Effect of Grafting and Growing Environment on Yield Performance of Two Bell Pepper Cultivars

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Summary

Peppers (*Capsicum annuum* L.) are a globally significant vegetable, particularly valuable in the Mediterranean and Balkan regions due to their diverse uses and nutritional benefits. They are produced in open fields, as well as greenhouses. Climate change and intensive production practices pose challenges to pepper cultivation, such as increased biotic and abiotic stresses, requiring new strategies for increased yield and quality. Grafting, a technique of combining elite vegetable varieties with specific rootstocks, has emerged as a promising solution to enhance yields and resilience. This study evaluated the impact of grafting and growing environments on the yield of two bell pepper hybrids, Gelby F1 and Vedrana F1, grafted onto three commercial rootstocks under greenhouse and open field conditions. The results indicated that grafted plants, especially those on the SM Tant rootstock, generally outperformed non-grafted plants in terms of fruit mass, number of fruits per plant and marketable yield. The greenhouse environment favoured larger and heavier fruits. This study emphasizes the importance of selecting compatible rootstock/scion combinations to optimize yield and quality in specific growing conditions.

Key words

bell peppers, grafting, fruit weight, marketable yield, yield

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Received: July 10, 2024 | Accepted: October 29, 2024 | Online first version published: December 27, 2024

Introduction

Peppers (*Capsicum annuum* L.) are considered as one of the most important vegetables globally. According to López-Marín et al. (2021) sweet peppers are the most valuable for the Mediterranean region and are usually grown in greenhouses providing higher yields and quality compared to open field production. Similarly for the Balkan region, Rizani et al. (2021) described peppers as vegetables with high demand in Kosovo, grown both in greenhouses and on open fields. The diverse use of pepper fruits contributed in building its economic significance, while the rich nutritional content is revealing to be important in combating micronutrient deficiencies (Olatunji and Afolayan, 2018). However, due to climate change and intensive production practices pepper production is facing numerous challenges such as increased incidence of biotic and abiotic stresses (Kyriacou et al., 2017). The new breeding strategies additionally have to face the consumers' preferences for specific organoleptic fruit characteristics, such as shape, size, flavour and colour (Devi et al., 2021). Grafting of elite vegetable varieties on specific rootstocks (Imandi and Bahadur, 2023; Kyriacou et al., 2017; Pérez-Alfocea, 2021) is a promising solution for increased food demand, more reliable food production, stable yields under different stresses and a high income per unit area. The study of Leonardi et al. (2017) confirms that grafting can significantly improve vegetable yield as a result of increased plant growth, fruit weight and number of fruits per plant. According to the literature review of Bie et al. (2017), grafting can increase yield to different extents in various vegetable crops ranging from 3.4 to 92 % in melon, 22.7 - 43 % in watermelon, 8.8 – 57 % in cucumber, 9.2 % in pepper, 27.7 % in eggplant, 5.4 – 80.3 % in tomato, because of increased and effective use of resources and prolonged harvest. However, individual experiments show that grafting does not always increase the yield parameters. The meta-analysis of Grieneisen et al. (2018) covering data from 159 publications on yield and quality of grafted tomatoes reveales that crop yield is mostly affected by the specific scion-rootstock combinations, as well as the production conditions.

Another perception is that grafted plants tend to produce higher yields and high-quality fruits in open-field production, compared to non-grafted plants (Rouphael et al., 2010) Djidonou et al., 2013). These experimental results are usually supported by the root morphology of scions and their increased capacity for water and nutrient absorption. But this theory is less likely to apply in pepper production, taking in consideration that pepper is not suitable for grafting onto other species except ones belonging to *Capsicum* (Bletsos and Olympios, 2008; Eltayb et al., 2013; Loewen, 2018; Rana et al., 2015).

