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'Tropical Sunki' mandarin and hybrid citrus rootstocks under 'Pera' sweet orange in cohesive soil and As climate without irrigation

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ABSTRACT: The search for alternative rootstocks to the 'Rangpur' lime tree is a challenge to the sustainability of citrus in the *Tabuleiros Costeiros* (Coastal Tablelands) of Northeastern Brazil. New varieties should meet high drought tolerance with water deficit, cohesive soils, resistance to citrus diseases and inducing high production of fruit. In this work, the performance of 'Pera' sweet orange was evaluated on 'Tropical Sunki' mandarin and 27 hybrid citrus rootstocks in Umbaúba, Sergipe. A local selection of the 'Rangpur' lime was the control. Planting was in 2013 at tree spacing of 6.0 × 3.0 m, without irrigation. Tree size, fruit yield and quality, tree survival rate and graft-compatibility were assessed until 2019. Experimental design was completely randomized blocks with 29 treatments, three replicates and four plants in the plot. Two selection indices were applied to the data to assist in decision making. The 'Tropical Sunki' mandarin induced similar cumulative fruit yield in relation to the 'Rangpur' lime, suggesting a good drought tolerance of the former rootstock. The TSKC × (LCR × TR) - 073 induced slightly lower productivity, compensated by higher productive efficiency and higher concentration of soluble solids, whereas LCR × TR - 001 and HTR - 166 were highly efficient dwarfing rootstocks. The multiplicative and the rank sum indices showed high correlation, both classifying 'Tropical Sunki' mandarin, 'Santa Cruz Rangpur' lime, LVK × LCR - 010 and - 038, HTR - 127, in addition to the three aforementioned hybrids, as superior to the local selection of 'Rangpur' lime.
Key words: *Citrus ×sinensis*, *Poncirus trifoliata*, plant breeding, rainfed cultivation, selection index.

INTRODUCTION

Brazil is the main producer of sweet orange [*Citrus ×sinensis* (L.) Osbeck] and exporter of its juice and byproducts in the world, having produced about 18 million tons in 650 thousand ha in 2019 (IBGE 2020). The states of Bahia and Sergipe in the tropical Northeast region comprise about 10% of the Brazilian production. The regional citrus industry is located mainly in the *Tabuleiros Costeiros* (Coastal Tablelands), a wide landscape unit ranging from equatorial climate (Af type) and tropical savannah with dry winter (Aw type) or dry summer (As type) to hot semiarid (BSh type) climates, and annual rainfall from 900 to 2,200 mm (Alvares et al. 2013). Relief is flat to slightly wavy and the typical hardsetting soils with a cohesive layer at 0.30 to 0.70 m depth limit the root system development and, thus, enhance the drought effects in citrus producing areas (Gomes et al. 2012; Souza et al. 2008). Moreover, citrus cropping is mainly family farming with low technological level and without irrigation, albeit with high socioeconomic importance to the local communities (Sombra et al. 2018). As a result of these conditions, the fruit yield of citrus trees is relatively low in the region, with an average of 11.9 t·ha^{-1} in 2019 (IBGE 2020).

Historically, the citrus industry in the *Tabuleiros Costeiros* has been based on the monoculture of 'Pera' sweet orange grafted onto the 'Rangpur' lime (*Citrus ×limonia* Osbeck), because that scion variety bears year-round, whereas this rootstock is highly tolerant to drought and to the Citrus tristeza virus (CTV) (Cunha Sobrinho et al. 2013). However, the low diversification of rootstocks is critical for the sustainability of the industry in the region (Carvalho et al. 2019). The 'Rangpur' lime induces poor fruit quality to the scion variety, which impairs the processing of high-quality pasteurized juice that is increasingly demanded in the international market (Spreen et al. 2020). It is also highly sensitive to other major citrus diseases, such as blight, *Phytophthora* spp. gummosis, citrus nematodes and citrus sudden death (CSD) (Pompeu Junior 2005). Although this last disease is not reported in Northeastern Brazil (Bassanezi et al. 2016), it poses a serious threat to the local citriculture. Other drought-tolerant rootstocks that were indicated for the *Tabuleiros Costeiros*, such as the 'Rough' (*Citrus ×jambhiri* Lush.) and the 'Volkamer' [*Citrus ×volkamerina* (Risso) V. Ten. & Pasq.] limes (Prudente et al. 2004), are also CSD-intolerant (Bassanezi et al. 2016), or late-bearers, such as the 'Cleopatra' mandarin (*Citrus reshni* hort. ex Tanaka) (Pompeu Junior 2005). The trifoliate orange [*Poncirus trifoliata* (L.) Raf.] and most of its commercial hybrid rootstocks tolerate CSD but are intolerant to drought and graft-incompatible with 'Pera' (Pompeu Junior 2005). Consequently, alternative rootstocks have been investigated in the region in combination with different scion varieties (Carvalho et al. 2016 b, 2019, 2020; França et al. 2016; Teodoro et al. 2020).

Given this scenario, in this work the horticultural performance of 'Pera' sweet orange grafted on the 'Tropical Sunki' mandarin and 27 hybrid citrus rootstocks compared to the 'Rangpur' lime were evaluated for seven years. Planting was rainfed on a hardsetting soil and under As-type climate, which are the typical conditions for the citrus cropping in the *Tabuleiros Costeiros*. In order to assist the breeder's decision on the most promising rootstocks, two selection indices were applied on the evaluated dataset.

MATERIALS AND METHODS

The scion variety studied was the 'Pera' sweet orange cultivar CNPMF D-6 (CNPMF: Centro Nacional de Pesquisa de Mandioca e Fruticultura Tropical). Nursery trees were grown in containers in screen house. The evaluated rootstocks were obtained by the citrus breeding program of Embrapa Mandioca e Fruticultura in Cruz das Almas, Bahia (Table 1). A local selection of the 'Rangpur' lime used by growers was used as control. The experimental design was completely randomized blocks with 29 treatments, three replications and four plants in the single-line plot.

The experiment was carried out from 2013 to 2019 in the municipality of Umbaúba, Sergipe, Brazil (11º22'37" S, 37º40'26" W). The local climate is As-type, according to the Köppen's classification, with annual mean air temperature and relative humidity of 24 °C and 81.4%, respectively. The annual mean rainfall in the evaluation period was recorded as 1176.1 mm (Fig. 1). The soil type at the experimental area is a yellow argisol with medium texture and cohesive layer from 0.20 to 0.60 m depth. In 2018, soil samples were collected in the citrus planting line and analyzed at the soil laboratory of Embrapa Mandioca e Fruticultura, obtaining the following values at 0–20 and 20–40 cm, respectively: pH ($CaCl_2$) 6.72 and 6.27; P 13.5 and 3.75 mg·dm^{-3}; O. M. 21.2 and 11.7 g·kg^{-1}; K 0.23 and 0.18; Ca 2.22 and 2.18; Mg 0.86 and 0.74; Al 0; Na 0.012; CEC 4.53 and 4.55 cmol$_c$·dm^{-3}; and V 74 and 68%.

