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Performance of eggplant grafted onto cultivated, wild, and hybrid materials of eggplant and tomato

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Abstract

Eggplant (*Solanum melongena*) is amenable to grafting and this technique can be exploited to improve production of this vegetable crop. Here, we study the performance of the 'Cristal F1' eggplant cultivar grafted onto a total of 17 rootstocks, including five families, each of which is made by two parents and their hybrid, as well a commercial eggplant rootstock and a self-grafted control. Three families consist of eggplant rootstocks, including a *S. melongena* intraspecific family and two interspecific families of *S. melongena* with *S. incanum* and *S. aethiopicum*. Two other families are made of interspecific hybrids between tomato (*S. lycopersicum*) and *S. habrochaites*. Overall, eggplant rootstocks showed a good compatibility and graft success, while tomato rootstocks had a poor compatibility and only *S. habrochaites* rootstocks could be evaluated for yield and fruit production. Important differences were found for susceptibility to nematodes, with some *S. melongena* accessions showing the best results. Eggplant hybrids were intermediate to their parents in nematode resistance and tomato rootstocks proved to be very susceptible to nematodes. Yield, fruit number and earliness were higher in the most vigorous rootstocks, in particular in the *S. melongena* × *S. aethiopicum* hybrid. Good performance was also observed for some *S. melongena* accessions, but poor results were obtained when using *S. incanum*, *S. aethiopicum* and *S. habrochaites* rootstocks. Some differences were observed for fruit size and shape among the different rootstocks, but for the best rootstocks no differences of commercial relevance were apparent. The results suggest that *S. melongena* germplasm and both intraspecific and interspecific eggplant hybrids seem to be promising materials for developing new rootstocks for eggplant production.

Keywords: Interspecific hybrids; Nematodes; *S. aethiopicum*; *S. incanum*; *S. melongena*; *S. lycopersicum*; *S. habrochaites*; Vigour.

Introduction

Interest in vegetable grafting has increased in recent years due to the advantages for improving production, especially in intensive high-input cropping systems. Grafting of vegetable crops is used to provide resistance to soil pests and pathogens, to increase the tolerance to abiotic stresses, to improve water or nutrient uptake, or to enhance the vigour of the scion (King et al., 2010; Lee, 1994).

Eggplant (*Solanum melongena* L.) is widely cultivated in tropical and temperate regions around the world and is amenable to grafting (Bletsos et al., 2003; King et al., 2010). Eggplant is susceptible to numerous diseases and parasites, in particular to *Ralstonia solanacearum*, *Fusarium* and *Verticillum* wilts, nematodes and insects (Collonnier et al., 2001; Daunay, 2008). Soil-borne pathogens and pests such as *Verticillum*, *Fusarium* and *Meloidogyne* spp. may cause yield losses of up to 78% (Bletsos et al., 2003). Nowadays, the wild relative *Solanum torvum* Sw., which has resistance to a wide range of soil borne pathogens, like *Ralstonia solanacearum*, *Verticillium dahliae*, *Fusarium oxysporum*, and *Meloidogyne* spp. root-knot nematodes, is frequently used for eggplant grafting (Bletsos et al., 2003; Daunay, 2008; King et al., 2010; Singh and Gopalakrishnan, 1997). However, *S. torvum* frequently has irregular seed germination (Ginoux and Laterrot, 1991; Gisbert et al., 2011). Tomato (*S. lycopersicum* L.) intraspecific hybrids and interspecific hybrids with the wild relative *S. habrochaites* S. Knapp & D.M. Spooner are also used as rootstocks for eggplant production (Bletsos et al., 2003; King et al., 2010; Liu et al., 2009). However, incompatibility between the tomato rootstocks and eggplant scions has been reported on occasion, and adequate rootstock-scion combinations have to be used to avoid deleterious effects on production and quality (Kawaguchi et al., 2008; Leonardi and Giuffrida, 2006; Oda et al., 1996). Other materials, like the wild species *Solanum sisymbriifolium* Lam. and the hmong eggplant *Solanum integrifolium* Poir. have been proposed as rootstocks for grafting of eggplant, but the results were not very promising (Rahman et al., 2002).

Recently, we proposed the utilization of eggplant interspecific hybrids derived from crosses between the cultivated *S. melongena* and its wild ancestor *S. incanum* L., or with the cultivated scarlet eggplant *S. aethiopicum* L. Kumba group as an approach for developing new highly vigorous rootstocks for eggplant that improved yield and earliness without affecting fruit quality (Gisbert et al., 2011). Both interspecific hybrids have a good and regular germination, representing an advantage over *S. torvum* (Ginoux and Laterrot, 1991). In addition, tolerance to *F. oxysporum* f. sp. *melongenae* and resistance to *R. solanacearum* (Cappellii et al., 1995; Hébert, 1985) has been described in materials of both *S. incanum* and *S. aethiopicum* (Cappellii et al., 1995; Hébert, 1985). Also, the natural environments where *S. incanum* grows are dry (Lester and Hasan, 1991), suggesting that hybrids might be tolerant to drought. *S. melongena* and *S. aethiopicum* have shown to be amenable for in vitro culture (Gisbert et al., 2006), so this may also facilitate micropropagation of the interspecific hybrids.

