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Total Phenolic Concentration and Browning Susceptibility in a Collection of Different Varietal Types and Hybrids of Eggplant: Implications for Breeding for Higher Nutritional Quality and Reduced Browning

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Abstract. **Phenolic compounds have numerous beneficial effects on human health. In consequence, the development of new varieties with higher content of phenolics is of interest for the improvement of the nutritional quality of eggplant (*Solanum melongena* L.). However, the oxidation of eggplant phenolics causes browning of the cut surfaces of the fruit and reduces its apparent quality. The authors investigated the relationship among, as well as the variation and heritability of, the content of phenolics, ascorbic acid, and soluble solids; pH; and the degree of browning and color difference of the cut surface of the fruit flesh in a collection of 69 eggplant varieties. These included landraces from different origins, commercial varieties, experimental hybrids, and four accessions of the related *S. aethiopicum* L. and *S. macrocarpon* L. species. Analyses of variance revealed significant differences among the materials studied for all traits considered. The concentration of phenolics in *S. melongena* spanned a threefold range, although the highest (1122 mg·kg^{-1}) and lowest (134 mg·kg^{-1}) concentrations of phenolics were found in *S. macrocarpon* and *S. aethiopicum* respectively. Concentrations of ascorbic acid were very low, a mean 27 times lower than those of phenolics, and soluble solids content ranged from 3.60% to 6.60% with a pH that ranged from 5.01 to 5.93. Commercial varieties had, as a mean, a 20% lower concentration of phenolics than landraces, as well as a lower degree of browning and color difference. Positive correlations existed between phenolic concentration and degree of browning (r = 0.388) and color difference (0.477), although only 15.1% and 22.8% of the total variation in degree of browning and color difference, respectively, could be attributed to variation in phenolics. Ascorbic acid, soluble solids content, and pH were not correlated to either degree of browning or color difference. The heritability was moderate for phenolic concentration (0.50) and high for degree of browning (0.71) and color difference (0.82). The information obtained indicates that there are opportunities for the development of new varieties with a high concentration of phenolics and low or moderate browning.**

Eggplant has a high antioxidant capacity (Cao et al., 1996), and this is attributed to its high content in phenolic compounds. The main class of phenolics in eggplant includes hydroxycinnamic acid conjugates (Whitaker and Stommel, 2003) and, of these, chlorogenic acid (5-O-caffeoylquinic acid and its isomers) typically accounts for 70% to 95% of total phenolics in eggplant fruit flesh (Stommel and Whitaker, 2003). The beneficial effects on health of chlorogenic acid and related compounds present in minor quantities in eggplant are numerous, and apart from their potent antioxidant activity, they also include free radical scavenging and antitumoral activities (Sawa et al., 1998; Triantis et al., 2005).

The selection of eggplant accessions with an increased concentration of phenolics as a way to develop new varieties with improved nutritional quality was suggested by Stommel and Whitaker (2003). These authors studied the concentration of hydroxycinnamic acid conjugates in the fruit flesh in a core collection of eggplant and found considerable variation, with a difference of almost fourfold among the varieties with highest and lowest concentrations. This indicates that there are ample possibilities for developing new commercial varieties with an increased concentration of phenolic compounds.

However, a drawback of increasing the concentration of these antioxidants in eggplant is that the oxidation of phenolics causes the browning of the fruit flesh after its exposure to the air, and this may lead to a reduction in the apparent quality (Macheix et al., 1990). When a fruit is cut, either for home consumption or for industrial processing, the destruction of fruit cellular compartmentation allows the orthodiphenolic substrates (hydroxycinnamic acid derivatives) to be accessible to polyphenol oxidases, which catalyze their oxidation to quinones, which react nonenzymatically with O_2, sulfhydryl compounds, amines, amino acids, and proteins to give brown-colored compounds (Ramírez et al., 2002). The activity of polyphenol oxidases varies among eggplant varieties (Dogan et al., 2002), which suggests that selection for a combined high concentration of phenolics and low browning should be

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feasible. Other factors, like intracellular pH, which affects the activity of the polyphenol oxidase (PPO) enzymes (Concellón et al., 2004; Dogan et al., 2002), or the presence of ascorbic acid in the fruit flesh tissues, which prevents the oxidation of orthodiphenols (Macheix et al., 1990), might also have a role in the modification of the browning process in eggplant. Given the preference of consumers and the industry for varieties with white flesh and a low degree of browning (Prohens et al., 2005), new varieties with a high content of phenolics should also have a moderate flesh browning.

Apart from the variation existing in the eggplant types traditionally grown in Europe, America, western Asia, and Africa, there are other varieties corresponding to eastern Asian materials that have different plant and fruit characteristics (Daunay et al., 1997; Hallard, 1996; Lester and Hasan, 1991) and that could be sources of variation for a high content of phenolics, low browning, or both. Also, the gboma eggplant (*Solanum macrocarpon*) and scarlet eggplant (*S. aethiopicum*), which are cultivated species related to *S. melongena* (Sakata and Lester, 1997), mainly grown in Africa, but also in other parts of the world, like the case of scarlet eggplant in southern Italy (Polignano et al., 2004), could be useful for the genetic improvement of eggplant. Both species hybridize with the common eggplant (Ano et al., 1991; Bletsos et al., 2004), and might represent genetic resources of interest for the improvement of the quality of the common eggplant and for other traits like resistance to diseases (Gisbert et al., 2006). All these materials contain important genetic diversity for concentrations of hydroxycinnamic acid conjugates (Stommel and Whitaker, 2003).

During this investigation we determined the variation in phenolic concentration and fruit flesh browning in a collection of eggplant from different varietal types, the relationship between both traits, and the effects of other physicochemical traits on browning of eggplant. The use of a set of hybrids and their respective parents also allowed us to obtain information on the heritability of phenolic concentration and browning-related traits in eggplant. This is of interest for breeding new eggplant varieties that combine an improved nutritive value with a low degree of browning.