Therefore, it is more difficult to breed or to select a suitable vigorous rootstock for pepper than for Cucurbit crops. However, there are such pepper rootstocks that can significantly increase total and marketable yields in all grafted scions, compared to the non-grafted controls under open-field conditions, mainly due to the significantly higher number of fruits (Gisbert-Mullor et al., 2020a). Grafting is primarily used for efficient management of plant responses to biotic and abiotic stresses, rather than to improve productivity and quality as a main goal. In that respect, studies have shown that grafted pepper plants can produce higher yields in open-field production under suboptimal conditions (Vega-Alfaro et al., 2021b). But in other experiments the yield and fruit number equalled that of non-grafted plants (Alfaro, 2020). Similarly, no statistical differences were observed in open-field production for total fruit number and yield of grafted plants (Ergun and Aktas, 2018; Loewen, 2018; Vega-Alfaro et al., 2021a), or for marketability (number of marketable/total fruits) and fruit weight (Fisk, 2017).

For protected cultivation systems, a plethora of literature data refers to higher yields in grafted plants. This advantage is mostly due to rootstocks' ability to better cope and tolerate the disadvantages of the protected cultivation (primarily soil-borne diseases as a result of monocropping), maintaining the overall health and fitness of the grafted plants. Another reason is that grafted plants use technological advancements more efficiently, such as extended season, heating, aeration, shading, etc., compared to non-grafted plants. In line with these findings, Djidonou et al. (2020) identified that across four locations, grafted tomato yields were significantly higher in high tunnel cultivation in relation to the open field, due to a significantly higher number of fruits per plant and average fruit weight. Similarly, Vega-Alfaro et al. (2021b) found significant differences between the two production environments for yield, fruit number, fruit weight and time to flowering of different non-grafted, self-grafted and grafted pepper plants.

One of the advantages of grafting is that grafted plants usually have a higher number of fruits per plant (although not always significantly different from the non-grafted control) and a lower number of fruits with Blossom End Rot (BER), thus contributing to increased total and marketable yield. Such examples were identified in all or almost all pepper-grafted combinations by Colla et al. (2008); López-Marín et al. (2012); Doñas-Uclés et al. (2014); López-Marín et al. (2017); Loewen (2018); Gálvez et al. (2021) and Gisbert-Mullor et al. (2023).

The variability of the results in different studies can be due to rootstock x scion interactions as the fruits from scions do not acquire individual fruit weight characteristics which are inherent to the rootstock; but they can increase the fruit weight of the scion due to the enhanced root architecture of the rootstock (Vega-Alfaro et al., 2021b). Therefore, in some experiments significantly higher yields were rootstock-dependent (López-Marín et al., 2009; Soltan et al., 2017). However, scions can significantly influence the performance of the rootstock, affecting root morphology and nutrient uptake (Sallaku et al., 2022), as well as stress resilience (Gautier et al., 2020) in grafted plants, leading to increased yield (Allagui et al., 2013; Gisbert et al., 2010). In contrast, many studies concluded that although grafted plants had improved yields with an increased number of fruits in most of the trials, they were not statistically different from the non-grafted controls (Bogoescu et al., 2019; Doltu and Tănasă, 2022; Doñas-Uclés et al., 2015; Gisbert-Mullor et al., 2020b; Leal-Fernández et al., 2013; Loewen, 2018; Sánchez-Torres et al., 2016).

Accordingly, the aim of this study is to evaluate the effect of grafting and the growing environment on the yield of two bell pepper hybrids Gelby F1 and Vedrana F1 grafted onto three commercial rootstocks in greenhouse conditions and on open fields.

Material and Methods

Two pepper hybrids belonging to (*Capsicum annuum* L. var. *grossum* Sendt.) group or bell peppers that are well established in the agricultural practice in Kosovo and the region were used as scions. Gelby F1 is mainly intended for greenhouse production (tunnels and glasshouses), but it can be grown also in an open field. Vedrana F1 is recommended for growing in greenhouses in temperate climate, but it also gives good results in warmer climates when grown in an open field. Three rootstocks were used in the experiment: R1 - SM Tant (*Capsicum annuum* L. × *Capsicum chinense* Jacq.) creates strong and vigorous plants throughout the season, including cold periods while R2 - Vital Paprika (*C. annuum* × *C. chinense*) produces a branched root system that is tolerant of many soil diseases, including *Phytophthora* spp.. The last rootstock – R3 - 6210 is a cross between two pepper genotypes distinguished by powerful development and good compatibility with many varieties and hybrids of pepper. It is highly tolerant of *Phytophthora* spp., nematodes and viruses. Non-grafted plants were used as control (R0). Plants were sown at the end of April for all cultivars, timing the planting date at the beginning of July. The experiment was set out in randomized block design with four replications (20 plants or 5m^2 per block/replicate) in greenhouse (GH) and on open field (OF). The experiment was performed in the village of Godanz, Municipality of Stime, Republic of Kosovo (at a latitude 42° 27'30.68' S and longitude 21° 02 '09.56' 'E or coordinates MGRS/USNG 34T EN 02959 00688, at an altitude of 583 m), over three years from 2019 to 2021.