The planting was in 2013 at tree spacing of 6.0 m between rows and 3.0 m in within. The cultivation was rainfed and trees were never pruned. Pest control was preventive through the spraying of contact insecticides against the citrus blackfly [*Aleurocanthus woglumi* Ashby, 1915 (Hemiptera: Aleyrodidae)]. Fertilization consisted of the annual application of 20–10–20 NPK at 650 g·tree^{-1} in May/June (rainy season) and two foliar applications of micronutrients cocktails. Mechanical mowing of the cover crops was performed before harvesting.

Table 1. Tree height (TH), canopy volume (CV), number of fruits per tree (NF), cumulative fruit yield (FY), fruit production efficiency (EF), tree survival rate (TS), earliness of production (EP), alternate bearing index (ABI), fruit diameter (FD), fruit length (FL), peel thickness (PT) and soluble solids concentration in the juice (SS) of 'Pera' sweet orange [*Citrus* × *sinensis* (L.) Osbeck] grafted onto 29 rootstocks until seven years after planting. *Tabuleiros Costeiros*, Umbaúba, Sergipe, Brazil.

Rootstock	TH[1]	CV[1]	NF[1]	FY[2]	EF[1]	TS[2]	EP[2]	ABI[2]	FD[3]	FL[3]	PT[3]	SS[3]
	(m)	(m^3)		($t{\cdot}ha^{-1}$)	($kg{\cdot}m^{-3}$)	------- (%) -------		---------------- (mm) ----------------				(°Bx)
'Rangpur' lime (local selection)	2.17b	4.78b	134a	95.9a	5.16c	100a	51.5a	0.33c	71.9a	72.5b	3.11b	10.15b
'Santa Cruz Rangpur' lime	1.93b	4.62b	148a	89.2a	5.53c	92a	57.2a	0.24b	73.4a	74.0a	3.53a	10.24b
HTR-070	1.52a	2.32d	43d	30.7g	3.81d	92a	36.3c	0.24b	70.2b	71.5b	3.61a	10.77a
HTR-083	1.63a	1.48e	45d	39.5f	7.89b	100a	36.6c	0.24b	68.0b	71.0b	3.43b	11.81a
HTR-127	1.98b	3.74c	94b	74.4c	6.28b	100a	47.2b	0.19b	72.8a	74.5a	3.77a	10.05b
HTR-131	2.15b	5.50b	72c	62.2d	4.92c	100a	40.6c	0.36c	75.6a	76.2a	3.94a	9.75b
HTR-166	1.47a	1.22e	56d	41.4f	15.79a	75a	47.4b	0.31c	74.3a	75.7a	3.44a	10.60b
LCR × TR - 001	1.49a	0.95e	78c	45.0f	15.08a	83a	55.2a	0.22b	73.8a	76.1a	3.86a	10.56b
LVK × LCR - 010	2.13b	7.46a	108b	73.9c	2.56e	100a	45.1b	0.20b	75.9a	77.1a	3.62a	10.08b
LVK × LCR - 038	2.08b	5.18b	93b	59.7d	3.33d	100a	53.2a	0.19b	73.8a	74.4a	3.84a	10.92a
LVK × LVA - 009	1.98b	3.48c	95b	64.2d	5.75c	100a	54.5a	0.39c	72.3a	74.1a	3.57a	11.07a
'Tropical Sunki' mandarin	2.05b	5.46b	137a	92.4a	4.63c	92a	55.8a	0.35c	73.5a	74.1a	3.41b	10.13b
TSKC × (LCR × TR) - 001	1.68a	2.33d	69c	74.3c	5.45c	100a	38.1c	0.21b	70.3b	70.4b	3.01b	10.96a
TSKC × (LCR × TR) - 016	1.42a	0.54e	40d	31.9g	5.50c	100a	38.5c	0.29c	69.6b	75.4a	3.69a	10.63b
TSKC × (LCR × TR) - 032	1.65a	3.08c	73c	61.4d	4.14d	100a	34.7c	0.23b	69.9b	72.3b	3.43b	10.98a
TSKC × (LCR × TR) - 059	1.90b	2.67c	74c	46.4f	3.97d	92a	45.4b	0.12a	69.9b	70.8b	3.18b	11.68a
TSKC × (LCR × TR) - 073	2.07b	3.82c	119b	82.2b	7.26b	100a	53.4a	0.38c	72.4a	74.6a	3.54a	10.93a
TSKC × CTARG - 001	2.47b	6.19b	116b	51.4e	4.76c	100a	57.0a	0.28c	71.7b	72.6b	3.45b	10.06b
TSKC × CTARG - 019	2.05b	4.82b	105b	67.0d	5.12c	83a	47.0b	0.18b	72.5a	72.8b	3.18b	10.22b
TSKC × CTARG - 036	2.12b	3.94c	79c	61.5d	3.55d	92a	42.8b	0.32c	74.3a	75.3a	3.84a	10.46b
TSKC × CTARG - 043	1.67a	2.80c	70c	49.5e	3.63d	92a	41.2b	0.16b	68.8b	71.1b	2.95b	11.01a
TSKC × CTQT1439 - 004	2.30b	5.81b	108b	82.6b	3.15d	100a	45.5b	0.25b	70.3b	71.8b	3.14b	11.13a
TSKC × TRBK - 007	2.18b	4.89b	112b	54.6e	4.39c	83a	72.0b	0.51d	70.8b	71.7b	3.34b	10.86a
TSKFL × CTC13 - 005	1.88b	3.09c	74c	61.2d	5.09c	100a	43.4b	0.33c	72.3a	73.5a	3.43b	10.44b
TSKFL × CTC25 - 010	2.23b	4.97b	34d	14.1h	2.44e	67b	-	-	69.4b	71.9b	3.35b	11.43a
TSKFL × CTC25 - 002	2.12b	7.72ª	75c	56.1e	2.67e	100a	40.7c	0.19b	70.5b	71.9b	3.17b	10.42b
TSKFL × CTTR - 006	1.87b	3.89c	52d	42.3f	1.60e	100a	40.4c	0.25b	69.4b	71.3b	3.29b	10.24b
TSKFL × CTTR - 012	1.70a	1.90d	43d	30.9g	3.23d	83a	36.8c	0.31c	70.7b	74.9a	3.42b	10.30b
TSKFL × CTTR - 022	1.87b	4.82b	67c	56.3e	4.59c	92a	40.5c	0.27b	71.3b	73.2b	3.30b	10.30b
Mean	1.92	3.91	83	58.4	5.22	94	48.2	0.26	71.0	72.5	3.40	10.49
CV %	10.28	18.01	46.2	7.03	15.53	9.4	6.09	24.28	5.07	4.88	15.82	9.03