Material and Methods

Plant material. Materials used consisted of 69 varieties of *S. melongena*, two of *S. aethiopicum*, and two of *S. macrocarpon* (Table 1). Among the *S. melongena* varieties there were materials corresponding to different varietal types: landraces of Spanish (n = 18), African (n = 8), and Caribbean (n = 1) origins; European commercial hybrids (n = 6); commercial nonhybrid varieties (n = 6); materials of southeast Asian origin (n = 6); and experimental hybrids obtained between parents included in the study (n = 24). These materials were chosen to represent the genetic diversity of eggplant. Experimental hybrids were included to obtain information on the heritability of the traits studied, which is of great relevance for the eggplant breeding programs. *Solanum aethiopicum* and *S. macrocarpon* are cultivated species mainly grown in Africa and are related to the common eggplant (Daunay and Lester, 1988).

Seeds of all materials were put to germinate in Petri dishes in May 2004. Germinated seeds were subsequently transferred to seedling trays and, at the beginning of July 2004, five plants per variety were transplanted in a completely randomized design to a field plot (sandy loamy soil) in the campus of the Universidad

Table 1. Varieties of common eggplant (*Solanum melongena*), scarlet eggplant (*S. aethiopicum*), and gboma eggplant (*S. macrocarpon*) used in a study of total phenolic concentration and browning susceptibility.

Variety	Origin	Fruit type[z]
	Spanish landraces	
ALM1	Castilla-La Mancha, Spain	Semilong
ANS3	Andalucía, Spain	Semilong
ANS6	Andalucía, Spain	Round
ANS24	Andalucía, Spain	Semilong
ANS26	Andalucía, Spain	Semilong
ART1	Castilla-La Mancha, Spain	Semilong
CS16	Cataluña, Spain	Long
IVIA25	Comunidad Valenciana, Spain	Striped
IVIA371	Comunidad Valenciana, Spain	Striped
IVIA400	Comunidad Valenciana, Spain	Striped
IVIA604	Comunidad Valenciana, Spain	Striped
MUR1	Murcia, Spain	Round
MUS3	Murcia, Spain	Striped
MUS8	Murcia, Spain	Round
VS3	Comunidad Valenciana, Spain	Semilong
VS9	Comunidad Valenciana, Spain	Round
VS10	Comunidad Valenciana, Spain	Semilong
VS22	Comunidad Valenciana, Spain	Striped
	African landraces	
Balady	Egypt	Semilong
BBS118	Ivory Coast	Semilong
BBS175	Ivory Coast	Semilong
BBS186	Ivory Coast	Semilong
BBS189	Ivory Coast	Semilong
BBS190	Ivory Coast	Semilong
BBS191	Ivory Coast	Semilong
Rami	Egypt	Semilong
	Caribbean landraces	
SUDS5	Havana, Cuba	Semilong
	Commercial hybrids (European)	
10-201 F_1	Rijk Zwaan B.V., De Lier, The Netherlands	Semilong
10-501 F_1	Rijk Zwaan B.V.	Semilong
Calanda F_1	Ramiro Arnedo S.A., Calahorra, Spain	Semilong
Ecavi F_1	Rijk Zwaan B.V.	Semilong
Mulata F_1	Ramiro Arnedo S.A.	Semilong
Petra F_1	Semillas Fitó S.A., Barcelona, Spain	Semilong
	Commercial nonhybrid varieties and breeding lines (European)	
Black Beauty	Vilmorin, La Ménitré, France	Semilong
Dourga	Institut National de la Recherche Agronomique, Paris (INRA)	Long
De Barbentane	Vilmorin	Long
Larga Negra	Ramiro Arnedo S.A.	Long

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Table 1. Continued.

Variety	Origin	Fruit type[z]
LF3-24	INRA	Long
Listada de Gandía	Semillas Clemente, Vitoria, Spain	Striped
	Asian materials	
ASIS1	Beijing, China	Round
Kermit	Thailand	Round
Kurome	Japan	Long
Long White Angel	China	Long
Thai Long Green	Thailand	Long
Thai Round Green	Thailand	Round
	Experimental hybrids	
H1	IVIA25 × IVIA371	Striped
H2	IVIA371 × IVIA25	Striped
H5	ANS6 × ASIS1	Round
H6	ANS24 × ASIS1	Semilong
H7	ANS26 × ANS3	Semilong
H8	ANS26 × VS22	Long
H9	ASIS1 × ANS24	Semilong
H10	ASIS1 × SUDS5	Round
H11	ASIS1 × VS9	Round
H12	CS16 × ASIS1	Semilong
H13	IVIA25 × ANS24	Semilong
H14	IVIA371 × MUS8	Semilong
H15	IVIA604 × VS22	Semilong
H16	MUS3 × ANS3	Semilong
H17	MUS8 × ANS6	Semilong
H18	MUS8 × IVIA371	Semilong
H19	MUS8 × IVIA400	Semilong
H20	MUS8 × SUDS5	Semilong
H21	MUS8 × VS9	Round
H22	MUS8 × VS10	Semilong
H24	VS9 × IVIA25	Semilong
H26	VS9 × MUS8	Semilong
H27	VS9 × SUDS5	Semilong
H28	VS9 × VS22	Semilong
	Solanum aethiopicum	
BBS157	Ivory Coast	Round
BBS159	Ivory Coast	Round
	S. macrocarpon	
BBS171	Ivory Coast	Round
BBS196	Ivory Coast	Round

[z]The round, semilong, and long types considered here are distinguished by the length-to-breadth ratio of the fruit (≈1 for the round, >1.2 and < 2 for the semilong, and >2 for the long) and are characterized for presenting either uniform fruit color or a secondary color distributed in broad stripes. The striped (known as ''listada'' in Spain) type is typical of the Spanish Mediterranean region, and is characterized by an obovate to oblong shape and white or yellowish background color covered by narrow purple stripes.