Hybrids of vegetable crops frequently present heterosis for vigour (Bassett, 1986) and, in consequence have a potential utility as rootstocks. Apart from vigour, hybrids are used as rootstocks in many vegetable crops since they can incorporate resistances to pathogens from both parents (Daunay, 2008; Lee and Oda, 2003). Intraspecific hybrids of *S. melongena* are easy to obtain, have a good germination, and are frequently used in commercial eggplant production (Daunay, 2008). Interspecific hybrids of *S. melongena* and *S. incanum* are easily crossed and the fruit resulting from the crosses bear many seeds with high viability (Lester and Hasan, 1991). Hybrids of *S. melongena* with *S. aethiopicum* are more difficult to obtain by sexual crosses than those with *S. incanum*, but viable seeds are produced (Behera and Singh, 2002). A similar situation occurs with the interspecific hybrids of *S. lycopersicum* with *S. habrochaites*, and commercial seed of these hybrids is produced for being used as rootstocks for tomato and eggplant (Cortada et al., 2008).

In this work, we assess the potential use as eggplant rootstocks of two *S. melongena* intraspecific hybrids; two *S. melongena* interspecific hybrids (*S. incanum* × *S. melongena*; *S. melongena* × *S. aethiopicum*) and two interspecific hybrids of tomato (*S. lycopersicum* × *S. habrochaites*) and their respective parents. These materials were chosen as they represent highly vigorous interspecific hybrids that have been recommended for eggplant grafting (Cortada et al., 2008; Gisbert et al., 2011). In addition, the inclusion of parents in the experiment may provide information on vigour and inheritance of traits conferred by the rootstocks. The performance of these materials is compared with non-grafted and self-grafted plants of the cultivar used as scion, and with a commercial eggplant rootstock. Our aim is to obtain relevant information for improving the production of eggplant through the development of new rootstocks.

Material and Methods

Plant material

The hybrid cultivar ‘Cristal F1’ (Semillas Fitó, Barcelona, Spain) was used as scion. ‘Cristal F1’ belongs to the black coloured fruit group and is one of the most popular commercial hybrids in Spain. A total of 18 treatments comprising the non-grafted ‘Cristal F1’ and 17 rootstocks, which included two controls corresponding to the self-grafted ‘Cristal F1’ and to commercial eggplant rootstock AGR 703 (Agromar Seeds, Antalya, Turkey), as well as five families, each made of two parents and their hybrid, were evaluated (Table 1). Three families corresponded to eggplant rootstocks, including an intraspecific *S. melongena* family (family 1), an interspecific *S. incanum* and *S. melongena* family (family 2), and an interspecific *S. melongena* and *S. aethiopicum* family (family 3); the two other families consisted of tomato rootstocks, each of which corresponded to an interespecific *S. lycopersicum* and *S. habrochaites* family (families 4 and 5) (Table 1).

Grafting

Plants of the ‘Cristal F1’ (CR) scion at the 2-3 true leaves stage (25-35 d old) were grafted onto rootstock plants having 3-4 true leaves (40-50 d old) using the cleft procedure (Lee, 1994). A total of 10 plants for each combination of scion/rootstock were grafted. After grafting, plantlets were kept for 5 d within a closed plastic tunnel in a greenhouse with extreme day and night temperatures of 30 and 18 ºC, respectively. After that, plantlets were acclimatized outside of the plastic tunnel until transplant. The number of plantlets with successful grafting at 5 and 10 d after grafting (DAG) was recorded. Scion/rootstock combinations with less than five plantlets available (corresponding to the rootstocks *S. lycopersicon* SL1 and SL2 and *S. lycopersicum* × *S. habrochaites* hybrids SL1×SH1 and SL2×SH2) were discarded for yield and fruit quality evaluation.

Table 1. Plant materials used for the eggplant grafting experiments, type of material, and their origin.