The evaluated yield variables were recorded on fruits in technological maturity from 10 plants per replication for the average fruit mass, number of fruits per plant, marketable and non-marketable yield per plant. For average fruit mass 10 healthy and undamaged fruits, representative for the varieties, were weighed as whole fruits (total part) and fruit mass after removing placenta, seeds and pedicel (edible part). Total mass of marketable and unmarketable fruits per plant was also measured using Mettler Toledo® PB5001 Balance (max. capacity 5100 g, readability 0.1 g). Unmarketable fruits were considered ones that were misshapen, undersized, damaged by sunscald or BER. The total yield per hectare was extrapolated based on the sum results for weight of all fruits from each harvest in each experimental block during the crop cycle.

Multivariate analysis of variance (MANOVA) was performed on the initial data in order to examine differences among the study years. Since there were no significant differences, the average data for each year was further analysed. A two-way ANOVA was performed to examine the influence of grafting combinations and growing environment (GH/OF) on the yield performance. After verifying the significance of the interaction for each variable, a one-way ANOVA was performed. Fisher's least significance difference (LSD) test and Duncan's multiple range test at $P < 0.05$ were used for mean comparison. All data were analysed in statistical software SPSS (SPSS, 2015).

Results

In this study, several yield parameters were examined to understand the effects of the growing environment and grafting status on bell pepper production.

Fruit Mass

The fruit mass was measured as the weight of the whole fruit in grams and as the weight of the edible part of the fruit without seeds and pedicles. The environment in which the plants were cultivated had a significant impact on fruit mass. Both, grafted and non-grafted combinations yielded larger fruits when cultivated in a greenhouse as opposed to an open field. Statistical differences between grafted and non-grafted plants were found between the combinations of Gelbi F1 grafted on Vital Paprika and 6210 and the combinations of Vedrana F1 grafted on SM Tant and Vital Paprika, which had significantly heavier fruits than the corresponding non-grafted hybrids (Table 1). The ratio of edible portion to the entire fruit mass is a trait with practical implications. In our experiment, this ratio was between 70 and 80% and followed the same pattern of grafting effect as the average fruit mass.

Table 1. Mean values from three years (2019-2021) of fruit mass and edible part of the fruit in grafted and non-grafted Vedrana F1 and Gelby F1 bell pepper cultivars grown in open field and the greenhouse conditions

Grafting status		Fruit mass (g)		Edible part of the fruit (g)	
		Open Field	Greenhouse	Open Field	Greenhouse
'Gelby' F1	R_0	120.9 ± 1.61^{h}	131.3 ± 0.88^{g}	89.8 ± 2.21^{e}	90.6 ± 4.32^{e}
	R_1	121.5 ± 2.13^{h}	133.2 ± 1.09^{fg}	89.4 ± 4.10^{e}	92.6 ± 4.85^{de}
	R_2	121.5 ± 1.25^{h}	137.6 ± 1.54^{e}	90.0 ± 0.99^{e}	97.3 ± 3.58^{bcde}
	R_3	121.6 ± 1.98^{h}	134.1 ± 1.58^{f}	90.1 ± 1.85^{e}	94.7 ± 3.05^{cde}
'Vedrana' F1	R_0	145.8 ± 1.27^{d}	161.9 ± 2.00^{c}	104.3 ± 4.05^{b}	125.6 ± 2.93^{a}
	R_1	143.9 ± 1.16^{d}	180.0 ± 3.38^{a}	100.7 ±0.65b^{cd}	121.3 ± 2.75^{a}
	R_2	144.8 ± 0.69^{d}	171.7 ± 0.41^{b}	102.3 ± 1.08^{bc}	123.5 ± 3.69^{a}
	R_3	144.3 ± 0.96^{d}	162.0 ± 0.75^{c}	100.7 ±0.73^{bcd}	129.1 ± 19.26^{a}
		F (2. 46) = 522.112, $P < 0.001$		F (2. 46) = 596.211 $P < 0.001$	