Means followed by the same letter in the column belong to the same group by the Scott–Knotts test ($P \leq 0{,}05$); [1]average values until 2016; [2]mean values in the 2015–2019 period; [3]mean values in the 2015–2017 period; LCR - 'Rangpur' lime (*Citrus* × *limonia* Osbeck); HTR - trifoliate hybrid; TR - trifoliate orange [*Poncirus trifoliata* (L.) Raf.]; LVK - 'Volkamer' lime [*C.* ×*volkamerina* (Risso) V. Ten. & Pasq.]; LVA - 'Valencia' sweet orange [*C.* × *sinensis* (L.) Osbeck]; 'Tropical Sunki' mandarin [*C. sunki* (Hayata) hort. ex Tanaka]; TSKC - common 'Sunki' mandarin; CTARG - 'Argentina' citrange (*C.* × *sinensis* × *P. trifoliata*); CTQT - 'Thomasville' citrangequat [*Fortunella margarita* (Lour.) Swingle x (*C.* × *sinensis* × *P. trifoliata*)]; TRBK - 'Benecke' trifoliate orange; TSKFL - 'Florida Sunki' mandarin; CTC - C citrange; CTTR - 'Troyer' citrange. (-) not evaluated because of high tree loss.

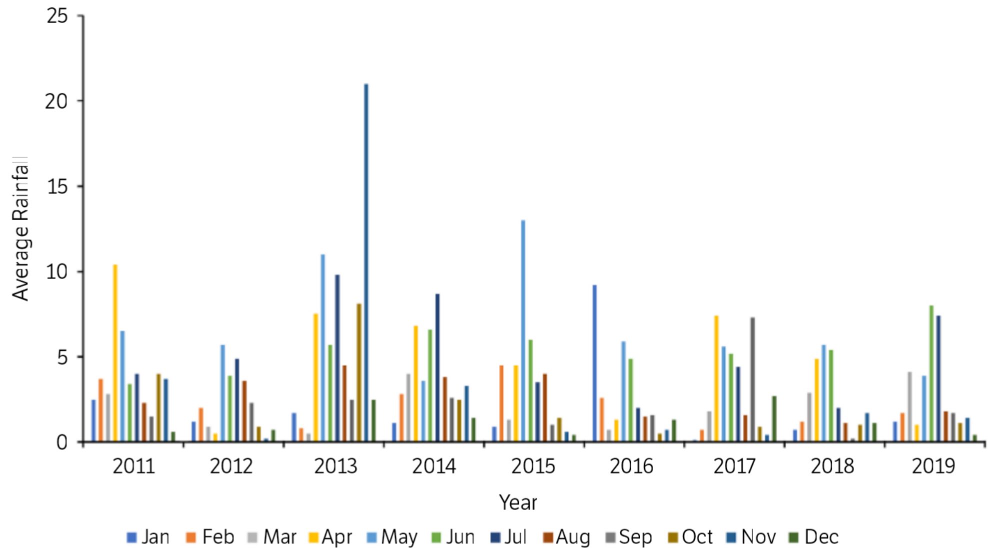

Figure 1. Monthly rainfall (mm) at the location of the experiment, Umbaúba (SE), Brazil, 2011-2019.

In 2016, the tree height (H) from the collar end to the apex and the perpendicular and parallel equatorial canopy diameters (with the mean diameter, D, being calculated) were measured. The canopy volume was calculated by $V = 2/3 \times [(\pi \times D^2/4) \times H]$, adapted from Cantuarias-Avilés et al. (2011). The fruit number per tree was counted and the production was weighted in a digital scale from 2015 to 2019 and the cumulative fruit yield in the period was calculated. The average fruit weight was calculated by the relation between the production weight and the fruit number per tree in the period from 2015 to 2017. The fruit production efficiency was calculated by the relation between the fruit production and the canopy volume in 2016. The earliness of production was estimated by the relation between the cumulative fruit production in 2015 and 2016 and in the entire period (Prudente et al. 2004). The alternate bearing index in the 2015–2019 period was calculated as $ABI = 1 / (n-1) \times \{[(a2-a1) / (a2 + a1) + (a3-a2) / (a3 + a2) + ... + (an - an-1) / (an + an-1)]\}$, where n is the number of years and a1, a2, ..., an-1, an correspond to production of evaluated years (Pearce and Dobersek-Urbanc 1967). The tree survival rate was calculated by the relation between the cumulative number of trees alive in 2019 and the total number of trees in the plot. In 2019, the graft-compatibility was assessed by the visual examination of the graft union, after a bark strip of 2 × 4 cm was removed with a penknife in three trees randomly selected in each treatment. A grade scoring adapted from Fadel et al. (2019) was performed: 0 - absence of symptoms; 1 - fine line at the graft union; 2 - marked line; 3 - sunken line; and 4 - sunken line and gum exudation at graft union, and tree yellowing and stunting. In addition, the trunk diameter was measured 5 cm above and below the graft union and the ratio was calculated. The following fruit quality variables were assessed according to the procedures described by IAL (2008): fruit height and diameter, peel thickness, juice content, soluble solids concentration (SS), titratable acidity (TA), maturity index (SS/TA) and the industrial index (number of 40.8 kg-boxes of sweet orange to produce one ton of frozen and concentrated orange juice). For the analyses, ten uniform fruits were sampled in each plot, based on the visual assessment of fruit maturity (yellowish to orange peel color) and the mean values of the 2015–2017 period are presented.

Data were submitted to variance analysis after all statistical assumptions were attended and the means were grouped by the Scott–Knotts test ($P \leq 0.05$) using the SISVAR software (Ferreira 2011). Graft-compatibility was presented as the percentage distribution of trees within each score per treatment.

In order to assist the selection of the most promising rootstocks, two selection indices were applied on the dataset of variables that were significant by the variance analysis. Initially, the value 1 was divided by the means of the variables that are inversely related to the selection goal, in this case, tree height, canopy volume and industrial index, because less vigorous rootstocks that induce better fruit quality are preferred to manage citrus trees.

The rank sum index (Mulamba and Mock 1978) was calculated as Eq. 1:

$$\left(I_{MM} = \sum_{j=1}^{m} n_{ij} \right) \tag{1}$$

where n_{ij} is the ranking order number of the treatment *i* in relation to the variable *j*. For this index, treatments at higher ranks present higher I_{MM}.