Plant material	Code	Species	Type of material	Origin[a]
Eggplant materials				
Scion and control				
'Cristal F1'	CR	*S. melongena*	Commercial F1 hybrid variety	Semillas Fitó, Barcelona, Spain
Control rootstock				
AGR 703	AGR	*S. melongena*	Commercial F1 rootstock	Agromar Seeds, Antalya, Turkey
Family 1				
ANS6	SM1	*S. melongena*	Local landrace	Spain
ASIS1	SM2	*S. melongena*	Local landrace	China
ANS6×ASIS1	SM1×SM2	*S. melongena* × *S. melongena*	Hybrid between local landraces	Spain & China
Family 2				
MM577	SI	*S. incanum*	Wild	Israel
IVIA371	SM3	*S. melongena*	Local landrace	Spain
MM577×IVIA371	SI×SM3	*S. incanum* × *S. melongena*	Interspecific hybrid	Israel & Spain
Family 3				
PI263727	SM4	*S. melongena*	Local landrace	Puerto Rico
PI413784	SA	*S. aethiopicum*	Local landrace	Burkina Faso
PI263727×PI413784	SM4×SA	*S. melongena* × *S. aethiopicum*	Interspecific hybrid	Puerto Rico & Burkina Faso
Tomato materials				
Family 4				
RDD	SL1	*S. lycopersicum*	Breeding line	UPV, Valencia, Spain
ECU523	SH1	*S. habrochaites*	Wild	Ecuador
RDD×ECU523	SL1×SH1	*S. lycopersicum* × *S. habrochaites*	Interspecific hybrid	Spain & Ecuador
Family 5				
NE1	SL2	*S. lycopersicum*	Breeding line	UPV, Valencia, Spain
ECU436	SH2	*S. habrochaites*	Wild	Ecuador
NE1×ECU436	SL2×SH2	*S. lycopersicum* × *S. habrochaites*	Interspecific hybrid	Spain & Ecuador

[a] For commercial seed and breeding lines, the seed company or institution and headquarters location is indicated; for germplasm accessions the country of origin is indicated.

Growing conditions and root-knot nematodes susceptibility

Plants of the non-grafted CR control as well as of the scion/rootstock combinations were transplanted on 2 July 2010, to a sandy loamy soil naturally infested with root-knot nematodes in the campus of the Universitat Politècnica de València (Valencia, Spain) in a completely randomized design. The infestation level correspond to 4290±209 *M. incognita* (Kofoid and White) Chitwood nematodes per Kg^{-1} of soil (dry weight; average of 10 soil samples for different parts of the field). For eggplant rootstocks, ten plants per treatment, except for the rootstocks *S. melongena* SM3 (7 plants), *S. incanum* × *S. melongena* SI×SM3 (8 plants), *S. aethiopicum* SA (5 plants), for which less than ten plantlets were available, were used for yield and fruit quality evaluation. For the tomato rootstocks only the *S. habrochaites* SH1 (6 plants) and SH2 (6 plants) were evaluated for yield and fruit quality, as the rest of tomato materials (*S. lycopersicum* SL1 and SL2, and *S. lycopersicum* × *S. habrochaites* SL1×SH1 and SL2×SH2) had very few plants for evaluation. In addition, five plants of each of the 17 non-grafted rootstocks used were transplanted at the same date in a contiguous experimental plot for evaluation of the vigour (measured as plant height) of the materials used as rootstocks. In both cases, plants were spaced 1 m between the rows and 0.8 m apart within the row and drip irrigated. Standard horticultural practices for eggplant in our area were followed. At the end of the experiment (15 October 2010), plants were uprooted and root-knot nematodes presence was visually rated according to a galling index (GI) assessed on a 0-5 scale reflecting the percentage of galled roots (0=0%; 1=1-20%; 2=21-40%; 3=41-60%; 4=61-80%, and 5=81-100%) (Oka et al., 2004).

Yield and fruit quality evaluation

The early and total yield (kg/plant) and number of fruits per plant was measured for each individual plant of every scion/rootstock combination. Only fruits harvested before 22 August 2010 (20 days since the first harvest) were considered for early yield estimation. For each treatment, the 20 first fruits were evaluated for quality characteristics, which included fruit weight (g), fruit length (cm), fruit width (cm), fruit length/width, fruit curvature, and fruit calyx length. Fruit curvature and fruit calyx length were measured according the European Eggplant Genetic Resources Network (EGGNET) descriptors, and which corresponded to a 1-9 scale for fruit curvature (1=none and 9=U-shaped) and to a 1-9 scale for fruit calyx length, which indicates the length of the berry covered by the calyx (1=very short [<10%] and 9=very long [>75%]) (Prohens et al., 2005).

Results

Graft success and plant survival

Grafting of ‘Cristal F1’ (CR) scion on *S. melongena* rootstocks (including the *S. melongena* intraspecific hybrid SM1×SM2) had a 100% degree of success both at 5 d and 10 d, with the exception of SM3 rootstock, in which grafting success was 70% (Table 2). Also a 100% success was also obtained when grafting CR on *S. incanum* SI and on the *S. melongena* × *S. aethiopicum* hybrid SM4×SA. For the rest of eggplant rootstocks tested, the interspecific hybrid *S. incanum* × *S. melongena* (SI×SM3) had 80% graft success at both dates, while *S. aethiopicum* (SA) had a 60% graft success at 5 d, and 50% at 10 d. The tomato rootstocks tested had much lower levels of graft success (Table 2). In this respect, although at 5 d, a 100% grafting success was observed on *S. lycopersicon* SL1, values as low as 50% were obtained in *S. lycopersicon* SL2. At 10 d the grafting success in the tomato materials decreased, ranging from 60% in both *S. habrochaites* accessions (SH1 and SH2) to only 30% in *S. lycopersicon* × *S. habrochaites* (SL1×SH1 and SL2×SH2) hybrids and in *S. lycopersicon* SL2 (Table 2). Overgrowth at the graft junction was not observed for any scion/rootstock combination.

