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Quercetin Content in Field-Cured Onions (*Allium cepa* L.): Effects of Cultivar, Lifting Time, and Nitrogen Fertilizer Level

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Variation in quercetin content was investigated in field-cured onions (*Allium cepa* L.) that had been supplied with different nitrogen fertilizer levels and lifted at different developmental stages. Quercetin content varied significantly between years and was well correlated to global radiation in August. Field curing generally resulted in significant increases in quercetin content compared to levels at lifting. Nitrogen fertilizer level did not affect quercetin content, suggesting that nitrogen leakage from soil may be minimized without effects on flavonol content. Lifting time had minor effects on quercetin content in field-cured onions. Cultivar differences in quercetin content were significant but not consistent in all years. 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.

KEYWORDS: ***Allium cepa*; onion; quercetin glucosides; curing; drying; nitrogen fertilizer; lifting time; cultivar**

INTRODUCTION

World onion production is currently ≈44 million tonnes, making it the second most important horticultural crop after tomatoes (*1*). The common yellow onion (*Allium cepa* L.) belongs to the Lilliaceae family and is grown all over the world. Since antiquity, the onion has been traditionally used in folk medicine for its therapeutic action. Research directed at disease prevention rather than cure is currently attempting to produce onions with a high content of nutraceuticals (*2*). Reports of health benefits from onions include anticarcinogenic properties, antiplatelet activity, antithrombotic activity, and antiasthmatic and antibiotic effects (*1*). At present there is considerable debate about the specific components responsible for the beneficial health effects of onions. Two main groups of chemical compounds have been proposed: the flavor precursors alk(en)-yl sulfoxides (ACSOs) and the flavonoids (*1*). Red-skinned varieties contain anthocyanins, and both red and yellow onions contain flavonols, mainly quercetin and its derivatives. The functions of flavonoids in plants include pigmentation (to attract pollinators), protection of the plant from UV light and micro-organisms, defense against grazing animals, regulation of enzyme activity, and signal substances for nitrogen-fixing bacteria (*3*). In plants, flavonoids occur primarily as glycosides, with different sugar groups linked to one or more of the hydroxyl groups (*4*). Flavonoids are mainly found in the aboveground outer parts of plants, such as leaves, flowers, and fruit, whereas the content in stalks and roots is usually limited (*5*). The highest concentrations of flavonoids in onion are found in the outer dry scales, so the greatest loss of flavonoids takes place when the onions are peeled (*6*). The formation of flavonol glycosides normally depends on the action of light (*7*) and is induced by UV light (*8*). In onion, the main flavonol glycoside forms have been found to be quercetin 4′-monoglucoside and quercetin 3,4′-diglucoside (*9*). Bioavailability of flavonols in the human body has been a controversial issue for a long time. The absorption from different foods seems to differ; for example, the absorption of quercetin forms from tea was found to be half that from onions (*10*), and the absorption rate from apples was one-third that from onions (*11*). Cooking, frying, or warm-holding of onions has only minor effects on the flavonoid content available (*6*), and the losses of onion flavonoids caused by gastric acid and intestinal juices seem to be low (*12*). It was long believed that flavonoid glycosides were not absorbed but hydrolyzed to their aglycones by bacterial enzymes in the intestine (*13*, *14*), but later it was proposed that the flavonoid glycosides were in fact absorbed (*15*). However, in a recent review of the absorption and metabolism of flavonoids, it was concluded that a number of studies now support the view that quercetin glycosides are not absorbed intact in humans and are not able to reach the systemic circulation (*16*). Although the bioavailability of the aglycones formed after hydrolysis along the aerodigestive tract is considered to be low, conjugates formed during the metabolism of flavonoids, such as sulfate and glucuronic acid conjugates, have been found in relatively high concentrations. The biological importance of these metabolites and of degradation

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products formed during biological degradation of the flavonoid backbone remains to be elucidated (*16*).