Politécnica de Valencia, Valencia, Spain (GPS coordinates of the field plot: lat. 39°28′55″N, long. 0°20′11″W). A completely randomized design was used instead of a block design because the plot is quite uniform and previous experiments using block designs showed no block effect. Plants were spaced 1 m between rows and 0.4 m apart within the row and drip irrigated. The standard horticultural practices for eggplant in the Mediterranean coast of Spain (Baixauli, 2001) were followed. The fertilization, which consisted of 80 g/plant of a commercial fertilizer of 10N–2.2P–24.9K plus micronutrients (Hakaphos Naranja; Compo Agricultura, Barcelona, Spain), was applied with the drip irrigation system. Fruit harvesting began 6 weeks after transplant.

Experimental design and preparation of samples. Each plant was considered as a replication (i.e., five replications per variety), from which a single value was obtained for statistical analysis. For the chemical composition traits, a single measurement was made per replication, whereas for fruit flesh browning, several fruit per plant were measured (subsamples) and used for obtaining a mean value for each replication. Between two and seven fruit (depending on the fruit size) per plant were collected at commercial maturity (evaluated by the color and glossiness of the fruit skin and confirmed by the lack of seeds in the last stages of development) and brought to the laboratory, where they were washed and cut transversally for the measurement of the color of the flesh and its degree of browning after 10 min. After that, fruit were peeled and a longitudinal section, consisting of a triangular slice with the base (between 1 and 3 cm depending on the size of the fruit) being close to the peel and the tip being the center of the fruit, from peduncle to blossom scar was taken for each fruit. The fruit sections of each individual plant were bulked and squeezed in a domestic juice extractor. Immediately after juice extraction, 5 mL of the homogenate corresponding to each plant were poured on 10 mL of an extracting solution of acetone (70% v/v) and glacial acetic acid (0.5% v/v) and left for 24 h at room temperature for extraction of phenolics. Another aliquot of 5 mL of juice homogenate was also quickly poured on 10 mL of a solution of metaphosphoric acid (3% w/v) and acetic acid (8% v/v) for the immediate ascorbic acid concentration determination. The rest of the juice was used for the determination of soluble solids content (SSC) and for the measurement of pH.

Measurements. Fruit flesh color was measured with a Minolta chroma-meter (CR-300; Minolta Co. Ltd., Osaka, Japan), fitted with an 8-mm-diameter aperture and expressed in the ''CIELAB 1976 color coordinates.'' Fruit were cut transversally at the midpoint between the blossom and stem ends, and measurements were made in the central part immediately after being cut (0 min) and 10 min later. A well-sharpened knife with a straight edge was used to produce clean cuts. The whiteness of the fruit flesh was measured as the Euclidean distance of the color coordinates to the pure white color coordinates (L* = 100, a* = 0, b* = 0) using the formula

$$DW = [(100 - L^*)^2 + a^{*2} + b^{*2})]^{0.5}$$

where DW is the distance to the pure white color. The difference between DW at 10 min (DW_{10}) and at 0 min after the fruit was cut (DW_0; i.e., the increase in the distance to pure white) was used as a measure of degree of browning suffered by the fruit (degree of browning = $DW_{10} - DW_0$). The color difference was measured as the Euclidean distance between the color coordinates at 0 and 10 min after the cut:

$$CD = [(L^*_{10} - L^*_0)^2 + (a^*_{10} - a^*_0)^2 + (b^*_{10} - b^*_0)^2]^{0.5}$$

Both measures give different and complementary information related to the evolution of color.

Phenolic content was determined according to the Folin-Ciocalteu procedure (Singleton and Rossi, 1965). An aliquot of 1.25 mL of the extracted phenolic sample was centrifuged at

8050 g_n for 5 min and 65 µL of the supernatant were mixed with 0.5 mL diluted (10% v/v) Folin-Ciocalteu reagent (Sigma-Aldrich Chemie, Steinheim, Germany) and allowed to stand at room temperature for 5 min; 0.50 mL of a sodium carbonate solution (60 g·L^{-1}) was added to the mixture. After 90 min at room temperature, absorbance was measured at 725 and also at 760 nm in a UV-VIS spectrophotometer (Lambda 25; Perkin-Elmer, Madrid, Spain). Chlorogenic acid (Sigma-Aldrich Chemie) was used as a standard. The phenolic acid content was expressed as chlorogenic acid equivalents in milligrams per kilogram fresh fruit.

Ascorbic acid concentration (milligrams per kilogram) was determined by titrating the diluted (15% v/v) extracted juice with 2,6-dichlorophenolindolephenol dye. Soluble solids content was measured in the supernatant of a centrifuged (8050 g_n for 5 min) sample of juice with a hand-held refractometer (N-8 α; Atago Co. Ltd., Tokyo, Japan). The pH of the juice was measured with a digital pH meter (MP 220; Mettler Toledo, Barcelona, Spain).

Statistical analyses. Data were subjected to factorial analysis of variance (ANOVA) using a fixed-effects model for the effect of variety. The average (pooled) SE for each trait was obtained from the corresponding ANOVA. Linear correlation coefficients (r) between traits were calculated from regression analyses between pairs of traits. The coefficients of determination (r^2), which measure the variability explained by the linear regression, were also computed and expressed in percentage. *Solanum aethiopicum* and *S. macrocarpon* were excluded from the regression analyses to avoid the appearance of spurious correlations resulting from the mixture of heterogeneous materials (Aldrich, 1995). Additional regression analyses were used to obtain the regression coefficient (b) of the means of experimental hybrids over midparent values for each trait. In our case, the value of b represents an estimate of the narrow-sense heritability (h^2), which is an important parameter in the efficiency of selection in crossing programs (Wricke and Weber, 1986). All statistics were conducted using specific software (Statgraphics Plus 5.1, Statistical Graphics Corp., Rockville, MD).