All transplanted plants from the non-grafted control CR as well as of CR grafted on eggplant rootstocks developed well and survived until the end of the experiment (Table 2). However, for the tomato materials several plants grafted on the tomato rootstocks *S. lycopersicon* SL1 and SL2, *S. lycopersicon* × *S. habrochaites* SL2×SH2 and *S. habrochaites* SH2 died in the field (Table 2), so that in the end all scion/rootstock treatments involving tomato rootstocks, with the exception of *S. habrochaites* SH1 and SH2, had less than five surviving plants.

Table 2. Graft success at 5 and 10 days after grafting (DAG) and plant survival on the different rootstocks when using 'Cristal F1' (CR) eggplant as scion.

Rootstock	Graft success at 5 DAG (n=10)	Graft success at 10 DAG (n=10)	Plant survival after transplant (%)
Non-grafted CR	n.a.[a]	n.a.[a]	100
Eggplant rootstocks			
Controls			
CR	10	10	100
AGR	10	10	100
Family 1			
SM1	10	10	100
SM2	10	10	100
SM1×SM2	10	10	100
Family 2			
SI	10	10	100
SM3	7	7	100
SI×SM3	8	8	100
Family 3			
SM4	10	10	100
SA	6	5	100
SM4×SA	10	10	100
Tomato rootstocks			
Family 4			
SL1[b]	10	4	25
SH1	8	6	100
SL1×SH1[b]	6	3	100
Family 5			
SL2[b]	5	3	33
SH2	8	6	83
SL2×SH2[b]	6	3	67

[a] Not applicable.
[b] Given that less than 5 plants were available for these rootstocks, they were discarded for the evaluation of yield and fruit characteristics.

Rootstocks vigour and resistance to nematodes

Measurement of plant height in non-grafted eggplant rootstocks revealed considerable differences in plant vigour (Table 3). The greatest plant vigour was observed in the interspecific hybrid *S. melongena* × *S. aethiopicum* SM4×SA, which had an average height of almost 240 cm, and was significantly taller than any of the other rootstocks tested. The interspecific hybrid *S. incanum* × *S. melongena* SI×SM3 as well as *S. aethiopicum* SA and the *S. melongena* AGR, SM1, and SM4 presented height values between 186.3 and 200.2 cm and were significantly higher than the rest of materials (*S. melongena* CR, SM2, SM1×SM2, and SM3, and *S. incanum* SI), with heights between 111.6 and 131.8 cm. Plant height of tomato rootstocks was not evaluated as the plants are prostrate.

Values of the galling index (GI) for non-grafted and grafted rootstocks were similar and consistent, and in consequence, we present the pooled results. Considerable differences were found in the susceptibility to nematodes infection for the different rootstocks (Table 3). Non-grafted and self-grafted CR plants were susceptible to nematodes, with a value of 2.7, for GI. *S. incanum* SI and *S. melongena* SM2 were also susceptible and presented GI values of 2.5 and 2.4, respectively. The AGR control rootstock, as well as, *S. aethiopicum* SA were moderately susceptible to nematodes, with GI values of 1.8 and 2.2, respectively. *Solanum melongena* SM1 presented very low values of GI, with a value of just 0.4 for GI, significantly lower than that of the CR controls and AGR. Also, *S. melongena* SM3 and SM4, as well as the intraspecific hybrid SM1×SM2 and the interspecific hybrids of *S. melongena* with *S. incanum* (SI×SM3) and *S. aethiopicum* (SM4×SA) also had low levels of GI (between 0.8 and 1.5), significantly lower than those of the CR controls (Table 3). The hybrids generally had values intermediate between both parents. All tomato materials (*S. lycopersicum* SL1 and SL2, *S. habrochaites* SH1 and SH2, and their respective hybrids SL1×SH1 and SL2×SH2) were very susceptible to nematodes, with values of GI above 4.3 (Table 3).

Table 3. Plant height and root-knot nematode galling index (GI) of the rootstocks used. For plant height five non-grafted plants were evaluated, while for the GI, data correspond to both grafted and non-grafted plants.

Rootstock	Plant height (cm)	GI[a]
	Eggplant rootstocks	
	Controls	
CR	131.8[a]	2.7[d]
AGR	186.3[b]	1.8[bcd]
	Family 1	
SM1	190.8[b]	0.4[a]
SM2	111.6[a]	2.4[cd]
SM1×SM2	130.0[a]	1.5[abcd]
	Family 2	
SI	128.0[a]	2.5[cd]
SM3	128.2[a]	0.9[ab]
SI×SM3	200.2[b]	1.5[abc]
	Family 3	
SM4	192.8[b]	0.8[ab]
SA	184.6[b]	2.2[cd]
SM4×SA	239.4[c]	1.4[abc]
	Tomato rootstocks[b]	
	Family 4	
SL1	n.d.	5.0[e]
SH1	n.d.	4.9[e]
SL1×SH1	n.d.	4.3[e]
	Family 5	
SL2	n.d.	5.0[e]
SH2	n.d.	4.5[e]
SL2×SH2	n.d.	4.5[e]

[a] Mean values within a column separated by different letters are significantly different (P<0.05) according to Duncan's multiple range test.
[b] Plant height of the tomato rootstocks was not determined as the plants have a prostrate habit.