Onions are a natural part of the daily diet for most of the world's population and, therefore, an important source of the potentially health-promoting compound quercetin and its derivatives. For example, in Denmark, quercetin was found to comprise 37% of the flavonoid intake, and 16% of the total flavonol and flavanone intake was from onions, which is equivalent to 10 g of onion per day (*17*). In Poland, onion has been ranked as the seventh most important fruit and vegetable source of polyphenolic compounds in the diet (*18*). In a Dutch study, tea and onions were found to be the most important sources of flavonoid consumption (*19*). Previous investigations have mainly analyzed quercetin content in onions bought at the local market (*12*, *20*−*27*), and therefore information on how cultivation conditions and handling at harvest affect quercetin content is scarce. Reducing the leakage of nitrogen from the soil to the groundwater is an important goal of environmental care actions, but little is known about how reduced nitrogen fertilization affects the nutritional value and content of health-promoting compounds of onions including the effect on quercetin. Late lifting generally results in higher yields, but the onions start to sprout earlier after long storage (*28*). After lifting, the common practice in Sweden is to leave the onions lying in the field for a couple of days to dry and cure in full sunlight, but sometimes forced air in dark environments is used instead. The aim of the present work was to investigate the role of nitrogen fertilizer level, lifting time, cultivar, and field curing in flavonol synthesis in the common yellow onion. Additional experiments were performed to investigate the role of curing with or without foliage and with or without light and variation in quercetin glucoside content between different onion scales.

MATERIALS AND METHODS

Location of Field Study. The field study was performed in 2002, 2004, and 2005 at Torslunda Research Station, Öland, in southeastern Sweden (56° 38′ N, 16° 30′ E). Öland is one of Sweden's most important onion-growing districts. The soil at the site is a sand with a medium organic matter content (3%) and a low clay content.

Growing Technique. In 2002, insecticide-coated (carbamate type) seeds of two onion (*Allium cepa* L.) cultivars, cv. Barito F1 and cv. Summit F1, were sown. In 2004 and 2005, seeds of cv. Hyskin F1 without insecticide coating were also used. The seeds were sown directly in the field in the beginning of April each year. The rows were placed 0.5 m apart, and seed rate was ≈39 seeds per row-meter. Pest and weed management was performed according to conventional commercial practices in Sweden. Water was supplied by irrigation as required on the basis of rain and evaporation data until the middle of July. In August the onions were lifted from the ground and left for field drying and curing in windrows for ≈10 days before extraction of flavonoids.

Experimental Design. The experiment was carried out in five completely randomized blocks in 2002 and in four blocks in 2004 and 2005. In 2002 and 2004, each cultivar was grown with two different nitrogen fertilizer levels in each block as described below and lifted at two different times. In 2005, only one nitrogen fertilizer level was used in the whole experiment.

Fertilizer Treatments. Soil core samples (0−30 cm) were taken 2 days before sowing, and the N_{min} content of each soil sample was analyzed as follows. Fresh soil samples were shaken with 2 M KCl for 2 h and then filtered. The content of mineralized nitrogen (ammonium and nitrate) was analyzed in these extracts by flow injection analysis (FIA). On the basis of these soil analyses and using the target value of 40 kg of N ha^{-1} suggested by Gertsson and Bjorklund (*29*), nitrogen was supplied as NPK-micro. Additional phosphorus was supplied as PK, and additional potassium was supplied as KMg and KS, to ensure that there was sufficient sulfur in the soil. All fertilizers were spread and harrowed down into the soil before sowing. In the beginning of June each year, new soil samples were taken in the same way as described above and analyzed. Low nitrogen fertilizer treatments were supplied with calcium nitrate on the basis of analysis of the content of mineralized nitrogen in the soil (N_{min}) to a target value for June of 72 kg of N ha^{-1}. The high nitrogen fertilizer treatments received 80 kg of N ha^{-1} more than the low levels each year and are comparable to the nitrogen level used by many commercial growers.

Lifting Times. In August the onions were lifted from the ground at different stages determined by the approximate number of onions with fallen leaves. In 2002, 2004, and 2005 onions were lifted when 50% (early lifting) or 80% (late lifting) of the plants in the stands had fallen leaves.

Curing Times. After lifting, the onions were left on the field in windrows to dry and cure for 10−14 days, which is still common practice in many countries. After this time, the onion bulbs had developed papery outer scales and the necks were dry and tight.

Extraction Method. Directly after completion of field curing, onions with a diameter of 55−70 mm and a weight of ≈100 g were chosen for extraction. Each onion sample consisted of 10 onions from each experimental plot. The roots, the leaves, and the outer dry skins were removed to mimic domestic peeling. Each onion was divided longitudinally from the top to the base into eight (2002) or four (2004 and 2005) wedge-shaped pieces. Two opposite pieces from each onion were chopped and homogenized in a Waring blender. Four portions (2002 and 2004) or three portions (2005) of each onion sample, each comprising 5.00 g of homogenized onion tissue, were extracted for 2 weeks at −20 °C in 20 mL of acidified (150 mM HCl) 98% ethanol. This long extraction method was found to be convenient and resulted in good extraction efficiency and repeatability (unpublished data). The extracts were centrifuged at 16500*g* for 10 min at 4 °C, transferred into Eppendorf tubes, and stored at −20 °C until analysis. Before HPLC analysis, the Eppendorf tubes were thawed and centrifuged at 16500*g* for 5 min at 20 °C.