Results

Phenolics. The correlation coefficient between the concentration of phenolics determined at 725 or 760 nm was very high ($r = 0.985$; $P < 0.001$). Therefore, the phenolic concentration of each sample was calculated as the mean between the estimates at 725 and 760 nm.

Large differences in phenolic concentration were found among the materials studied, with a range from 134 mg·kg^{-1} in *S. aethiopicum* BBS157 to 1122 mg·kg^{-1} in *S. macrocarpon* BBS196 (i.e., a difference of more than eightfold; Table 2). When considering only the *S. melongena* materials, the range goes from 280 mg·kg^{-1} ('Listada de Gandía') to 834 mg·kg^{-1} (ALM1), which represents a difference of almost threefold. The range of variation within each varietal type is also high, and within each varietal type of *S. melongena* (except for the Caribbean type, which consists of a single variety) there are varieties with relatively high and low phenolic concentrations. However, it is noteworthy that the *S. melongena* varieties with a greater concentration of phenolics are included within the groups of Spanish and African landraces as well as among experimental hybrids and Asian materials, but not in the

Table 2. Mean values and average (pooled) SE (see last line of the table) for the concentrations of phenolics, ascorbic acid, soluble solids content (SSC), and pH of the eggplant varieties studied, grouped by varietal type.

Variety	Phenolics (mg·kg^{-1})	Ascorbic acid (mg·kg^{-1})	SSC (%)	pH
Spanish landraces				
ALM1	834	17.3	5.20	5.08
ANS3	765	21.7	6.49	5.31
ANS6	409	17.8	5.20	5.42
ANS24	752	19.1	5.74	5.55
ANS26	524	18.1	4.64	5.40
ART1	394	17.6	4.06	5.37
CS16	332	18.8	4.82	5.42
IVIA25	426	19.2	4.10	5.54
IVIA371	556	16.2	6.07	5.23
IVIA400	438	15.5	4.50	5.53
IVIA604	509	17.0	5.80	5.35
MUR1	483	15.2	4.52	5.07
MUS3	314	17.5	4.64	5.65
MUS8	344	20.2	5.00	5.24
VS3	656	15.1	4.58	5.22
VS9	521	21.2	5.38	5.34
VS10	404	18.6	3.68	5.29
VS22	401	15.5	6.40	5.13
African landraces				
Balady	524	17.6	4.72	5.20
BBS118	461	15.7	4.28	5.18
BBS175	718	13.8	5.00	5.40
BBS186	526	10.5	3.72	5.20
BBS189	480	10.3	5.28	5.29
BBS190	630	12.8	5.00	5.31
BBS191	561	11.5	4.30	5.01
Rami	429	11.8	5.22	5.25
Caribbean landraces				
SUDS5	335	20.1	5.23	5.23
Commercial hybrids (European)				
10-201	356	16.4	4.18	5.45
10-501	507	17.6	4.00	5.45
Calanda	420	17.4	5.02	5.21
Ecavi	517	17.2	4.06	5.27
Mulata	417	18.7	4.42	5.39
Petra	391	17.4	4.50	5.43
Commercial nonhybrid varieties (European)				
Black Beauty	409	17.8	5.50	5.12
Dourga	356	11.0	4.60	5.19
De Barbentane	464	18.5	4.60	5.45
Larga Negra	459	21.0	5.38	5.37
LF3-24	292	10.0	4.38	5.36
Listada de Gandía	280	11.6	3.60	5.45
Asian materials				
ASIS1	424	19.8	5.32	5.46
Kermit	556	16.1	5.20	5.58
Kurome	321	14.2	5.32	5.24
Long White Angel	318	13.1	4.10	5.18
Thai Long Green	442	21.7	5.50	5.35
Thai Round Green	716	14.4	5.38	5.51

continued next page

Table 2. Continued.

Variety	Phenolics (mg·kg^{-1})	Ascorbic acid (mg·kg^{-1})	SSC (%)	pH
Experimental hybrids				
H1	428	18.7	4.87	5.09
H2	522	20.0	6.44	5.27
H5	460	15.5	4.82	5.38
H6	401	13.2	5.20	5.45
H7	474	20.0	5.60	5.45
H8	422	19.6	6.00	5.48
H9	387	13.6	6.12	5.31
H10	391	19.2	5.54	5.32
H11	472	19.9	6.36	5.43
H12	373	17.5	5.20	5.40
H13	524	17.1	6.60	5.31
H14	448	16.2	4.86	5.38
H15	406	16.6	4.96	5.21
H16	742	17.4	4.98	5.52
H17	409	21.3	4.92	5.24
H18	336	17.0	4.66	5.08
H19	337	17.8	4.76	5.19
H20	333	17.2	4.82	5.24
H21	434	21.3	4.80	5.36
H22	389	18.4	4.26	5.35
H24	542	19.8	5.34	5.25
H26	477	20.2	4.40	5.41
H27	339	18.8	4.90	5.36
H28	520	21.0	5.38	5.54
Solanum aethiopicum				
BBS157	134	16.5	5.80	5.70
BBS159	191	22.6	5.50	5.93
S. macrocarpon				
BBS171	544	17.7	4.60	5.54
BBS196	1122	19.6	5.86	5.42
Average SE	35	0.6	0.34	0.05

The average SE has been obtained from the mean square error from the analysis of variance for one factor (variety).
SSC, soluble solids content.

