product, since the food structure is not damaged during sublimation; hence, it was verified that onion flavonoid content increases after the freeze-drying process [131]. The stability of flavonoids of freeze-dried onion after long-term storage was mainly due to the inactivation of various enzymes, as well as ethylene activity [145]. Moreover, the implementation of the freeze-drying technique itself resulted in an increase in the extractable flavonoids by 32 and 25% for flavonols and anthocyanins, respectively, because of the structural changes of bulb tissues that made flavonoids more readily available [131].

8. Conclusions

Onion, as an important crop in the Allium family, contains a high amount of phenolics compounds, which to a great extent is attributed to human overall dietary intake. It is worth noting that the content of the phenolic compounds can be varied in different onion cultivars. For example, red onion cultivars generally contain the highest level of flavonoids. In addition, agronomic practices (sowing date, fertilization, and harvesting time) can also affect the phenolic content of onions.

The storage of onions is a complex process that can be influenced by many factors. Pre-harvest conditions that affect the storability of onion bulbs are related to genetic background and growing conditions, including cultivar, fertilizer, and harvest stage. In addition, storage conditions (time, temperature, relative humidity, controlled atmospheres) are important for retaining high quality bulbs as well as for prolonging the life of onions. Optimized storage conditions can subsequently be employed after processing to further reduce the loss of phenolic content in raw and processed onions. Some new techniques such as different drying methods, which are applied in onion production have benefits in retaining quality, and bioactive compounds and increasing storage potential during storage. Most of the studies so far have been performed at a laboratory scale, but further research is necessary to apply the knowledge to industry needs to maintain onion quality.

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