HPLC Analysis Method. The analyses of the onion extracts were performed on an Agilent 1100 HPLC system. The column used was a Phenomenex Luna 5u C18(2) (150 × 4.6 mm, 5 μm). The mobile phase consisted of (A) 50 mM acetic acid (HAc) in Millipore ultrapure water with 5% acetonitrile (v/v) and (B) acetonitrile with 5% methanol (v/v). The flow rate was 1.0 mL min^{-1} and the injection volume 20 μL (2002) or 10 μL (2004 and 2005, respectively). The binary gradient used was as follows: 0−2 min, 0% eluent B; 2−17 min, 0−45% B; 17−20 min, 45−80% B; 20−21 min, 80% B; 21−23 min, 80−0% B; 23−25 min, 0% B. External standards used for identification and quantification were quercetin (Sigma-Aldrich Chemie Gmbh) and quercetin 4′-glucoside (Extrasynthese). The absorbance was measured at 370 nm using an Agilent 1100 (G1315B) diode array detector (Agilent Technologies). Results are presented as milligrams of quercetin 4′-glucoside equivalent per kilogram of fresh weight of onion (mg kg^{-1} of fw) for all forms of quercetin.

Dry Matter Analyses. Two portions of ≈10 g of homogenized onion sample from each plot were placed in aluminum cups and dried at 70 °C for 24 h, followed by 105 °C for 1 h.

Extended Curing Experiment, 2005. In 2005, the effects of light, temperature, and relative humidity during curing were investigated more thoroughly. Besides ordinary field curing, three replicates, of 10 onions each, of the three cultivars were placed directly after lifting in one of five different environments: a tent covered with transparent plastic, a tent covered with dark nontransparent plastic, a stone wall shed, a climate chamber, or a sealed plastic carrier bag within the climate chamber. The tent was composed of a wooden structure ≈1 m high built on a concrete base. Half of it was covered with a transparent plastic film and the other half with two layers of black nontransparent plastic film. The transparent film reduced the UV light transmittance by 20% (measured by Philips TL 12, 4W, UV light lamp). The stone wall shed was completely dark, with ambient temperature (average = 15.7 °C) and high relative humidity (99%). The climate chamber was completely dark and had a higher average temperature (18.7 °C) and a lower relative humidity (75%). Within the climate chamber, onions were also placed in large plastic bags, which were sealed and not opened before extraction. Temperature and relative humidity were recorded with

Table 1. Temperature (T, °C) and Relative Humidity (RH, Percent) in the Different Curing Treatments, 2005

treatment	T_{mean}	T_{max}	T_{min}	RH_{mean}	RH_{max}	RH_{min}
plastic bag in climate chamber	19.1	20.8	18.0	100		
climate chamber	18.7	19.9	17.7	75	86	62
stone wall shed	15.7	16.2	14.8	99	100	98
transparent plastic covering	23.2	42.0	13.1	66	98	25
dark plastic covering	18.7	28.7	12.8	78	95	48
field curing	16.7	25.1	10.6	79	97	48

Tinytag Plus dataloggers (Gemini Data Loggers Ltd.). The mean temperature and mean relative humidity for each environment during the extended curing experiment in 2005 are summarized in **Table 1**. The tent covered with transparent plastic resulted in high daytime temperatures. The tent covered with dark plastic had almost the same conditions as normal field curing except for the absence of light. The stone wall shed had high relative humidity, resulting in slow drying and curing. The climate chamber had higher temperature but lower relative humidity compared to the stone wall shed, and this resulted in attractive looking, partly cured onions with brownish foliage. The onions put in sealed large plastic bags within the climate chamber had a fresh appearance, but the green foliage was greasy and had a strong unattractive smell. Due to condensation, the datalogger could not measure relative humidity in the sealed plastic bags.

Extended Curing Experiment, 2003. In 2003, Barito F1 onions were obtained from a commercial grower's field in the same geographical region as where the other experiments were performed. Onion samples were taken from different parts of the field at early and late stages (see Lifting Times) and analyzed as in 2002. In addition, onions with fallen and erect leaves from the same rows were collected once the leaves had just started to fall down. Wedge-shaped pieces were extracted after field curing as in 2002. In addition, the remaining scale parts of the same onions were separated into three portions, the two outer fleshy scales ("outer"), the next two scales ("middle"), and the rest of the scales ("inner"), and the portions were extracted and analyzed separately. To investigate the role of the foliage (the green leaves) for flavonol synthesis during curing, additional early- and late-lifted onions with the foliage cut off were left for field curing beside the other onions, which had their foliage still attached.