The multiplicative index (Elston 1963) was adapted according to Garcia and Sousa Junior (1999). Because values lower than 1 have negative logarithms, variables lower than 1 were multiplied by a constant (c = 10). Then, the logarithmic transformation was applied to all *i* variables and the distributions were weighed, that is, the p_i (logarithm of each i variable) was calculated. For each p_i, the value $k_i = [n\ (\min p_i) - (\max p_i)] / n - 1$ was subtracted, where min and max are the minimum and maximum values of p_i in each variable dataset and *n* is the number of the evaluated treatments. Because the obtained histograms of variables were not similar, it was calculated $p_i" = \log [(p_i - k_i) \times 10^3]$ to avoid negative logarithms of $p_i"$. Finally, the multiplicative index was calculated by $I_e = (pi - ki)$ for all treatments, which were ranked according to the descending order of I_e values. Both selection indices were calculated using the Spearman's test the SAS software (SAS 2011).

RESULTS AND DISCUSSION

Up to seven years of age, the evaluated rootstocks did not differ regarding the variables canopy diameter, fruit weight, scion/rootstock trunk relation, titratable acidity, juice content, industrial yield, ratio and vitamin C, with the respective averages: 1.98 m, 194.5 g, 0.89, 0.59, 50.67%, 312 boxs·t^{-1}, 18.41 and 34.61 mg·100 mL^{-1}.

Two groups of tree height were obtained and only eight hybrids were classified as dwarfing rootstocks (tree height < 1.80 m). Considering the canopy volume, true dwarfing hybrids included LCR × TR - 001, HTR - 083 and - 166 and TSKC × (LCR × TR) - 016 (ranging from 0.5 to 1.5 m^3), in contrast to the most vigorous ones, TSKFL × CTC25 - 002 and LVK × LCR - 010 (7.7 and 7.5 m^3, respectively). The remaining rootstocks were grouped within intermediate tree size classes (Table 1). The management with smaller trees facilitates cultural practices and harvesting of fruits, and dwarfing rootstocks may be useful depending on the scion variety, management and edaphoclimatic conditions (Donadio et al. 2019). Carvalho et al. (2016 a; 2020) also observed that 'Pera' sweet orange trees were decreased by other hybrid trifoliate rootstocks, whereas LVK × LCR - 010 confirmed its high vigor in the *Tabuleiros Costeiros*. In the cerrado region (Aw climate, deep red Oxisol), LCR × TR - 001 decreased the tree size of 'Valencia' sweet orange (Ramos et al. 2015; Costa et al. 2020). Since the fruit production efficiency is conversely related to the tree size, dwarfing rootstocks induced the most efficient canopies, notably HTR - 166 and LCR × TR - 001 (superior to 15 kg·m^{-3}), as compared to more vigorous rootstocks (Table 1). Therefore, the former hybrids could be evaluated in high-density and irrigated orchards, being potential alternatives to the 'Flying Dragon' trifoliate orange [*P. trifoliata* (L.) Raf. var. *monstrosa* (T. Ito) Swingle], which, in turn, is highly intolerant to drought (Cantuarias-Avilés et al. 2011).

The two evaluated selections of 'Rangpur' lime, the one of local use by growers and 'Santa Cruz', induced the greatest cumulative productivity to the 'Pera' sweet orange, in addition to the 'Tropical Sunki' mandarin (Table 1). The average productivity of these three rootstocks in the evaluated period was around 18.4 t·ha^{-1}, being higher than the Bahia (12.3 t·ha^{-1}) and Sergipe (11.6 t·ha^{-1}) averages for sweet orange fruit yield, yet lower than the Brazilian average (28.95 t·ha^{-1}) in 2020 (IBGE 2020). The 'Tropical Sunki' mandarin induced high productivity to other sweet orange varieties, such as 'Tuxpan Valencia', 'Jaffa', 'Pineapple' and 'Sincorá', compared to drought-tolerant 'Rangpur' lime and 'Rough' lime rootstocks in similar rainfed conditions in northeastern Brazil (França et al. 2016; Teodoro et al. 2020; Carvalho et al. 2019). Costa et al. (2020) observed similar productivity of 'Valencia' sweet orange grafted on the 'Rangpur' lime and 'Tropical Sunki' mandarin without irrigation under tropical savannah climate, thus, taken together, these results reinforce the potential of the later rootstock for the citrus industry, including the most important Brazilian scion variety, the 'Pera' sweet orange (Cunha Sobrinho et al. 2013; Fundecitrus 2020). Although the hybrid citrus rootstocks evaluated in this work lead to cumulative productivity lower than the 'Rangpur' lime, the standard rootstock for the region, two groups induced slightly inferior cumulative fruit yields (mean of 77.5 t·ha^{-1},

~15% lower than the 'Rangpur' lime group), but still higher than the averages of Bahia and Sergipe (Table 1). This corroborates Costa et al. (2020), who reported intermediate fruit yield of 'Valencia' sweet orange grafted onto TSKC × (LCR × TR) - 073 and TSKC × CTQT1439 - 004, and França et al. (2016) for 'Tuxpan Valencia' bearing good crops on TSKC × (LCR × TR) - 001.

With the exception of TSKFL × CTC25 - 010, all evaluated rootstocks resulted in high tree survival rates up to seven years of age (Table 1). In the assessment period, no symptoms of citrus diseases related to the rootstocks were observed at the experimental area. Most evaluated rootstocks did not present graft-incompatibility with 'Pera' sweet orange, which was corroborated by the scion/rootstock trunk ratio of around 1. However, the aforementioned hybrid induced a low production efficiency and the lowest fruit yield, suggesting a lack of adaptation to the local conditions, either showing graft issues with the CNPMF D-6 Pera cultivar (Tables 1 and 2, Fig. 2). The graft incompatibility is considered a physiological disorder between the scion and the rootstock tissues that result in an inadequate, incomplete or absent graft union and further poor plant development (Pompeu Junior 2005). 'Pera' sweet orange is well-known as incompatible with trifoliate orange rootstock (*P. trifoliata*) and many of its hybrids like 'Swingle' citrumelo (Pompeu Junior 2005), in addition to the 'Volkamer' and 'Rough' limes rootstocks (Donadio 1999; Girardi and Mourão Filho 2006). Pompeu Junior and Blumer (2014) observed the occurrence of incompatibility between two selections of 'Rangpur' lime × 'Carrizo' citrange (*C.* ×*sinensis* × *P. trifoliata*) and a 'Cleopatra' mandarin × 'Swingle' trifoliate citrandarin with 'Pera IAC'; on the other hand, Schinor et al. (2013) reported that some trifoliate hybrids rootstocks may be graft-compatible with this scion variety. Moreover, the occurrence of graft incompatibility can be also influenced by the climate conditions (Oliveira et al. 2008), which may relate to the severe drought standing out, especially in the last two seasons of this work. Therefore, these reports highlight the importance of addressing any graft union disorder for the rootstock selection.