Yield

The non-grafted CR control had a yield of 3.22 kg/plant, while the yields of CR grafted onto the different materials evaluated ranged from 1.29 kg/plant when using the *S. habrochaites* SH1 rootstock to 4.44 kg/plant when using the *S. melongena* SM1 rootstock (Table 4). CR plants grafted onto the commercial rootstock AGR, on *S. melongena* SM1, on *S. melongena* SM4 and on the hybrid *S. melongena* × *S. aethiopicum* SM4×SA had yields above 4.0 kg/plant. *S. melongena* (including the SM1×SM2 intraspecific hybrid) had, in general, a good performance, with yields above 3.0 kg/plant, while *S. melongena* relatives *S. incanum* SI and *S. aethiopicum* SA had low yields, with values of 1.91 and 2.01 kg/plant, respectively (Table 4). The hybrids of families 1 and 2 did not differ significantly in yield from their parents, while for the family 3 the hybrid had significantly higher yields than the lower yielding parent (*S. aethiopicum* SA). Yields of eggplant materials grafted onto tomato materials *S. habrochaites* SH1 and SH2 gave poor yields, always below 2.5 kg/plant (Table 4). Early yields ranged from 0 kg/plant when using the SI rootstock to 0.84 kg/plant when using the SM4×SA rootstock, but no significant differences were found between the non-grafted and self-grafted CR controls and any of the rootstock-scion combinations (Table 4). Early yield in plants grafted onto SM4×SA significantly differed from those obtained in plants grafted onto SMA, as well as of those grafted onto family 2 rootstocks (SI, SM3 and SI×SM3) or *S. habrochaites* rootstocks (SH1 and SH2).

Table 4. Yield traits of 'Cristal F1' eggplant from non-grafted plants (non-grafted CR) and grafted onto different rootstocks.

Scion/Rootstock	n	Early yield (kg/plant)[a,b]		Early fruit/plant (n)[a,b]	Total yield (Kg/plant)[a,b]		Fruit/plant (n)[a,b]	
Non-grafted CR	10	0.17	abc	0.40 ab	3.22	bcd	7.60	abcde
Eggplant rootstocks								
Controls								
CR	10	0.36	abc	0.90 abc	3.28	bcd	8.80	bcdef
AGR	10	0.43	abc	1.14 abc	4.42	d	11.57	ef
Family 1								
SM1	10	0.48	bc	1.10 cd	4.44	d	12.00	f
SM2	10	0.45	abc	1.00 abc	3.52	bcd	9.50	bcdef
SM1×SM2	10	0.27	abc	0.70 abc	3.35	bcd	9.80	cdef
Family 2								
SI	10	0.00	a	0.00 a	1.91	ab	6.00	abc
SM3	7	0.05	ab	0.14 ab	3.18	bcd	8.86	bcdef
SI×SM3	8	0.04	ab	0.13 ab	2.60	abc	7.13	abcd
Family 3								
SM4	10	0.09	ab	0.20 ab	4.16	cd	11.10	def
SA	5	0.22	abc	0.50 abc	2.01	ab	5.60	ab
SM4×SA	10	0.84	c	2.20 d	4.33	d	11.70	f
Tomato rootstocks[c]								
Family 4								
SH1	6	0.05	ab	0.17 ab	1.29	a	4.00	a
Family 5								
SH2	5	0.15	ab	0.33 ab	2.09	ab	6.80	abc

[a] Mean values within a column separated by different letters are significantly different (P<0.05) according to Duncan's multiple range test.
[b] Data taking into account only the plants alive at the end of the experiment.
[c] Materials of SL1, SL1×SH1, SL2 and SL2×SH2 were not evaluated as less than 5 plants were available for these rootstocks.

The number of fruits per plant ranged between 4.0 and 12.0 when using the *S. habrochaites* SH1 and *S. melongena* SM1 rootstocks, respectively; the non-grafted control CR had a mean of 7.6 fruits/plant, while for the self-grafted CR it was of 8.8 fruits/plant (Table 4). The correlation between average values of yield and fruits per plant was high (r=0.98), and the results obtained for the number of fruits followed a similar pattern to that found for yield. The best performance in the number of fruits per plant was for *S. melongena* materials (including the intraspecific hybrid SM1×SM2) and for the interspecific hybrids of *S. melongena*, in particular for the hybrid with *S. aethiopicum* SM4×SA (Table 4). For the *S. melongena* relatives *S. incanum* SI and *S. aethiopicum* SA the number of fruits per plant was low, with values of 6.0 and 5.6, respectively. Tomato rootstocks *S. habrochaites* SH1 and SH2 also had a low number of fruits per plant with values of 4.0 and 6.8, respectively (Table 4). With respect to the number of early fruits, the highest value was obtained in plants grafted onto SMA×SA rootstock with 2.2 early fruits/plant, which differed significantly from the rest of treatments, with the exception of plants grafted onto SM1, in which on average had 1.1 early fruits per plant.