Weather Data. Weather data during all experimental years were recorded using an Adcon Telemetry (Adcon Telemetry Gmbh) weather station placed in the onion field.

Statistical Analyses. The results from the analyses were statistically analyzed in Minitab release 14.1 (Minitab Inc.). Results were subjected to ANOVA. If not stated, no interaction between factors was significant. Significance was determined at $p < 0.05$, and results reported were significantly different at this level unless otherwise stated.

RESULTS AND DISCUSSION

No interactions were found between quercetin content in the onions after field curing and the factors nitrogen fertilizer level, lifting time, and cultivar within any of the years. Therefore, each factor was analyzed separately with the whole data material as a basis.

Weather Data and Quercetin Content. The mean levels of total quercetin after field curing differed significantly between the years (**Table 2**) with a total mean content for all years of 280 mg kg^{-1} of fw. This level is comparable to Danish results showing yellow onion quercetin content to be 348 mg kg^{-1} of fw (*30*). In Texas, total quercetin concentration (sum of quercetin glucosides) was found to range from 256 to 513 mg kg^{-1} of fw and represented 88% of the total flavonol content (*31*).

The global radiation, measured as W m^{-2}, during the bulb-growing months of June−August was highest in the season of 2002. In 2003 it was somewhat lower, in 2004 it was even lower,

Table 2. Mean of Total Quercetin Glucosides, Q_{mean} (mg kg^{-1} of fw) for Each Year, Global Radiation, R (W m^{-2}), and Mean Temperature, T (°C), for Each of the Months When Onion Bulb Growth Occurs, and Total Global Radiation and Mean Temperature for the Whole Period from June through August 2002–2005 at Torslunda Research Station, Sweden

			June		July		August		total	mean
year	Q_{mean}[a]	n	R	T	R	T	R	T	R	T
2002	564 ± 72 a	40	7020	16.2	6224	17.7	6059	19.8	19303	17.9
2003	475 ± 61 b	24	6788	15.5	5842	18.5	5550	17.3	18180	17.1
2004	391 ± 70 c	48	6341	14.2	5666	15.6	5143	17.8	17150	15.9
2005	175 ± 34 d	24	6845	14.4	6729	18.2	4937	16.2	18511	16.3

[a] Values are mean ± standard deviation; values with the same letter are not significantly different at $p < 0.05$.

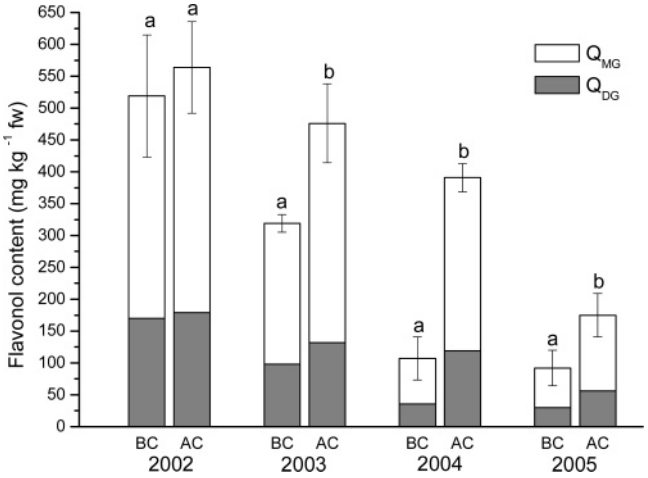

Figure 1. Effect of field curing on onion flavonol content: $n_{2002} = 40$; $n_{2003} = 24$; $n_{2004} = 48$; $n_{2005} = 24$; Q_{MG} = quercetin 4′-monoglucoside; Q_{DG} = quercetin 3,4′-diglucoside; BC = before curing; AC = after curing. Within each year bars with the same letter are not significantly different at $p < 0.05$.

and in 2005 the global radiation was lower than in 2002 but higher than 2003 (**Table 2**). The mean temperature was lowest in 2004 and highest in 2002 (**Table 2**). The total mean quercetin content for all treatments after field curing (**Table 2**) was well correlated to global radiation in August ($R^2 = 0.83$), but, in an earlier study, the correlation was found to be even higher before field curing ($R^2 = 0.98$) (*32*). The correlation was much lower for July ($R^2 = 0.34$) and for the whole onion growth period of June−August ($R^2 = 0.07$). The correlation between mean temperature in August and content of quercetin glucosides was not as high as for global radiation ($R^2 = 0.74$), and the correlation for the whole onion growth period of June−August was low ($R^2 = 0.53$). In the year 2002, with high flavonol content at lifting, almost no increase in flavonol content occurred during field curing. In all other years, however, the content of both quercetin monoglucoside and quercetin diglucoside increased significantly during field curing (**Figure 1**), but never reached levels higher than in 2002.