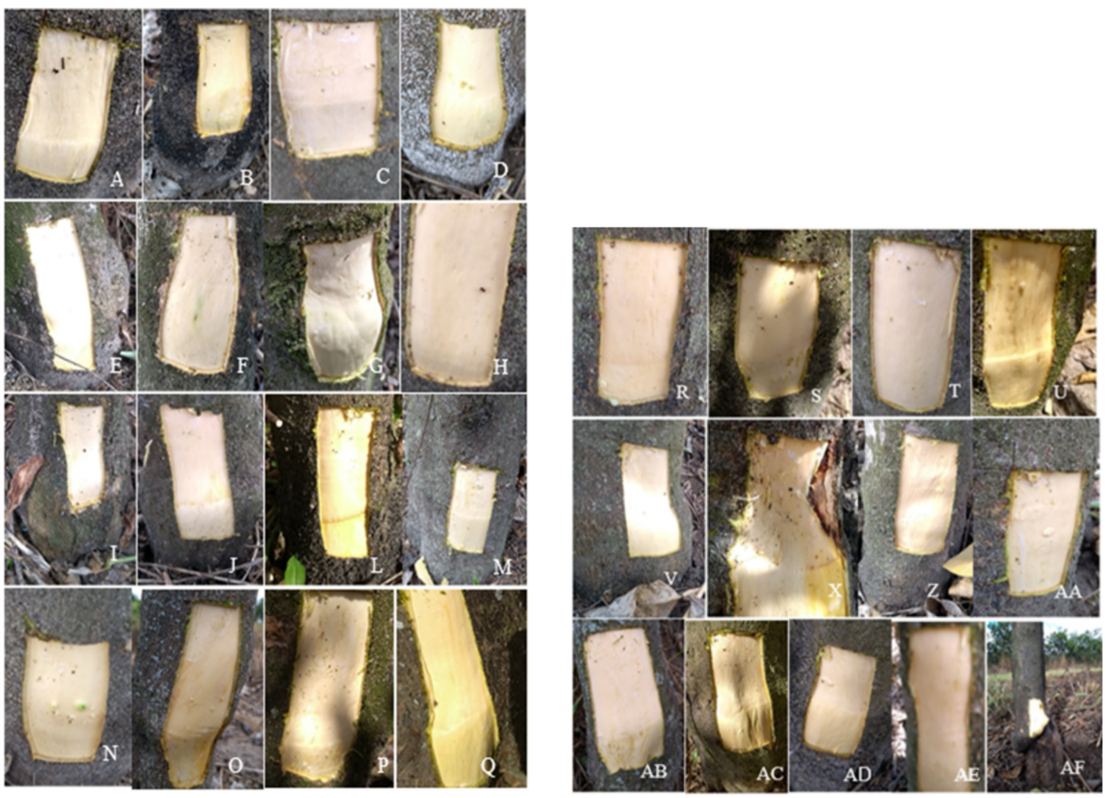

Figure 2. Graft union of seven year-old 'Pera' sweet orange [*Citrus* × *sinensis* (L.) Osbeck] grafted onto 29 rootstocks in the *Tabuleiros Costeiros*, Brazil. TSKC × CTARG - 001 (A); HTR - 070 (B); 'Tropical Sunki' mandarin [*C. sunki* (Hayata) hort. ex Tanaka] (C); TSKC × CTARG - 019 (D); HTR - 127 (E); HTR - 166 (F); TSKFL × CTC25 - 02 (G); LVK × LCR - 038 (H); TSKC × CTC13 - 005 (I); TSKC × CTARG - 043 (J); TSKFL × CTTR - 006 (L); LVK × LVA - 009 (M); LVK × LCR - 010 (N); TSKC × (LCR × TR) - 016 (O); TSKC × (LCR × TR) - 073 (P); LCR × TR - 001 (Q); 'Santa Cruz Rangpur' lime (C. × *limonia* Osbeck) (R); HTR - 083 (S); TSKC × (LCR × TR) - 032 (T); TSKC × (LCR × TR) - 001 (U); TSKC × CTQT1439 - 004 (V); TSKC × TRBK - 007 (X); TSKFL × CTTR - 022 (Z), local selection of the 'Rangpur' lime (AA); TSKC × (LCR × TR) - 059 (AB); TSKC × CTARG - 036 (AC); HTR - 131 (AD), TSKFL × CTTR - 012 (AE) and TSKFL × CTC25 - 010 (AF).

Table 2. Percentual distribution of trees within five graft-compatibility scores of seven years-old 'Pera' sweet orange [*Citrus* × *sinensis* (L.) Osbeck] trees grafted onto 29 rootstocks. *Tabuleiros Costeiros*, Umbaúba, Sergipe, Brazil. (n = 3).

Rootstock	Percentual distribution of trees within five graft-compatibility scores[1]				
	0	1	2	3	4
'Rangpur' lime (local selection)	0	100	0	0	0
'Santa Cruz Rangpur' lime	33	66	0	0	0
HTR-070	0	100	0	0	0
HTR-083	0	66	33	0	0
HTR-127	66	33	0	0	0
HTR-131	0	33	66	0	0
HTR-166	66	33	0	0	0
LCR × TR - 001	0	33	66	0	0
LVK × LCR - 010	0	100	0	0	0
LVK × LCR - 038	66	0	33	0	0
LVK × LVA - 009	0	33	66	0	0
'Tropical Sunki' mandarin	33	66	0	0	0
TSKC × (LCR × TR) - 001	0	100	0	0	0
TSKC × (LCR × TR) - 016	0	33	66	0	0
TSKC × (LCR × TR) - 032	33	66	0	0	0
TSKC × (LCR × TR) - 059	33	66	0	0	0
TSKC × (LCR × TR) - 073	0	100	0	0	0
TSKC × CTARG - 001	0	33	66	0	0
TSKC × CTARG - 019	0	100	0	0	0
TSKC × CTARG - 036	0	33	66	0	0
TSKC × CTARG - 043	33	33	0	33	0
TSKC × CTQT1439 - 004	0	0	100	0	0
TSKC × TRBK - 007	0	33	0	66	0
TSKFL × CTC13 - 005	100	0	0	0	0
TSKFL × CTC25 - 010	0	33	0	0	66
TSKFL × CTC25 - 002	66	33	0	0	0
TSKFL × CTTR - 006	0	33	0	66	0
TSKFL × CTTR - 012	33	33	33	0	0
TSKFL × CTTR - 022	0	100	0	0	0

[1]Scores adapted from Fadel et al. (2019): 0 - absence of graft incompatibility symptoms; 1 - fine line at the graft union; 2 - marked line at the graft union; 3 - sunken line at the graft union; and 4 - sunken line and gum exudation at graft union, and tree yellowing and stunting. Means followed by the same letter in the column belong to the same group by the Scott–Knotts test ($p \leq 0{,}05$); [1]average values until 2016; [2]mean values in the 2015–2019 period; [3]mean values in the 2015–2017 period; LCR - 'Rangpur' lime (*Citrus* × *limonia* Osbeck); HTR - trifoliate hybrid; TR - trifoliate orange [*Poncirus trifoliata* (L.) Raf.]; LVK - 'Volkamer' lime [*C.* × *volkamerina* (Risso) V. Ten. & Pasq.]; LVA - 'Valencia' sweet orange [*C.* × *sinensis* (L.) Osbeck]; 'Tropical Sunki' mandarin [*C. sunki* (Hayata) hort. ex Tanaka]; TSKC - common 'Sunki' mandarin; CTARG - 'Argentina' citrange (*C.* × *sinensis* × *P. trifoliata*); CTQT - 'Thomasville' citrangequat [*Fortunella margarita* (Lour.) Swingle x (*C.* × *sinensis* × *P. trifoliata*)]; TRBK - 'Benecke' trifoliate orange; TSKFL - 'Florida Sunki' mandarin; CTC - C citrange; CTTR - 'Troyer' citrange.