Fruit characteristics

Commercial fruit weight ranged between 300.3 g in plants grafted onto *S. incanum* SI and 474.9 g in plants grafted onto *S. melongena* SM1, while for the non-grafted CR control was of 427.8 g and for the self-grafted CR was of 417.9 g (Table 5). No significant differences were found among the eggplant materials, except that fruits from plants grafted onto *S. melongena* SM1 were larger than those of the rest of materials, with the exception of *S. melongena* SM2 and SM4, and that fruits grafted onto *S. incanum* SI presented a much lower weight than the rest of eggplant materials (Table 4). Also, fruits from plants grafted onto tomato materials *S. habrochaites* SH1 and SH2 did not reach 400 g of mean weight, while all the eggplant (with the aforementioned exception of *S. incanum* SI) had mean fruit weights above this value. The only differences between hybrids and parents were found for family 2, where the hybrid SI×SM3 had a value similar to the *S. melongena* SM3 parent and significantly higher than that of the *S. incanum* SI parent (Table 5).

When considering the fruit length and width, the results are similar to those obtained for fruit weight. In this respect, plants grafted onto *S. melongena* SM1 and SM4 and on the interspecific hybrid *S. incanum* × *S. melongena* SI×SM3 gave fruit with higher length than those grafted onto the non-grafted or self-grafted CR controls (Table 5). Also, fruits grafted onto *S. incanum* SI and onto *S. habrochaites* SH1 were significantly shorter than those of most of the eggplant materials. Regarding fruit width, the results show that fruits from plants grafted onto *S. melongena* SM1 have higher fruit width values than those from plants grafted onto *S. melongena* AGR, SM3, *S. incanum* SI, and *S. habrochaites* SH1 and SH2 (Table 5). Fruits from plants grafted onto *S. incanum* SI and onto *S. habrochaites* SH1 had fruit width values significantly lower than those of the rest of materials.

Regarding fruit length/width ratio, values ranged between 1.76 for fruits from *S. melongena* self-grafted CR and 2.02 for fruits grafted onto *S. incanum* SI. Fruits from the latter rootstock/scion combination were more elongated than those of *S. melongena* non-grafted and self-grafted CR, or grafted onto SM2, or SM1×SM2. Also, fruits from plants grafted onto the interspecific hybrid *S. incanum* × *S. melongena* SI×SM3 were more elongated than those of *S. melongena* non-grafted and self-grafted CR, and of those grafted onto SM2. Finally, fruits of self-grafted *S. melongena* CR were also significantly less elongated than those from plants grafted onto *S. melongena* SM3 and *S. habrochaites* SH1.

For the fruit curvature, values ranged between 1.0 for fruits from plants grafted onto *S. habrochaites* SH1 and 1.9 for fruits from self-grafted CR plants and from plants grafted onto the intraspecific *S. melongena* hybrid SM1×SM2 (Table 5). The only significant differences observed were between fruits from self-grafted CR plants, plants grafted onto the intraspecific *S. melongena* hybrid SM1×SM2 and onto *S. melongena* SM4, which were significantly more curved than those from plants grafted onto *S. habrochaites* SH1 and onto the interspecific hybrid *S. incanum*×*S. melongena* SI×SM3. No significant differences were found among the materials for the fruit calyx length (Table 5).

Table 5. Fruit traits of 'Cristal F1' eggplant fruit from non-grafted plants (non-grafted CR) and grafted onto different rootstocks. All means based on 20 commercial fruits.

Scion/Rootstock	Fruit weight (g)[a]		Fruit length (cm)[a]		Fruit width (cm)[a]		Fruit length/ width ratio[a]		Fruit curvature[a,b]		Fruit calyx length[a,c]	
Non-grafted CR	427.8	c	15.8	bcd	8.7	bc	1.83	ab	1.2	ab	1.0	a
Eggplant rootstocks												
Controls												
CR	417.9	bc	15.3	abc	8.7	bc	1.76	a	1.9	b	1.1	a
AGR	412.8	bc	16.5	def	8.5	b	1.95	bcd	1.6	ab	1.1	a
Family 1												
SM1	474.9	d	17.1	f	9.2	c	1.88	abcd	1.6	ab	1.1	a
SM2	447.6	cd	15.7	bcd	8.9	bc	1.78	ab	1.6	ab	1.0	a
SM1×SM2	418.5	bc	15.9	cde	8.7	bc	1.85	abc	1.9	b	1.0	a
Family 2												
SI	300.3	a	14.7	a	7.3	a	2.02	d	1.2	ab	1.0	a
SM3	423.3	bc	16.3	def	8.5	b	1.95	bcd	1.6	ab	1.0	a
SI×SM3	423.4	bc	17.1	f	8.6	bc	2.01	cd	1.1	a	1.0	a
Family 3												
SM4	451.8	cd	16.8	ef	8.8	bc	1.92	abcd	1.8	b	1.0	a
SA	417.9	bc	16.2	cdef	8.8	bc	1.87	abcd	1.5	ab	1.0	a
SM4×SA	409.8	bc	16.3	cdef	8.8	bc	1.86	abcd	1.5	ab	1.3	a
Tomato rootstocks[d]												
Family 4												
SH1	312.7	a	14.8	ab	7.6	a	1.95	bcd	1.0	a	1.0	a
Family 5												
SH2	377.3	b	16.0	cde	8.5	b	1.90	abcd	1.6	ab	1.1	a