European commercial varieties (Table 2). The greatest values among the European commercial hybrids and commercial nonhybrids were 507 and 464 mg·kg^{-1} respectively. When we consider the landraces on one side and the European commercial materials on the other, the landraces have a significantly greater ($t = 2.394$; $P = 0.022$) mean for the phenolic concentration (509 mg·kg^{-1}) than commercial materials (406 mg·kg^{-1}).

Ascorbic acid, soluble solids content, and pH. Ascorbic acid concentrations are much lower than those of phenolics and range between 10.0 mg·kg^{-1} for *S. melongena* 'LF3-24' and 22.6 mg·kg^{-1} for *S. aethiopicum* BBS159 (Table 2). A wide range of variation exists within each *S. melongena* varietal type. However, it is noteworthy that most of the African landraces have relatively low ascorbic acid concentrations in comparison with the rest of the eggplant varieties (Table 2). Similar to what occurs for the phenolic and ascorbic acid concentrations, an important variation has been found for SSC in the materials studied, as well as within each varietal type (Table 2). However, in this case, both the maximum and minimum values are encountered in *S. melongena* (3.60% in 'Listada de Gandía' and 6.60% in H13). The pH of the materials studied ranges between 5.01 for *S. melongena* BBS191 and 5.93 for *S. aethiopicum* BBS159 (Table 2). The two accessions of the latter species showed the highest pH values of the whole experiment. When considering *S. melongena* alone, the maximum value for pH is 5.65 (MUS3). Although there is also variation within varietal types for this trait, there are many varieties among African landraces with relatively low pH values (Table 2).

Fruit flesh color and browning. The values of DW_0 for the fruit flesh were between 16.66 and 34.66 for *S. melongena* varieties BBS189 and 'De Barbentane,' respectively; whereas for DW_{10}, they ranged from 20.43 for *S. melongena* 'Listada de Gandía' to 38.90 for *S. macrocarpon* BBS196 (Table 3). As for the other physicochemical traits, an important diversity is found within each varietal group for DW_0 and DW_{10} (Table 3). However, it is noteworthy that the varieties with the lowest DW_0 are included in the group of the African landraces.

Values for degree of browning among *S. melongena* materials range from 1.08 for Kurome to 7.92 for H16. As for the other traits, there is considerable variation within varietal types for browning. However, the European commercial types have, as a mean, a significantly ($t = -2.760$; $P = 0.009$) lower degree of browning values (2.64) than the landraces (4.26). Regarding color difference, the range of values goes from 1.42 for *S. aethiopicum* BBS157 to 13.03 for *S. macrocarpon* BBS196. Similar to what occurred for degree of browning, European commercial types exhibit a significantly ($t = -2.217$; $P = 0.033$) smaller change in color difference (3.81) than landraces (5.38).

Correlations between traits. Correlations between traits for *S. melongena* materials show that there are significant positive correlations of the phenolics with degree of browning and color difference (Table 4). Nonetheless, the percentage of the total variation in degree of browning and color difference explained by the variation in total phenolics (parameter r^2) is only 15.1% and 22.8% respectively, indicating that other factors contribute to a substantial portion of the variation in these traits. Consequently, it is possible to find varieties with a high concentration of phenolics and relatively low or intermediate degree of browning or color difference (Fig. 1). For example, ANS24 and Thai Round Green have a high content of phenolics (Table 2) and moderate degree of browning and color difference (Table 3). A positive weak correlation was also found between phenolics and SSC (Table 4). It is noteworthy that phenolic concentration was not correlated with DW_0, which indicates that the color of the fruit flesh immediately after being cut does not depend on the phenolic content, and is related to other factors, like the presence of chlorophylls (Daunay et al., 2004). However, there is a weak, but significant, positive correlation between the concentration of phenolics and DW_{10}. Correlations of phenolics with the ascorbic acid content and pH were nonsignificant (Table 4).

Ascorbic acid concentration was positively correlated with SSC and also with DW_0 and DW_{10} (Table 4). However, ascorbic acid concentration is not correlated with degree of browning or color difference parameters. Similarly, pH is not correlated to any of these browning-related parameters (Table 4).

DW_0 is positively correlated with DW_{10} (65.1% of the variation in DW_{10} explained by the variation in DW_0), but there is no relationship of DW_0 and degree of browning or color difference (Table 4), indicating that the color evolution change is independent of the initial value of the fruit flesh color. In contrast, DW_{10} is positively correlated with degree of browning

Table 3. Mean values and average (pooled) SE (see last line of the table) for the Euclidean distance of the flesh color coordinates to pure white (DW) at 0 (DW_0) and 10 min (DW_{10}) after the fruit has been cut, DB (degree of browning), and CD (color difference) of the eggplant varieties studied, grouped by varietal type.