Furthermore, four groups of alternate bearing were observed, with more productive rootstocks usually related to higher alternate bearing indices (Table 1), which is explained by the succession of high and low fruit loads of citrus that is typical in rainfed cultivation (Carvalho et al. 2020). Moreover, both selections of 'Rangpur' lime, the 'Tropical Sunki' mandarin and five hybrids were early-bearer rootstocks: LVK × LCR – 038 and - 009, TSKC × (LCR x TR) - 073, LCR × TR – 001 and TSKC × CTARG - 001 (Table 1). Carvalho et al. (2016 a) and Rodrigues et al. (2019) also pointed the earliness of production of the 'Pera' sweet orange grafted onto LVK × LCR - 038.

Fruit quality is also crucial for the selection of citrus rootstocks (Bowman and Joubert 2020). There were always two groups of rootstocks in quality variables with significant differences (Table 1). 'Rangpur' lime selections and lime hybrids were mainly related to larger fruits with thick peel, which is a common trait for such rootstocks (Bowman and Joubert 2020; Pompeu Junior 2005), although 'Tropical Sunki' also induced large fruits (Table 1). On the other hand, 12 hybrids induced higher soluble solids concentration in the 'Pera' juice, ranging from 10.8 to 11.8 °Bx, compared to 'Rangpur' lime and other rootstocks (Table 1). In Brazil, the minimum soluble solids concentration of sweet orange for the fresh market and processing is 10.0 °Bx (BRAZIL 2018; CEAGESP 2011). These values above the recommended are due to the fact that the planting is in rainfed system, which provides fruits with low percentage of juice, favoring the accumulation of soluble solids, ratio and flavonoids (Grilo et al. 2017). Hereupon, fruit maturation curves should be evaluated on the most promising hybrid rootstocks in the region to support further juice industrialization especially of not from concentrate (NFC).

To assist the breeders' decision on the rootstocks with better overall performance, the rank sum index (Mulamba and Mock 1978) and the multiplicative index (Elston 1963; Garcia and Souza Junior 1999) were applied to the dataset of traits presenting significant differences between the evaluated rootstocks. Selection indices are frequently used in crop breeding programs, especially at initial stages, because several traits can be evaluated at once in a simple procedure to select superior genotypes (Crevelari et al. 2018). Most evaluated variables presented CV% lower than 20% (Table 1), which is commonly reported in similar studies and adequate for using the proposed indices (Costa et al. 2020; Crevelari et al. 2018; Schinor et al. 2013). There was a positive correlation between the rank sum (I_{MM}) and the multiplicative (I_e) indices ($r = 0.77^{**}$), indicating high degree of accordance and, consequently, a more reliable selection of the superior rootstocks. In this sense, the I_{MM} and the I_e classified the 'Rangpur' lime at 16th and 14th positions, respectively, and both classified the 'Tropical Sunki' mandarin at the 8th position. Therefore, only eight rootstocks at higher or same positions are highlighted, which were very close for both indices (I_{MM}/I_e): LCR × TR - 001 (1st/3rd), 'Santa Cruz Rangpur' lime (2nd/2nd), HTR - 127 (3rd/6th), TSKC × (LCR x TR) - 073 (4th/4th), HTR - 166 (5th/10th), LVK × LVA - 009 (6th/5th), LVK × LCR - 038 (7th/1st) and LVK × LCR - 010 (8th/7th) (Tables 3 and 4).

The hybrid LCR × TR - 001 was a dwarfing rootstock that induced high tree survival rate and the highest production efficiency of relatively large fruits (Tables 3 and 4). This hybrid induced similar performance to the 'Valencia' sweet orange in the north of the state of São Paulo, where it was also drought-tolerant (Ramos et al. 2015; Costa et al. 2020). The rootstocks HTR - 166 and - 127 were other efficient dwarfing rootstocks that induced good size of fruits and high productivity. On the other hand, TSKC × (LCR × TR) - 073 gathered high fruit yield and tree survival, intermediate tree size and high soluble solids concentration. Its siblings proved to be promising semi-dwarfing drought-tolerant rootstocks grafted with 'Valencia' selections (Ramos et al. 2015; Carvalho et al. 2016 a; França et al. 2016). A similar performance was presented by LVK × LCR - 038, which previously induced early bearing to the 'Pera' sweet orange in As and Af climates (Carvalho et al. 2016a; Rodrigues et al. 2019). This hybrid tolerated seasonal water deficiency and did not show CSD symptoms (Costa et al. 2020) but, in other experimental areas, it was affected by the *Phytophthora* spp. gummosis. Finally, despite its high ranking in this work and in the Amazon basin (Rodrigues et al. 2019), LVK × LVA - 09 was a poor rootstock of 'Valencia' sweet orange (Costa et al. 2020) and sensitive to the CTV in Bahia (Rodrigues et al. 2014).

The hybrid with the highest soluble solids content was HTR-083, with 11.8 °Bx. This rootstock also induced low-sized trees, high productive efficiency and excellent fruit quality, in addition to a high plant survival rate (100%), which suggests its good adaptation in the *Tabuleiros Costeiros* in high density orchards. However, due to the low accumulated fruit production and later fruit production, it was not better ranked. The low accumulated fruit production is explained by the small size that it induced to the canopy.

The 'Tropical Sunki' mandarin ranked second for cumulative fruit yield, but there was some tree loss and the fruit quality and the tree size were not different from those induced by the 'Rangpur' lime. This low fruit quality may have been due to this rootstock inducing a later fruit maturation than 'Rangpur' lime rootstock. It should be also highlighted that the 'Santa Cruz' selection was superior when compared to the local selection of 'Rangpur' lime, as previously observed in the region (Carvalho et al. 2016 a; Sampaio et al. 2016). 'Tropical Sunki' mandarin and 'Santa Cruz Rangpur' lime were originally selected due to propagation advantages (Soares Filho et al. 1999, 2002), but proved to be alternative rootstocks in field conditions.