Note: Duncan's Multiple Range Test ($P < 0.05$), mean values with different superscripts are significantly different from each other; R_0 – ungrafted control, R_1 - . (*Capsicum annuum* L. × *Capsicum chinense* Jacq.); R_2 - Vital Paprika (*C. annuum* × *C. chinense*); R_3 - 6210

Number of Fruits per Plant

Grafting typically offers the advantage of a higher number of fruits per plant, often surpassing its non-grafted counterparts (though not always with statistical significance). In this experiment the grafted combinations had a higher number of fruits compared to the non-grafted control. In general, the number of fruits per plant was recorded to be higher in the greenhouse trial where all the differences are significantly higher compared to the open field production (Table 2). For Vedrana cultivar the highest number of fruits was obtained when grafted on SM Tant, both in open field and in greenhouse conditions. The highest values were observed in the combination of Gelby F1 and the rootstock SM Tant with (13.4 ± 0.13) fruits plant^{-1}.

Table 2. Mean values from three years (2019-2021) of number of fruits per plant in grafted and non-grafted Vedrana F1 and Gelby F1 bell pepper cultivars grown in open field and the greenhouse conditions

Grafting status		Number of fruits per plant	
		Open Field	Greenhouse
'Gelby'F1	R_0	6.4 ±1.61^{h}	11.1 ± 0.17^{d}
	R_1	8.1 ± 2.13^{h}	13.4 ± 0.13^{a}
	R_2	7.3 ± 1.25^{h}	12.1 ± 0.05^{c}
	R_3	7.7 ± 1.98^{h}	13.0 ± 0.26^{ab}
'Vedrana'F1	R_0	6.1 ± 1.27^{d}	10.2 ± 0.27^{e}
	R_1	7.9 ± 1.16^{d}	12.7 ± 0.10^{c}
	R_2	7.1 ± 0.69^{d}	11.7 ± 0.08^{cd}
	R_3	6.7 ± 0.96^{d}	11.2 ± 0.10^{d}
		F (2, 46) = 68.006, $P < 0.001$	

Note: Duncan's Multiple Range Test ($P < 0.05$), mean values with different superscripts are significantly different from each other; R_0 – ungrafted control, R_1 – SM Tant (*Capsicum annuum* L. × *Capsicum chinense* Jacq.); R_2 - Vital Paprika (*C. annuum* × *C. chinense*); R_3 - 6210

Table 3. Mean values from three years (2019-2021) of marketable and unmarketable yield in grafted and non-grafted Vedrana F1 and Gelby F1 bell pepper cultivars grown in open field and the greenhouse conditions

Grafting status		Marketable yield (g plant^{-1})		Unmarketable yield (g plant^{-1})	
		Open Field	Greenhouse	Open Field	Greenhouse
'Gelby'F1	R_0	944.5 ± 10.1^{gh}	1444.5 ± 5.0^{e}	127.7 ± 8.1^{bc}	14.1 ± 3.5^{g}
	R_1	987.6 ± 13.2^{fg}	1595.5 ± 4.4^{d}	123.3 ± 3.6^{d}	14.9 ± 5.4^{f}
	R_2	967.9 ± 6.1^{fg}	1662.7 ± 11.9^{c}	132.4 ± 8.4^{a}	13.6 ± 5.7^{e}
	R_3	952.8 ± 10.0^{g}	1623.9 ± 3.2^{cd}	113.2 ± 3.2^{e}	12.6 ± 8.2^{d}
'Vedrana'F1	R_0	1010.3 ± 17.4^{g}	1616.0 ± 8.2^{cd}	134.7 ± 7.8^{a}	11.9 ± 9.3^{f}
	R_1	1080.9 ± 12.4^{f}	1921.8 ± 8.7^{a}	126.7 ± 7.9^{bc}	14.1 ± 2.5^{a}
	R_2	1062.4 ± 12.2^{f}	1855.9 ± 10.2^{b}	131.3 ± 9.8^{ab}	12.5 ± 8.2^{b}
	R_3	1020.0 ± 17.2^{g}	1806.9 ± 17.4^{b}	124.9 ± 6.4^{cd}	13.3 ± 8.9^{c}
		F (15, 63) = 44289.37		F (15, 63) = 547.467	