[a] Mean values within a column separated by different letters are significantly different (P<0.05) according to Duncan's multiple range test.
[b] Measured on a 1 to 9 scale, where 1=none and 9=U-shaped according to the European Eggplant Genetic Resources Network (EGGNET) descriptors (Prohens et al., 2005).
[c] Relative to the fruit length; measured on a 1 to 9 scale where 1=very short (<10%) and 9=very long (>75%) according to EGGNET descriptors.
[d] Materials of SL1, SL1×SH1, SL2 and SL2×SH2 were not evaluated as less than 5 plants were available for these rootstocks.

Discussion

The use of grafting vegetables onto rootstocks with the aim of reducing the effects of biotic stresses was initiated in Asia during the late 1920s and has been expanding over the world in the last years (King et al., 2010; Lee 1994). This technique, when appropriate rootstocks are available, is useful to cope with soil biotic and abiotic stresses (Schwarz et al., 2010). In this work, we tested different materials including intraspecific and interspecific hybrids of eggplant as well as materials of *S. lycopersicum*, *S. habrochaites* and interspecific hybrids among them as eggplant rootstocks. This study was performed in a plot naturally infested with *M. incognita* nematodes. Although replication over several seasons or different environments might have reduced potential bias in the results as a result of genotype×environment interaction, Liu and Zhou (2009) found that rankings between grafting treatments for early yield, total yield, and fruit yield in eggplant did not present relevant changes over several years of testing.

An important issue in grafting is having a good graft union and graft compatibility, which depends on the combination of scion and rootstock (Kawaguchi et al., 2008). Using the cleft grafting approach, we have obtained graft success rates of 100% when using eggplant rootstocks, with the exception of SM3 rootstock (70%), the interspecific hybrid *S. incanum* × *S. melongena* (SI×SM3) with 80% graft success, and *S. aethiopicum* (SA) which had a graft success of 60%. Although intraspecific incompatibility is not frequently reported (Mudge et al., 2009), our data suggest that some incompatibility may exist between the *S. melongena* SM3 accession and the *S. melongena* cultivar used as scion (‘Cristal F1’). Further studies should be undertaken to investigate the reasons of this apparent intraspecific incompatibility. Also, a moderate incompatibility was observed when using SA but not when using their derived interspecific hybrid with eggplant. In this respect, we also found full compatibility of eggplant with another *S. aethiopicum* × *S. melongena* hybrid (Gisbert et al., 2011). Regarding the tomato rootstocks, high incompatibility was observed in *S. lycopersicon* (SL1 and SL2) and *S. lycopersicum* × *S. habrochaites* hybrids (SL1×SH1 and SL2×SH), which were discarded for yield and fruit quality evaluation. With the two *S. habrochaites* accessions, the successful rates were of 60%. Although other reports show good results when grafting eggplant onto commercial tomato rootstocks (Liu et al., 2009), our results agree with previous reports that pointed that tomato-eggplant rootstock-scion combination are only moderately compatible (Kawaguchi et al., 2008), and that without an adequate selection of rootstock-scion combinations, deleterious effects may appear (Kawaguchi et al., 2008; Leonardi and Giuffrida, 2006; Oda et al., 1996).

Despite the high soil infestation (4290 nematodes Kg^{-1} soil), 100% of survival was observed for plants grafted onto eggplant rootstocks, whereas for plants grafted onto tomato rootstocks survival ranged from 25 to 100%. High infestation with nematodes, together with the incompatibility manifested with tomato rootstocks may be the cause of the death of plants after transplant grafted onto our tomato rootstocks (Cortada et al., 2008; Kawaguchi et al., 2008).