Variety	DW_0[z]	DW_{10}	DB	CD
Spanish landraces				
ALM1	26.89	31.54	4.65	6.37
ANS3	28.22	36.08	7.87	11.22
ANS6	23.46	26.81	3.35	4.04
ANS24	25.76	28.89	3.12	4.33
ANS26	22.87	24.48	1.61	2.62
ART1	25.20	30.12	4.92	6.23
CS16	28.66	30.88	2.22	3.79
IVIA25	28.74	32.42	3.68	4.49
IVIA371	21.94	27.54	5.60	6.33
IVIA400	20.62	21.95	1.32	1.61
IVIA604	21.50	25.44	3.93	4.25
MUR1	29.23	31.99	2.76	4.04
MUS3	24.03	31.86	7.83	8.74
MUS8	22.24	24.19	1.95	2.67
VS3	25.53	29.78	4.25	5.91
VS9	23.76	29.50	5.74	7.06
VS10	25.09	26.66	1.57	1.89
VS22	22.06	23.35	1.29	1.62
African landraces				
Balady	25.81	29.92	4.11	5.37
BBS118	17.95	23.95	6.00	6.58
BBS175	27.66	32.44	4.78	7.52
BBS186	16.66	24.76	7.27	7.90
BBS189	16.66	20.76	4.09	4.46
BBS190	17.93	22.25	4.31	5.84
BBS191	22.66	28.66	6.00	6.78
Rami	21.78	25.52	3.74	4.94
Caribbean landraces				
SUDS5	24.11	31.20	7.09	8.67
Commercial hybrids (European)				
10-201	27.67	29.49	1.82	2.85
10-501	24.63	26.71	2.08	2.87
Calanda	24.66	27.74	3.08	4.14
Ecavi	28.42	31.27	2.85	4.28
Mulata	26.58	29.68	3.11	4.24
Petra	26.49	28.95	2.46	3.69
Commercial nonhybrid varieties and breeding lines (European)				
Black Beauty	22.74	25.77	3.02	3.72
Dourga	22.91	27.29	4.38	4.92
De Barbentane	34.66	37.33	2.67	5.75
Larga Negra	29.64	31.79	2.15	4.34
LF3-24	25.19	27.85	2.66	3.31
Listada de Gandía	19.07	20.43	1.36	1.57
Asian materials				
ASIS1	23.41	25.21	1.79	2.76
Kermit	23.17	30.37	7.21	8.83
Kurome	33.82	34.90	1.08	3.78
Long White Angel	27.07	29.43	2.36	3.25
Thai Long Green	33.95	35.97	2.02	4.98
Thai Round Green	25.12	28.11	2.99	4.60
Experimental hybrids				
H1	19.21	23.02	3.82	4.08
H2	20.84	23.50	2.66	3.01
H5	22.50	23.71	1.21	2.01
H6	19.10	22.23	3.12	3.47
H7	26.60	31.89	5.29	7.26
H8	27.23	31.86	4.63	5.76
H9	21.43	23.22	1.79	2.30
H10	20.73	25.11	4.38	5.06
H11	24.29	27.65	3.37	4.87
H12	24.18	26.06	1.88	2.67
H13	29.81	37.42	7.60	8.99
H14	20.27	23.24	2.97	3.47
H15	21.25	22.91	1.66	2.08
H16	26.69	34.62	7.92	10.57
H17	22.41	25.28	2.87	3.64
H18	20.94	22.81	1.86	2.25
H19	20.40	22.54	2.14	2.50
H20	21.20	26.00	4.80	5.63
H21	23.98	27.03	3.05	4.13
H22	22.13	23.88	1.75	2.07
H24	20.80	24.44	3.64	4.06
H26	23.60	26.23	2.63	3.33
H27	23.32	27.89	4.57	5.40
H28	21.98	23.40	1.42	1.82
Solanum aethiopicum				
BBS157	26.78	27.42	0.65	1.42
BBS159	28.92	28.90	–0.02	5.65
S. macrocarpon				
BBS171	29.86	35.17	5.31	10.42
BBS196	31.38	38.90	7.53	13.03
Average SE	0.81	1.06	0.68	0.90

[z]$DW_0 = [(100 - L_0^*)^2 + a_0^{*2} + b_0^{*2})]^{0.5}$, $DW_0 = [(100 - L_0^*)^2 + a_0^{*2} + b_0^{*2})]^{0.5}$, $DB = DW_{10} - DW_0$, $CD = [(L^*_{10} - L^*_0)^2 + (a^*_{10} - a^*_0)^2 + (b^*_{10} - b^*_0)^2]^{0.5}$.

The average SE has been obtained from the mean square error from the analysis of variance for one factor (variety).

CD, color difference; DB, degree of browning; DW_0, Euclidean distance of the fruit flesh color to pure white at 0 min after the fruit was cut; DW_{10}, Euclidean distance of the fruit flesh color to pure white at 10 min after the fruit was cut.

continued next column

and color difference (Table 4). Degree of browning and color difference present a high significant correlation. In fact, 89.7% of the variation in one of these traits is explained by the variation in the other trait.

Heritability. The coefficient of linear regression of hybrids over the midparent value (narrow-sense heritability) for phenolics is moderate (0.50) and significant ($P < 0.05$), indicating that selection of parents with a high content of phenolics to obtain hybrids with a high content of these antioxidants will be efficient. However, the values of the heritability for ascorbic acid concentration, SSC, and pH are low (<0.30) and nonsignificantly different from zero.

There is a high heritability in DW_0 and DW_{10}, with values of 0.64 and 0.79 respectively (i.e., the selection of parents with a low DW_0 or DW_{10} will be efficient to obtain hybrids with low DW_0 and DW_{10} values). Also, the browning-related parameters of degree of browning and color difference have

Table 4. Coefficients of correlation between traits studied (above diagonal) and coefficients of determination (%; below the diagonal) for the *Solanum melongena* materials studied.

	Phenolics	Ascorbic acid	SSC	pH	DW_0	DW_{10}	DB	CD
Phenolics		0.057 NS	0.281*	0.051 NS	0.094 NS	0.259*	0.388***	0.477***
Ascorbic acid	0.3		0.292*	0.220 NS	0.307*	0.258*	–0.033 NS	0.046 NS
SSC	7.9	8.5		0.016 NS	–0.035 NS	0.120 NS	0.172 NS	0.217 NS
pH	0.3	4.8	<0.1		0.190 NS	0.155 NS	<0.001 NS	0.059 NS
DW_0	0.9	9.4	0.1	3.6		0.807***	–0.035 NS	0.148 NS
DW_{10}	6.7	6.7	1.4	2.4	65.1		0.415***	0.628***
DB	15.1	0.1	3.0	<0.1	0.1	17.2		0.947***
CD	22.8	0.2	4.7	0.3	2.2	39.4	89.7	

NS,*,**,***Nonsignificant at $P < 0.05$ and significant at $P < 0.05$, <0.01, and <0.001 respectively.
CD, color difference; DB, degree of browning; DW_0, Euclidean distance of the fruit flesh color to pure white at 0 min after the fruit was cut; DW_{10}, Euclidean distance of the fruit flesh color to pure white at 10 min after the fruit was cut; SSC = soluble solids content.