Note: Duncan's Multiple Range Test ($P < 0.05$), mean values with different superscripts are significantly different from each other; R_0 – ungrafted control, R_1 - SM Tant (*Capsicum annuum* L. × *Capsicum chinense* Jacq.); R_2 - Vital Paprika (*C. annuum* × *C. chinense*); R_3 - 6210

Marketable and Unmarketable Yield

The results from our experiment demonstrate that grafting had a noticeable and consistent positive impact on the marketable yield. All grafted plants outperformed their respective non-grafted scions in terms of marketable yield in both production conditions. In particular, Vedrana F1 grafted on SM Tant produced the highest marketable yield (Table 3) under greenhouse conditions (1921.8 ± 8.7 g plant^{-1}). For Gelby F1 the highest marketable yield was obtained with Vital Paprika rootstock in greenhouse (1662.7 ± 11.9 g plant^{-1}).

Deformed or significantly misshapen fruits and the ones affected by disease or visible physiological disorders such as Blossom End Rot, typically fall into the category of nonmarketable produce. In this trial the share of nonmarketable fruits was exceptionally low. The results varied and the grafted combinations had a lower unmarketable yield than the corresponding non-grafted hybrids on open field, with exception of Gelby F1/Vital Paprika. In greenhouse trials, the nonmarketable yield for Gelby F1 was higher than non-grafted plants in combination with SM Tant, while the best results were achieved with 6210 rootstocks. For Vedrana F1 in greenhouses, grafting did not improve the unmarketable yield, with SM Tant being the least favourable combination.

Total Yield

Regarding the total yield from each experimental block, our observations indicated no significant adverse effects of the grafting process. On the contrary, the rootstocks pushed to a higher yield in the grafted variants. The highest values for both hybrids were achieved when grafted on the rootstock SM Tant (Table 4).

In the open field experiment, the differences between the grafted and non-grafted varieties were not statistically significant. Under greenhouse conditions, a significant difference in total yield between non-grafted plants and those grafted onto the SM Tant rootstock was observed. Additionally, notable differences were found in the grafting combination of Gelby F1/Vital Paprika and across all combinations involving Vedrana F1. For example, Vedrana F1/SM Tant had the highest value of 71.9 t ha -1 (SD: 0.34).

Table 4. Mean values from three years (2019-2021) of total yield in grafted and non-grafted Vedrana F1 and Gelby F1 bell pepper cultivars grown in open field and the greenhouse conditions

Cultivar/Rootstock combination	Total yield (t ha^{-1})	
	Open field	Greenhouse
Gelby F1 (ungrafted control)	37.2 ± 0.88^{ab}	62.5 ± 0.24^{c}
'SM Tant'	39.1 ±1.86^{a}	66.1 ± 0.17^{a}
'Vital Paprika'	38.2 ± 0.32^{ab}	64.3 ± 0.54^{b}
'6210'	37.9 ± 0.43^{ab}	63.4 ± 0.08^{bc}
Vedrana F1 (ungrafted control)	40.5 ± 0.80^{ab}	66.7 ± 0.34^{d}
'SM Tant'	43.1 ± 0.57^{a}	71.9 ± 0.34^{a}
'Vital Paprika'	42.4 ± 0.75^{ab}	70.0 ± 0.48^{b}
'6210'	41.9 ± 0.64^{ab}	68.2 ± 0.29^{c}

Note: Results based on one-way ANOVA for each hybrid compared to its grafted combinations separately