Growing season temperature can explain some annual and regional variability in onion flavor (*33*). We did not analyze flavor, and no clear effect of growing temperature on flavonol content could be found in our experiment. It has been proposed that UV-B light is important for quercetin biosynthesis in onions. In experiments on harvested onions, it has been demonstrated that the content of quercetin almost doubles in onion slices irradiated with UV light. Three different UV lamps were used, and the effect was the same for all, leading to the conclusion

Table 3. Effect of N Fertilizer Level (Low, High), Lifting Time (Early, Late), and Cultivar (Barito, Summit, Hyskin) on Content (mg kg^{-1} of fw) of Quercetin 3,4′-Diglucoside (Q_{DG}), Quercetin 4′-Monoglucoside (Q_{MG}), and Quercetin Aglycone (Q) in Onions with a Diameter of 55–70 mm after Field Curing[a]

							increase during curing (%)		
year	treatment	*n*	Q_{DG}	Q_{MG}	Q	total	Q_{DG}	Q_{MG}	total
2002	low N	20	177 ± 22 a	384 ± 54 a	tr[b]	561 ± 74 a	2	9	7
	high N	20	180 ± 20 a	387 ± 53 a	tr	567 ± 72 a	9	12	11
2004	low N	24	119 ± 21 a	278 ± 44 a	tr	397 ± 63 a	213	248	236
	high N	24	119 ± 23 a	265 ± 56 a	tr	384 ± 78 a	261	327	304
2002	early lifting	20	180 ± 22 a	394 ± 57 a	tr	574 ± 78 a	5	15	12
	late lifting	20	177 ± 20 a	377 ± 48 a	tr	554 ± 67 a	5	6	6
2003	early lifting	12	147 ± 18 a	344 ± 35 a	tr	491 ± 51 a	50	76	67
	late lifting	12	116 ± 13 b	344 ± 58 a	tr	460 ± 69 a	18	40	34
2004	early lifting	24	114 ± 20 a	270 ± 50 a	tr	384 ± 69 a	235	291	273
	late lifting	24	124 ± 22 a	273 ± 51 a	tr	397 ± 72 a	235	274	261
2005	early lifting	12	50 ± 5 a	106 ± 13 a	tr	156 ± 18 a	100	112	108
	late lifting	12	62 ± 10 b	131 ± 27 b	tr	194 ± 36 b	77	77	78
2002	Barito	20	183 ± 23 a	404 ± 53 a	tr	587 ± 75 a	12	26	22
	Summit	20	174 ± 17 a	367 ± 46 b	tr	540 ± 62 b	0	0	0
2003	Barito	24	132 ± 23	344 ± 47	tr	475 ± 62	35	56	49
2004	Barito	16	114 ± 13 a	278 ± 29 a	tr	392 ± 39 a	208	239	229
	Hyskin	16	142 ± 17 b	318 ± 30 b	tr	460 ± 45 b	294	382	351
	Summit	16	101 ± 10 c	219 ± 29 c	tr	320 ± 38 c	197	232	220
2005	Barito	8	53 ± 7 a	116 ± 19 ab	tr	169 ± 26 ab	89	97	94
	Hyskin	8	63 ± 11 a	135 ± 29 b	tr	198 ± 40 b	91	99	96
	Summit	8	52 ± 7 a	106 ± 17 a	tr	158 ± 23 a	79	80	80

[a] Values are mean ± standard deviation. Values with the same letter in each column, in each treatment group and within each year, are not significantly different at $p < 0.05$. [b] Trace (<10 mg kg^{-1} of fw).

that quercetin synthesis may respond to a wide range in the UV spectrum (*34*). In another study, exposure of leaves of *Brassica napus* to supplementary UV-B radiation resulted in an overall increase in the amount of soluble flavonoids of ≈150% compared to control plants, with a specific increase in the amount of quercetin glycosides of up to 36-fold (*35*). These findings support our conclusion that global radiation rather than mean temperature is the determining factor for quercetin glucoside biosynthesis in onions.