Explotation of hybrid vigour in vegetable crops, including eggplant, is considered to be one of the outstanding achievements in vegetable breeding, (Bassett, 1986; Daunay, 2008). Plant height used as an indicator of vigour showed that the interspecific hybrid SM4×SA was the most vigorous followed by the commercial *S. melongena* rootstock (AGR), the *S. melongena* SM1 accession, and the interspecific hybrids (SI×SM3). Heterosis in eggplant largely depends on the genetic divergence among parents involved in the cross (Rodríguez-Burruezo et al., 2008). In consequence a high vigour of the interspecific hybrids with eggplant was expected. Differences in vigour among rootstocks may also have resulted from different levels of resistance to nematodes. In this respect, the fact that no differences for height were observed between the hybrid SM1×SM2 and its parent SM1 might be associated to the high nematode resistance observed in the *S. melongena* SM1 accession, which had a GI=0.4 in a scale of 0 (no galled roots) to 5 (81-100% of galled roots). Apart from SM1, low GI values were also observed in SM4 (GI=0.8) and SM3 (GI=0.9), which also presented significant differences with respect to the CR control, and to SM2, SI, SA and tomato rootstocks. This shows that although resistance to nematodes has been described in *S. aethiopicum* (Cappellii et al., 1995; Hébert, 1985), the accession used here by us was not resistant to nematodes. On the other hand, as reported by other authors (Boiteux and Charchar, 1996), we have found important differences among *S. melongena* accessions for resistance to nematodes. In our case, although an exhaustive evaluation of nematode resistance in these eggplant accessions is needed, the intermediated GI values in hybrids derived from the three *S. melongena* varieties, indicate that these materials are promising materials as sources of variation breeding new eggplant cultivars or rootstocks with improved nematodes resistance (Daunay, 2008).

Rootstock-scion combination effects showed that plants grafted onto SM4×SA had a higher amount of early and total fruits compared with the CR un-grafted and self-grafted controls. Earliness could also be associated with the high vigour of this rootstock. Earliness was also observed in the interspecific hybrids between *S. melongena* and *S. aethiopicum* or *S. incanum* tested by Gisbert et al. (2011). Both parents of the *S. melongena* × *S. aethiopicum* hybrid used in Gisbert et al. (2011) differed from those used in the present work, and in the case of the *S. incanum* × *S. melongena* hybrid the *S. incanum* parent was the same, but the S. *melongena* was different. Whereas *S. melongena* × *S. aethiopicum* hybrids have had a similar behavior in both works, the results obtained in *S. incanum* × *S. melongena* crosses differed despite sharing a common parent (SI). The fact that the *S. melongena* parent SM3 used here for obtaining the interspecific hybrid with *S. incanum* seems to be moderately incompatible with the CR scion might account for the different performance observed between our previous work (Gisbert et al., 2011) and the results observed here for the *S. incanum* × *S. melongena* hybrid. This indicates the importance of using compatible parents to obtain fully compatible hybrids, as well as the need of evaluating specific rootstock-scion combinations as we have observed in pepper and it is reported in other works (Gisbert et al., 2010; King et al., 2010). Yield was negatively affected when *S. aethiopicum*, *S. incanum*, or *S. habrochaites* were used for grafting. The rest of treatments evaluated gave yields between 3.22 kg/plant in non-grafted plants to 4.44 kg/plant in plant grafted onto SM1, which presented the highest nematode resistance. The interspecific hybrid SM4×SA, with moderate resistance had 4.33 kg/pl. Our observations on yield and earliness are consistent with previous results, where eggplant varieties with the highest yield entered much earlier into production than low yielding materials (Muñoz-Falcón et al., 2008).

Fruit quality is important for the marketability of fruit, and grafting can influence traits related to quality (Rouphael et al., 2010). Although we found no differences for most eggplant traits of apparent quality, differences were found for some characters. For example, although fruit shape in eggplant is genetically determined and highly inheritable (Frary et al., 2003; Muñoz-Falcón et al., 2008), rootstocks influenced fruit length, width and fruit length/width ratios, possibly due to differences in vigour and to changes in the concentration of growth regulators induced by the rootstock (Aloni et al., 2010). These effects have been observed mainly in fruits from plants grafted onto SI and SH1, which presented the lower weight and width, and the lowest length (in fruits from SI grafted plants) compared with the rest of treatments. A higher length was also observed in fruits from plants grafted onto SM1 and SI×SM3. Fruits from SM1 grafted plants also presented the highest weight. No significant differences respect non-grafted or self grafted plants for fruit trait were observed in fruits grafted onto AGR, SM2, SM1×SM3, Family 3 rootstocks (SM4, SA, SM×SA) and SH2 despite the incompatibility showed by SA and SH2 rootstocks.

Conclusions

Our results show that grafting can contribute to significant improvements in the production of eggplant. Highly vigorous rootstocks having a good compatibility with the scion provide the best results in terms of plant survival, earliness, and yield, without detrimental effects on quality. High vigour has been found in some *S. melongena* accessions and intraspecific hybrids as well as in interspecific hybrids with eggplant. Although not all hybrids had a better performance than the best parent, this shows that the exploitation of heterosis for vigour in intraspecific or interspecific hybrids is a good alternative for developing new rootstocks; in any case, the vigour and compatibility of the hybrids with the eggplant scion need to be tested. Important differences in resistance to nematodes can also be exploited to select rootstocks and resistant hybrids which allow improved production in nematodes infested fields. The poor results obtained with tomato materials suggest that further research on rootstocks for eggplant should be directed to eggplant materials and related species.

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