Discussion

Our findings for fruit mass (heavier fruits in the greenhouse trial) are in contrast with the findings of Vega-Alfaro et al. (2021b), who observed larger individual fruit weight in open fields when comparing high-tunnel production environments, irrespective of scion or rootstock type. They found no significant variation in individual fruit weights across different rootstocks in high tunnel. In the study of Soltan et al. (2015) it was found that fruit weight is heavily dependent on the rootstock used for grafting, emphasizing the necessity to test new grafting combinations in different environments to ensure commercial success. The appropriate rootstock choice was emphasized by Vega-Alfaro et al. (2021a) where the rootstock 'Primero Red' elevated the individual fruit weight of the scion compared to self and non-grafted checks, regardless of the scion used. Doñas-Uclés et al. (2014) observed significant differences in fruit weight between different years of experiments, with grafted treatments consistently outperforming non-grafted plants. Rizani et al., (2021) reported similar findings for grafted Somborka cultivar compared to non-grafted, while the differences between the rootstocks were not statistically significant. On the other hand, some studies reported a decrease in individual fruit weight, as observed by Gisbert et al. (2010), where grafting of two pepper hybrids resulted in an 11%-21% reduction. Nevertheless, this did not affect the final yield because the grafted plants had more fruits per plant at the end of the production cycle. Also, Ergun and Aktas (2018) conducted an open field experiment and found that fruit weight was not affected by grafting, while the total yield was higher in grafted compared to non-grafted plants.

Regarding the number of fruits per plant, our results are in conformity with a previous publication by Ulas et al. (2020) where a significant variation ($P < 0.001$) in the fruit count per plant was noted across different grafting combinations. Additionally, statistically significant variations ($P < 0.001$) were reported when comparing the fruit count per plant among different pepper inbred lines grafted onto various pepper rootstocks and non-grafted plants. Gisbert et al. (2010) grafted Almuden and Coyote hybrids onto two *Phytophthora capsici*-resistant rootstocks and found that the total fruit count per plant was higher for grafted plants as opposed to non-grafted ones. Similarly, Rizani et al. (2021) reported a significant increase in the yield of grafted Somborka cultivar as compared to its non-grafted counterpart in an open-field experiment, leading to a higher overall plant yield. Interestingly, Vega-Alfaro et al. (2021b) found no significant changes in the total fruit count per plant resulting from grafting or the type of rootstock.

The practice of grafting can significantly influence the yield of a plant through various mechanisms, including enhanced water and nutrient uptake, increased hormone production and improved scion vigour, documented in various studies on grafted vegetables (Lee, 1994; Paradiso et al., 2018; Zaaroor et al., 2016). Marketable yield was analyzed by Loewen (2018) when 'Karisma' bell pepper cultivar was grafted onto different rootstocks. When 'Maxifort' was used as the rootstock for this particular pepper scion, there was a considerable reduction (85%) in both the marketable and total yield as opposed to non-grafted plants. In contrast, 'Scarface' as a rootstock was found to bolster the marketable yield by 32%, with an increase in fruit size (15%-18%) and an improvement in the marketability of 9-12% when compared to non-grafted 'Karisma' pepper plants. Yet, further research indicates that the choice of rootstock significantly affects both total and marketable yields, as demonstrated in the experiment of Colla et al. (2008), where grafted plants exhibited 22-46% superior marketable yield compared to their non-grafted counterparts. This conclusion was supported by Bogoescu et al. (2019), who assessed three distinct rootstocks from Romania under greenhouse conditions. This study found that both the rootstock used and the cultivation method significantly influenced the marketable yield. Grafting improved marketable yield in plants grown under abiotic stress conditions, such as salinity (Maršić et al., 2021) and irrigation deficit (Gisbert-Mullor et al., 2020b). Doñas-Uclés et al. (2015) observed variable results regarding the commercial yield of Palermo pepper when grafted on five different rootstocks. Although the differences between the treatments were not statistically significant, only two rootstocks surpassed the non-grafted control in terms of commercial yield.