Fertilizer Level, Lifting Time, and Cultivar. It has previously been shown that nitrogen levels and temperature can influence flavor intensity and onion quality (*36*, *37*). In the present study, no flavor studies were performed. A decrease in soil nitrogen concentration may be associated with an increase in total quercetin concentration (*9*), and a limited nitrogen supply has been associated with higher levels of phenolics in plant (*8*). However, in the present study, high or low levels of nitrogen fertilizers during growth did not result in differences in quercetin content after field curing in any of the years (**Table 3**). Furthermore, there were no significant differences in percentage of nonmarketable onions, onion size, or yield between the high and low nitrogen levels in any of the years. The nitrogen levels used in this study were normal or slightly low compared to conventional production, and therefore no conclusions can be drawn about extreme nitrogen levels. From the results we conclude that it may be possible to grow and field cure onions with commercial yields and equally high quercetin content with minimized nitrogen fertilization based on soil analysis. The risk of nitrogen leakage from the soil can thereby be reduced, which may have a positive impact on the environment.

Early lifting of onions (50% fallen leaves or less) postpones the onset of sprouting after long-term storage, but the yield is reduced (*28*). Early-lifted onions have been observed to exhibit lighter color (*38*), which could indicate a lower quercetin content. The levels of phenolics in plant tissues can be influenced by the maturity of the plant (*8*), but it has been proposed that growth stage is not important for determining quercetin concentration (*39*). In our field study, late lifting resulted in significantly higher contents of both quercetin diglucoside and quercitin monoglucoside after field curing in 2005, but not in the other years (**Table 3**). Our conclusion is that the time of lifting seems to be a minor determinant of quercetin content in field-cured onions.

It is generally stated that differences in flavonol content within a commodity need to be understood in terms of maturation and environmental effects before cultivar differences can be exploited (*7*). There are differences between resistant and susceptible cultivars in their polyphenol content, suggesting that these compounds play an important role in defense mechanisms (*40*). However, in our study no correlation was found between quercetin content and percentage of nonmarketable onions.

It has been found that onion cultivar differences in quercetin content can be high, up to 11-fold (*41*) The majority (≈90%) of the total flavonols have been shown to be confined to the epidermal tissue of each onion scale. This means that scale thickness or any other factor that alters the ratio of epidermal to storage tissue could indirectly affect gross flavonol concentration. Such factors may account for some inter- and intracultivar variability (*42*). In the present study, no visible differences in color or scale thickness were observed when the onion samples were being prepared for analysis. Quercetin monoglucoside and quercetin diglucoside have been reported to account for 93% of the total flavonoid content in the brown onion cv. Rijnsburger, with the diglucoside as the main component (*9*) and with only traces of free quercetin aglycone (*43*). We found that quercetin monoglucoside was the main onion flavonol component, in contrast to Price and Rhodes (*9*), who found higher contents of quercetin diglucoside. However, Lombard et al. (*31*) found that

Table 4. Content (mg kg^{-1} of fw) of Quercetin 3,4′-Diglucoside (Q_{DG}), Quercetin 4′-Monoglucoside (Q_{MG}), and Quercetin Aglycone (Q) in Onions with a Diameter of 55–70 mm before and after Drying and Curing in Different Curing Treatments, 2005[a]

treatment	Q_{DG}	Q_{MG}	Q	total
before treatment	31 ± 7 a	63 ± 19 ab	tr[b]	95 ± 26 a
plastic bag in climate chamber	27 ± 4 a	54 ± 11 ab	tr	81 ± 14 a
climate chamber	43 ± 8 b	81 ± 17 bc	tr	124 ± 25 b
stonewall shed	40 ± 7 b	84 ± 17 bc	tr	123 ± 23 b
transparent plastic covering	45 ± 8 bc	78 ± 16 bc	tr	123 ± 23 b
dark plastic covering	47 ± 6 bc	88 ± 15 c	tr	135 ± 20 b
field curing	53 ± 7 c	117 ± 18 d	tr	170 ± 25 c

[a] Values are mean ± standard deviation ($n = 12$). Values with the same letter in each column are not significantly different at $p < 0.05$. [b] Trace (<10 mg kg^{-1} of fw).

the monoglucoside content in all cultivars analyzed was ≥20% higher than the quercetin diglucoside content. The mean content for golden onion cultivars in northern Italy was found to be 572 mg kg^{-1} of fw quercetin monoglucoside compared to 49 mg kg^{-1} of fw quercetin diglucoside (*2*). The different relative proportions of these quercetin glucoside forms stated in different reports and countries could be an effect of different cultivars, as well as result of differences in analysis technique. It has been found that maceration can lead to the loss of quercetin diglucoside and the appearance of quercetin monoglucoside and free quercetin aglycone (*9*). However, there are also reports that both quercetin diglucoside and quercetin monoglucoside in onions are virtually unaffected by chopping (*44*). Quercetin has been found to be formed by deglucosidation of quercetin glucosides on the border between drying and dried brown onion scale areas (*23*). In our study, all partly dried scales were removed to mimic domestic peeling, thereby reducing the risk for differences in deglucosidation.