Table 3. Rank sum index (I_{MM}) and ranking of treatments in relation to the variables tree height (TH), canopy volume (CV), number of fruits per tree (NF), cumulative fruit yield (FY), fruit production efficiency (EF), tree survival rate (TS), earliness of production (EP), alternate bearing index (ABI), fruit diameter (FD), fruit length (FL), peel thickness (PT), soluble solids concentration in the juice (SS) and final ranking (Rank) of 'Pera' sweet orange [*Citrus* × *sinensis* (L.) Osbeck] grafted onto 29 rootstocks until seven years after planting. *Tabuleiros Costeiros*, Umbaúba, Sergipe, Brazil, 2015–2019.

Rootstock	TH	CV	NF	FY	EF	EP	ABI	TS	FD	FL	PT	SS	I_{MM}	Rank
LCR × TR - 001	3	2	14	22	2	6	10	3	5	3	2	15	87	1
'Santa Cruz Rangpur' lime	14	17	1	3	7	3	12	2	8	13	11	21	112	2
HTR-127	15	13	11	6	5	12	5	1	9	9	5	28	119	3
TSKC × (LCR × TR) - 073	19	14	4	5	4	8	27	1	11	8	10	9	120	4
HTR-166	2	3	23	24	1	11	20	4	3	4	13	14	122	5
LVK × LVA - 009	15	12	10	10	6	7	28	1	12	11	9	5	126	6
LVK × LCR - 038	20	23	12	15	23	9	5	1	5	10	3	10	136	7
'Tropical Sunki' mandarin	17	24	2	2	15	5	25	2	7	11	18	25	153	8
LVK × LCR - 010	23	28	7	8	27	16	8	1	1	1	7	26	153	8
TSKC × CTARG - 036	21	16	13	12	22	18	22	2	3	6	3	16	154	10
TSKC × (LCR × TR) - 016	1	1	28	26	8	24	19	1	25	5	6	13	157	11
TSKC × CTARG - 019	17	19	9	9	11	13	4	3	10	16	23	23	157	11
TSKFL × CTC13 - 005	12	11	16	14	12	17	23	1	12	14	14	17	163	13
TSKC × (LCR × TR) - 001	8	7	21	7	9	25	9	1	20	28	28	8	171	14
HTR-083	5	4	25	25	3	27	12	1	29	27	14	1	173	15
'Rangpur' lime (local selection)	25	18	3	1	10	10	23	1	14	18	27	24	174	16
TSKC × (LCR × TR) - 059	13	8	17	21	19	15	2	2	23	29	23	2	174	16
HTR-131	24	25	19	11	13	21	26	1	2	2	1	29	174	16
TSKC × (LCR × TR) - 032	6	10	32	13	18	29	11	1	23	19	14	7	183	19
TSKC × CTARG - 001	29	27	5	19	14	4	18	1	15	17	12	27	188	20
TSKC × CTARG - 043	7	9	20	20	21	19	3	2	28	26	29	6	190	21
TSKC × TRBK - 007	26	20	6	18	17	2	29	3	17	23	20	11	192	22
TSKC × CTQT1439 - 004	28	26	8	4	25	14	15	1	20	22	26	4	193	23
HTR-070	4	6	27	28	20	28	12	2	22	24	8	12	193	23
TSKFL × CTTR - 022	10	19	22	16	16	22	17	2	16	15	21	19	195	25
TSKFL × CTTR - 012	9	5	26	27	24	26	20	3	18	7	17	19	201	26
TSKFL × CTC25 - 010	27	22	29	29	28	1	1	4	26	20	19	3	209	27
TSKFL × CTC25 - 002	21	29	15	17	26	20	5	1	19	20	25	18	216	28
TSKFL × CTTR - 006	10	15	24	23	29	23	15	1	26	25	22	21	234	29

LCR - 'Rangpur' lime (*Citrus* × *limonia* Osbeck); HTR - trifoliate hybrid; TR - trifoliate orange [*Poncirus trifoliata* (L.) Raf.]; LVK - 'Volkamer' lime [*C.* ×*volkamerina* (Risso) V. Ten. & Pasq.]; LVA - 'Valencia' sweet orange [*C.* ×*sinensis* (L.) Osbeck]; 'Tropical Sunki' mandarin [*C. sunki* (Hayata) hort. ex Tanaka]; TSKC - common 'Sunki' mandarin; CTARG - 'Argentina' citrange (*C.* × *sinensis* × *P. trifoliata*); CTQT - 'Thomasville' citrangequat [*Fortunella margarita* (Lour.) Swingle × (*C.* × *sinensis* × *P. trifoliata*)]; TRBK - 'Benecke' trifoliate orange; TSKFL - 'Florida Sunki' mandarin; CTC - C citrange; CTTR - 'Troyer' citrange.

Table 4. Multiplicative index (I_e), x_{ij} - k_j parameters of the variables tree height (TH), canopy volume (CV), number of fruits per tree (NF), cumulative fruit yield (FY), fruit production efficiency (EF), tree survival rate (TS), earliness of production (EP), alternate bearing index (ABI), fruit diameter (FD), fruit length (FL), peel thickness (PT), soluble solids concentration in the juice (SS) and final ranking (Rank) of 'Pera' sweet orange [*Citrus ×sinensis* (L.) Osbeck] grafted onto 29 rootstocks until seven years after planting. *Tabuleiros Costeiros*, Umbaúba, Sergipe, Brazil, 2015-2019.