The unmarketable yield was documented in the study of Doñas-Uclés et al. (2014), where notable differences in the occurrence of BER were evidenced among fruits across various grafting treatments. Still, the highest incidence of BER was observed in non-grafted control plants. In opposition to these findings, the investigation by Colla et al. (2008) who evaluated the performance of two pepper hybrids, revealed that the rootstock did not significantly influence the yield of unmarketable fruit, and no noticeable differences were detected in the weight and shape index of marketable fruits across both cultivars. In accordance with our results, Gisbert-Mullor et al. (2020b) noted a beneficial reduction in the yield of unmarketable fruit as a result of the grafting process in their experiment involving three pepper landraces. All grafted landraces showed a decrease in unmarketable yield (27% - 61%) and in the yield of BER-affected fruit (28% - 71%) compared to the control. This lesser incidence of fruit with BER symptoms in grafted plants could be a result of the rootstock's superior resistance to abiotic stress. Contrary to these results in a previous study Gisbert et al. (2010) demonstrated that varying grafting combinations could significantly influence the quality of the fruit produced, depending on the specific pepper cultivar. In the Coyote cultivar, grafting led to the appearance of unmarketable fruit, ranging from 7.91% to 10.58%, depending on the specific grafting treatment, as compared to non-grafted plants that yielded commercially viable fruit. Similar trend was observed in the Almuden cultivar where the percent of unmarketable fruit ranged from 2.32% to 15.63% in grafted plants, 12.5% in self-grafted plants, while non-grafted treatments had only 1.32%.

Yield in vegetable crops is influenced by a complex network of factors, including the cultivar of the plant, the environmental conditions, and the agricultural practices used. Each of these can either increase or decrease yield in ways that are not always straightforward. The influence of grafting on pepper yield varies greatly and depends on the specific rootstock/scion combinations and the production system in use, as revealed in the meta-analysis by Grieneisen et al. (2018), as well as by Leal-Fernández et al. (2013), as confirmed with our findings. On the other hand, Doñas-Uclés et al. (2014) did not observe significant differences in the yield between the non-grafted cultivar Palermo and the combinations in which it was grafted on three rootstocks. Based on their results,

Garcia-Bañuelos et al. (2017) reported that under greenhouse conditions the yield increased in all grafted combinations of five varieties of bell pepper that were grafted on two *Phytophthora*-resistant rootstocks. Another yield increase in grafted plants was observed by Doltu and Tănasă (2022), who analysed the effect of four rootstocks on two varieties of bell peppers.

Our results as well confirm the complexity of factors involved in grafting, such as the type of scion, the rootstock, the growing conditions and the characteristics of the specific plant cultivar and they all significantly impact the effectiveness of grafting in increasing yield. It also emphasizes the importance of careful selection of rootstock/scion combinations to optimize yield for specific growing environments. Our findings indicate that even in partially controlled greenhouse conditions, the benefits of grafting can be emphasized, particularly with a compatible rootstock such as SM Tant. The potential explanation for this may be due to more controlled stressors and microclimate in the greenhouse setting, enabling better conditions for grafted plants to capitalize their potential for improved resilience and vigour, leading to a substantial increase in yield.

Conclusion

Based on the analyses of the following yield parameters: fruit mass (g) of the whole fruit and only the edible part without seed and pedicle, number of fruits per plant, and marketable and non-marketable yield per plant, we conclude that the grafting status affected the yield parameters. The rootstock SM Tant emerged as the most favourable, both in the open field and in the greenhouse, mainly due to the higher number of fruits per plant, followed by Vital Paprika. A consistent positive impact on marketable yield was evident, which may be attributed to a larger number of fruits per plant. These findings indicate that the choice of rootstock can significantly affect the quantity and quality of the yield, emphasizing the importance of rootstock selection in grafted plant production. In terms of the growing environment, the overall conclusion is that it significantly influenced the fruit mass, suggesting that the provision of optimal growth conditions will result in the development of heavier fruits and higher yields.

CRediT authorship contribution statement

Albina Kika Krasniqi: performed the experiments, analysed the data and drafted the manuscript. **Biljana Drvoshanova:** contributed in data analysis and editing of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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