In our study, differences in flavonol content between cultivars after field curing were significant in all years (**Table 3**). In 2002 and 2004, cv. Barito had higher flavonol levels than cv. Summit, but in 2005 no statistical difference could be found. In 2004, cv. Barito had significantly lower levels of flavonols than cv. Hyskin, but in 2005 the same tendency was not significant. In 2002 and 2005, the levels of quercetin diglucoside were the same in all cultivars, but in 2004 all cultivars showed statistically different levels. Our conclusion is that there were some differences in quercetin levels after field curing between the cultivars in our study, but the differences were not consistent throughout the years, suggesting that the cultivars react differently to annual variations in climatic factors.

Extended Curing Experiment, 2005. There were no significant interactions between the factors cultivar and curing treatment. The increase in total flavonol content during normal field curing was 79% (**Table 4**). Onions cured in plastic bags showed no increase in flavonol content at all, and all other treatments resulted in an ≈33% increase in both quercetin diglucoside and quercetin monoglucoside (**Table 4**). These results suggest that humidity and temperature during curing have small effects compared to light. In the absence of light, there was still an increase in quercetin glucosides during curing, but field curing in full sunlight resulted in the highest increase. The 20% UV light transmittance reduction could not fully explain the surprisingly low content of quercetin in the transparent plastic covering treatment. The high temperatures (**Table 1**) may have reduced quercetin synthesis in the transparent plastic treatment.

Price et al. (*43*) found that following the curing and drying process at 28 °C for 10 days, a significant 54% reduction in quercetin monoglucoside content occurred. No new peaks appeared in the chromatograms, so the likely explanation was that a thicker outer dry skin was removed after curing to make the sample representative of an edible part of the onion (*43*). In our study, we did not find this kind of reduction in quercetin glucoside content following field curing (**Table 4**).

Extended Curing Experiment, 2003. In 2003, onions with the leaves still erect and onions with fallen, but still green, leaves in the same row were lifted on the same date, when the leaves had just started to fall down, and then left for field curing for 10 days. After field curing, the onions with erect leaves had small but significantly higher levels of quercetin glucosides in the outer and middle scales (**Table 5**), but when the whole onions were analyzed, no statistical difference could be found between onions that had erect or fallen leaves at lifting.

There is a gradient in quercetin content from the outer to the inner scales of onion bulbs (*45*). The content of quercetin glucosides also varies within each scale from base to top, with highest content in the top (*25*). Both of these observations were explained by older cells in the outer scales and the upper part of each scale. During aging, the molar ratio of quercetin diglucoside/monoglucoside decreases, which means that the onion scales develop a higher monoglucoside content with age (*25*). In our study, no significant difference in quercetin glucoside ratio was found in any onion part or between onions that had erect or fallen leaves at lifting in 2003 (**Table 5**).

As a general rule, onion foliage should be allowed to desiccate as much as possible after lifting and before topping (*46*). The greatest number of rotted bulbs in storage has been shown to

Table 5. Content (mg kg^{-1} of fw) of Quercetin 3,4′-Diglucoside (Q_{DG}), Quercetin 4′-Monoglucoside (Q_{MG}), and Quercetin Aglycone (Q) after Curing in Different Parts of Cv. Barito Onions with a Diameter of 55–70 mm in the Same Row with Fallen or Erect Leaves, Lifted at the Stage When the Leaves Had Just Started To Fall Down, 2003[a]

						increase during curing (%)		
onion part	leaf status	Q_{DG}	Q_{MG}	Q	total	Q_{DG}	Q_{MG}	total
outer scales	erect	365 ± 37 a	1030 ± 83 a	22 ± 3 a	1417 ± 103 a	152	237	214
	fallen	295 ± 39 b	865 ± 91 b	21 ± 7 a	1181 ± 130 b	31	67	59
middle scales	erect	77 ± 10 a	244 ± 32 a	tr[b]	321 ± 40 a	492	804	703
	fallen	71 ± 3 a	196 ± 10 b	tr	266 ± 12 b	97	145	129
inner scales	erect	25 ± 4 a	77 ± 10 a	tr	102 ± 14 a	1150	1825	1600
	fallen	27 ± 4 a	63 ± 14 a	tr	91 ± 19 a	440	600	550
whole onion	erect	117 ± 7 a	341 ± 36 a	tr	466 ± 57 a	139	199	186
	fallen	126 ± 24 a	332 ± 19 a	tr	449 ± 26 a	40	74	60

[a] Values are mean ± standard deviation ($n = 8$). Values with the same letter in each column and pair are not significantly different at $p < 0.05$. [b] Trace (<10 mg kg^{-1} of fw).