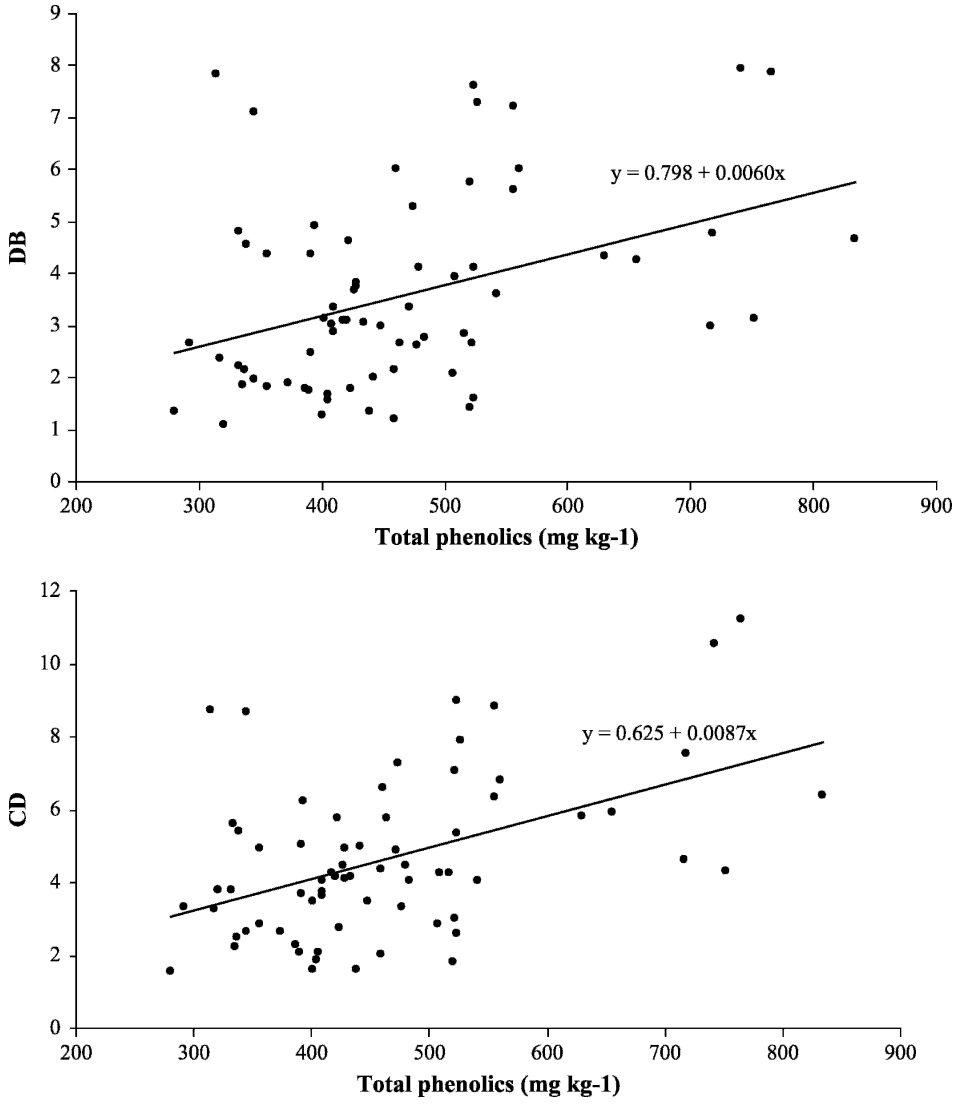

Fig. 1. Relationship among total phenolic content (measured in milligrams per kilogram) and the degree of browning [DB (above)] and color difference [CD (below)] of fruit flesh after exposure to the air for 10 min for the *Solanum melongena* materials studied.

high heritability values (0.71 and 0.82 respectively), indicating that parents that present a high degree of browning or color difference will give hybrids having high values for these traits.

Discussion

Our results confirm the findings of Stommel and Whitaker (2003) and Whitaker and Stommel (2003), demonstrating that there is a broad variation among *S. melongena* materials for phenolic concentration in the fruit flesh. This wide variation, together with the relatively high value of the heritability (0.50) determined in a set of hybrids, indicates that breeding programs aimed at developing new varieties with higher phenolic concentrations may be successful. Unpublished results by our group with six varieties suggest that the content of phenolics is relatively stable among years, which indicates that genetic variation accounts for an important part of the diversity for this trait. The fact that chlorogenic acid is by far the predominant phenolic compound, suggests that an important part of the genetic variation may be the result of a few genetic factors involved in the biochemical pathways leading to the accumulation of chlorogenic acid (Niggeweg et al., 2004).

The modern commercial varieties used in our study (commercial hybrids and commercial nonhybrids) have, as a mean, a lower concentration of phenolics than traditional varieties. The selection for a reduced degree of browning in commercial varieties has resulted probably in the indirect selection of materials with lower concentrations of phenolics (Prohens et al., 2005). If we compare the results obtained by Whitaker and Stommel (2003) for the concentration of hydroxycinnamic conjugates for seven commercial varieties of eggplant with those of Stommel and Whitaker (2003) for 97 eggplant germplasm accessions

grown in the same conditions, the germplasm materials have, as a mean, a concentration more than 50% greater than the commercial varieties, which agrees with our results.