Rootstock	TH	CV	NF	FY	EF	EP	ABI	TS	FD	FL	PT	SS	I_e	Rank
	x_{ij} - k_j	x_{ij} k_j	x_{ij} k_j	x_{ij} k_j	x_{ij} - k_j	x_{ij} - k_j	x_{ij} - k_j	x_{ij} k_j	x_{ij} k_j	x_{ij} -k_j	x_{ij} k_j	x_{ij} k_j		
LVK × LCR - 038	1.04	1.45	1.36	1.40	3.33	1.14	1.31	1.51	1.39	1.28	1.48	1.30	23.03	1
'Santa Cruz Rangpur' lime	1.18	1.43	1.51	1.50	5.53	1.21	1.20	1.42	1.36	1.27	1.32	0.96	21.71	2
LCR × TR - 001	1.48	0.89	1.28	1.31	15.08	1.18	1.24	1.26	1.39	1.42	1.48	1.15	20.63	3
TSKC × (LCR × TR) - 073	1.05	1.39	1.45	1.48	7.26	1.15	0.83	1.51	1.28	1.21	1.32	1.30	16.13	4
LVK × LVA - 009	1.14	1.37	1.37	1.42	5.75	1.16	0.80	1.51	1.27	1.28	1.34	1.34	15.83	5
HTR-127	1.14	1.38	1.36	1.46	6.28	1.01	1.31	1.51	1.32	1.27	1.45	0.79	15.47	6
LVK × LCR - 010	0.98	1.51	1.42	1.45	2.56	0.95	1.28	1.51	1.51	1.51	1.37	0.82	12.86	7
'Tropical Sunki' mandarin	1.07	1.46	1.49	1.51	4.63	1.18	0.93	1.42	1.37	1.30	1.23	0.87	12.40	8
TSKC × CTARG - 036	0.99	1.39	1.29	1.40	3.55	0.87	1.01	1.42	1.42	1.36	1.48	1.10	10.62	9
HTR-166	1.49	1.03	1.08	1.27	15.79	1.02	1.03	1.00	1.42	1.44	1.25	1.17	10.19	10
TSKFL × CTC13 - 005	1.22	1.34	1.26	1.40	5.09	0.89	0.98	1.51	1.27	1.24	1.24	1.09	10.12	11
TSKC × CTARG - 019	1.07	1.43	1.40	1.43	5.12	1.01	1.33	1.26	1.29	1.06	0.97	0.95	8.05	12
TSKFL × CTTR - 022	1.23	1.43	1.20	1.38	4.59	0.76	1.13	1.42	1.17	1.25	1.13	1.01	7.00	13
'Rangpur' lime (local selection)	0.93	1.43	1.49	1.51	5.16	1.11	0.98	1.51	1.23	1.05	0.84	0.89	5.90	14
TSKC × (LCR × TR) - 059	1.21	1.30	1.25	1.32	3.97	0.96	1.46	1.42	0.96	0.71	0.97	1.49	5.75	15
TSKC × CTQT1439 - 004	0.72	1.47	1.41	1.48	3.15	0.96	1.17	1.51	1.03	1.09	0.90	1.36	5.28	16
TSKFL × CTC25 - 002	0.99	1.51	1.26	1.38	2.67	0.77	1.31	1.51	1.06	1.16	0.95	1.08	4.61	17
HTR-070	1.46	1.27	0.80	1.14	3.81	0.40	1.20	1.42	1.01	0.86	1.36	1.24	1.91	18
TSKFL × CTTR - 012	1.35	1.21	0.81	1.15	3.23	0.46	1.03	1.26	1.09	1.36	1.24	1.01	1.71	19
TSKC × (LCR × TR) - 032	1.38	1.34	1.25	1.40	4.14	0.05	1.22	1.51	0.96	1.13	1.24	1.32	0.64	20
HTR-131	0.96	1.46	1.24	1.41	4.92	0.77	0.90	1.51	1.50	1.49	1.51	0.05	0.55	21
TSKC × CTARG - 001	0.05	1.48	1.44	1.35	4.76	1.20	1.11	1.51	1.21	1.14	1.26	0.80	0.51	22
TSKC × TRBK - 007	0.92	1.44	1.43	1.37	4.39	1.36	0.05	1.26	1.10	0.86	1.17	1.28	0.38	23
TSKC × CTARG - 043	1.37	1.32	1.22	1.34	3.63	0.79	1.37	1.42	0.65	1.15	0.05	1.33	0.26	24
TSKC × (LCR × TR) - 016	1.51	0.05	0.70	1.16	5.5	0.63	1.08	1.51	0.89	1.38	1.41	1.19	0.17	25
TSKC × (LCR × TR) - 001	1.36	1.27	1.22	1.45	5.45	0.60	1.26	1.51	1.03	0.05	0.52	1.31	0.16	26
HTR-083	1.40	1.12	0.85	1.26	7.89	0.44	1.20	1.51	0.05	0.68	1.24	1.51	0.12	27
TSKFL × CTTR - 006	1.23	1.39	1.01	1.28	1.6	0.75	1.17	1.51	0.84	0.90	1.11	0.96	0.13	28
TSKFL × CTC25 - 010	0.84	1.44	0.05	0.05	2.44	1.51	1.51	0.05	0.84	1.00	1.18	1.44	0.00	29

LCR - 'Rangpur' lime (*Citrus × limonia* Osbeck); HTR - trifoliate hybrid; TR - trifoliate orange [*Poncirus trifoliata* (L.) Raf.]; LVK - 'Volkamer' lime [*C. × volkameriana* (Risso) V. Ten. & Pasq.]; LVA - 'Valencia' sweet orange [*C. × sinensis* (L.) Osbeck]; 'Tropical Sunki' mandarin [*C. sunki* (Hayata) hort. ex Tanaka]; TSKC - common 'Sunki' mandarin; CTARG - 'Argentina' citrange (*C. × sinensis × P. trifoliata*); CTQT - 'Thomasville' citrangequat [*Fortunella margarita* (Lour.) Swingle × (*C. × sinensis × P. trifoliata*)]; TRBK - 'Benecke' trifoliate orange; TSKFL - 'Florida Sunki' mandarin; CTC - C citrange; CTTR - 'Troyer' citrange. x_{ij} - pooled average of the dataset means of each variable; k_j - lower average of each variable.

The results reported herein encourage the evaluation of diverse citrus hybrids as alternative rootstocks for 'Pera' sweet orange under constraining environments (Carvalho et al. 2016 a, 2019, 2020; Bowman and Joubert 2020; França et al. 2016; Schinor et al. 2013; Soares Filho et al. 2008). Besides presenting close fruit yield to that on the 'Rangpur' lime, such promising hybrids may improve the juice quality in tropical regions, especially aiming at the more valuable and increasingly demanded NFC product (Spreen et al. 2020). Furthermore, the productivity can be enhanced by irrigation or higher tree densities with the more efficient dwarfing rootstocks and the long-term responses to citrus diseases, such as blight, and sustained graft-compatibility will be further investigated before the commercial release.

CONCLUSION

'Tropical Sunki' mandarin, 'Santa Cruz Rangpur' lime and the hybrids TSKC × (LCR × TR) - 073, LVK × LCR - 010 and -038, LCR × TR - 001 and HTR - 127 and - 166 demonstrate great potential for the rootstock diversification for 'Pera' sweet orange in the *Tabuleiros Costeiros*, Brazil, and regions with similar edaphoclimatic conditions. The later three hybrids are more suitable for high density orchards.

AUTHORS' CONTRIBUTION

Conceptualization: Ribeiro, L.O., Carvalho, H.W.L.; Methodology: Ribeiro, L.O, Girardi, E.A. Costa, D.P.; Soares Filho, W.S.; Investigation: Ribeiro, L.O, Girardi, E.A; Soares Filho, W.S.; Carvalho, H.W.L.; Writing – Original Draft: Ribeiro, L.O.; Writing – Review and Editing: Ribeiro, L.O, Costa, D.P.; Girardi, E.A; Soares Filho, W.S.; Carvalho. H. W. L.; Ledo, C.A.S.; Carvalho, L.M.; Funding Acquisition: Girardi, E.A, Soares Filho, W.S.; Resources: Girardi, E.A.; Soares Filho, W.S; Supervision: Girardi, E.A.

DATA AVAILABILITY STATEMENT

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ERRATA

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