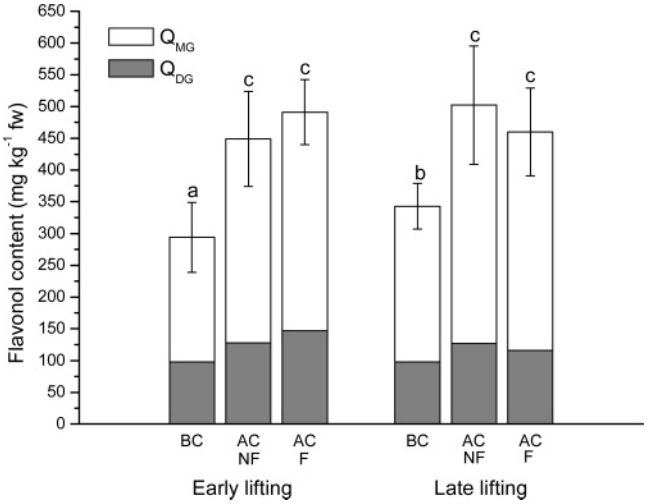

Figure 2. Effects of field curing in 2003, with or without foliage attached, on onion flavonol content: $n = 12$; Q_{MG} = quercetin 4′-monoglucoside; Q_{DG} = quercetin 3,4′-diglucoside; BC = before curing; AC = after curing; NF = no foliage attached during curing; F = foliage still attached during curing. Bars with the same letter are not significantly different at $p < 0.05$.

occur when onions are topped before field curing, probably as a result of rainfall within 12 h after topping (*38*). In our study, the early-lifted onions had significantly lower contents of quercetin monoglucoside at lifting (**Figure 2**) compared to late-lifted onions. After field curing, no difference was found in quercetin content between early- and late-lifted onions. Whether or not the foliage was still attached to the onions during the field-curing period had no significant effect on the content of quercetin glucosides, which is in line with the findings of a New Zealand study that timing of foliage removal had no effect on mean skin color score (*38*). This result suggests that the quercetin synthesis is situated within the onion scales and that no transportation from the foliage to the onion scales occurs.

Dry Matter Differences. Onions of cv. Barito had significantly lower dry weight after field curing than the other cultivars in all years, but the levels were somewhat different in the different years. In 2002, cv. Barito had a lower dry weight (12.1%) compared to cv. Summit (12.9%). In 2004, cv. Barito had a lower dry weight (11.6%) than both cv. Hyskin (12.7%) and cv. Summit (12.9%). In 2005, cv. Barito had a lower dry weight (11.9%) than cv. Hyskin (12.2%), which in turn had a lower dry weight than cv. Summit (12.9%). No other significant differences in dry weight were found between curing treatments, onions that were lifted early or late, or onions that received high or low nitrogen levels in any of the years.

Moisture loss in early-lifted sweet onions (with the foliage still erect) can be up to 10% during curing (*47*). In our study, the dry weight after field curing compared to the dry weight at lifting was only between 0 and 0.9% higher. These findings agree with those of Grevsen and Sorensen (*28*), who found that onions lifted at the stage when 50% had fallen leaves had approximately the same dry matter content as onions lifted at 80% fallen leaves. The annual variation they found in dry weight was between 11.6 and 12.3% for cv. Hyton in 1997−1998 (*28*), which is similar to our results.

In conclusion, the amount of global radiation in August seemed to be the major determinant of quercetin glucoside content in field-cured yellow onions. No transport of quercetin glucosides from the green leaves to the onion scales was detected during field curing. In most experimental years, a significant increase in level of quercetin glucosides was found in field-cured onions compared to the content at lifting, and the levels were higher in all onion scales. The increase was highest when the onions were cured in the field in full sunlight, but there was also a significant increase in completely dark environments, irrespective of temperature and relative humidity. Cultivar differences in quercetin glucoside levels varied and were not consistent between years. Nitrogen fertilizer level and lifting time were of minor importance for final quercetin glucoside content in onions after field curing.

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