Sources of variation for high phenolic concentration can be found among common eggplant materials. However, the highest concentration of phenolics has been found in one accession of the related gboma eggplant, which suggests that this species could contribute to the genetic improvement of the concentration of phenolics in cultivated eggplant. However, the fact that the hybrids between *S. melongena* and *S. macrocarpon* have a reduced fertility (Bletsos et al., 2004) restricts its use to a long-term breeding program. Stommel and Whitaker (2003) tested only one accession of *S. macrocarpon* and found low values for phenolic acid contents in this species. This apparent discrepancy is probably attributable to the small number of accessions of *S. macrocarpon* involved in the two studies, and indicates that a considerable diversity must also exist in this species. Apart from *S. macrocarpon*, other species might be useful for the improvement of the quantitative and qualitative content of phenolics in *S. melongena*. For example, there is variation among species and varieties in the types and amounts of different phenolic acid conjugates, and this might have a bearing on the nutritional value or health benefits. In this respect, Stommel and Whitaker (2003) found that accessions of *S. anguivi* Lam. and *S. incanum* L. had higher concentrations of total phenolics than common eggplant, but also had a high percentage of unusual caffeic acid conjugates.

Some phenolics have a bitter taste (Macheix et al., 1990). However, the bitterness and ''off'' flavor of some eggplant varieties seems to be incited by saponins and glycoalkaloids and not by the phenolic compounds characteristic of eggplant (Aubert et al., 1989).

Although there is variation among varieties for the concentration in ascorbic acid, the content in this antioxidant is, as a mean, 27 times lower than that of phenolics. This much lower concentration, together with the fact that chlorogenic acid and ascorbic acid have similar antioxidant activities (Kim et al., 2002; Triantis et al., 2005), demonstrates that phenolics and, in particular, chlorogenic acid account for most of the antioxidant capacity of eggplant. Therefore, a breeding program directed at enhancing the antioxidant capacity of eggplant by increasing the ascorbic acid concentration would produce limited results. Furthermore, the narrow-sense heritability of ascorbic acid concentration is lower than that of phenolics.

Consumers and the industry prefer varieties with a luminous white color (Prohens et al., 2005). We have found a wide variation in the distance of the fruit flesh color to the pure white among the materials studied, and surprisingly there are many landraces that have a flesh color that is closer to the pure white than commercial varieties. As occurs in other solanaceous crops (Haynes et al., 1996), the flesh color is highly heritable and, in consequence, the exploitation of the variation present in landraces could lead to new commercial varieties with a more luminous white flesh color. Because the main phenolics of the eggplant fruit flesh are colorless (Macheix et al., 1990), the whiteness of the recently cut flesh is not correlated to the phenolic concentration, allowing the development of highly luminous white-flesh varieties with high phenolic concentration from materials that have no presence of chlorophylls in the flesh. The fact that the ascorbic acid concentration is positively correlated with the distance to the b* (i.e., to yellow) color parameter might be related to the rapid oxidation of ascorbic acid to give pale-yellow dehydroascorbic acid (Rouet-Mayer et al., 1990; Schuler, 1990).

Color parameters based on the change of color coordinates of cut surfaces of the fruit have been useful previously to measure the browning-related traits in eggplant (Sapers and Douglas, 1987). In the current study we found considerable differences among varieties for degree of browning and color difference. Commercial hybrid and nonhybrid varieties have lower mean degree of browning and color difference values than the landraces. This is probably the result of the selection made for reduced browning in the breeding programs. Degree of browning and color difference have high heritability, which means that to obtain offspring with a low degree of browning or color difference, parents should also have low values for these traits. As in many other crops, the degree of browning and color difference are positively correlated with the phenolic concentration (Amiot et al., 1992; Hansche and Boynton, 1986). However, the values of the correlation coefficients are moderate, and the phenolic concentration accounts for only 12% and 23% of the variation in these traits. Therefore, it seems possible to develop varieties with high concentrations of phenolics and reduced fruit flesh color evolution. Both traits (degree of browning and color difference) are obtained from the same color parameters (L*, a*, and b*), and they are easy to calculate and provide complementary information. Therefore, to make a selection we recommend the simultaneous use of both parameters to have a better evaluation of the change in color. Ascorbic acid, which has antibrowning properties because it reduces enzymatically formed *o*-quinones to their precursor diphenols (Macheix et al., 1990), does not show any correlation with either degree of browning or color difference in eggplant. This is probably because of the very low concentrations of ascorbic acid in the eggplant fruit compared with the concentration of phenolics. Regarding the pH, which also has an influence on the activity of polyphenol oxidases (Yoruk and Marshall, 2003), it does not show a correlation with either degree of browning or color difference. In the range of pH observed in our investigation, the activity of the eggplant polyphenol oxidase does not vary much (Dogan et al., 2002; Pérez–Gilabert and García-Carmona, 2000). Other factors, like a different polyphenol oxidase activity among different varieties (Concellón et al., 2004) or other cellular factors, like the size of cells and interstitial spaces, which may differ among different varieties of a given species (Gould et al., 1990), may have a role in browning and color evolution of the fruit flesh.

In conclusion, our work shows that by using the variation present in the eggplant materials, it should be possible to select and develop new varieties with an increased concentration of phenolics and with a moderate degree of browning, similar to that of some currently successful commercial varieties. In this respect, some varieties with a high content of phenolics and a moderate degree of browning and color difference, like ANS24 and Thai Round Green, could be sources of variation of interest to achieve these objectives. As has occurred with other crops, like the tomato (Rodríguez–Burruezo et al., 2005), some sacrifice in perfect appearance may be acceptable by some consumers if nutritional value is increased. Because commercial varieties of eggplant have lost nutritional value compared with traditional varieties, modern breeding programs should take into account nutritional value as an additional breeding objective.

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