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Research Article

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Effect of three grafting dates on survival and early growth performance of seedling in eggplant (*Solanum melongena* L.), pepper (*Capsicum annuum*), and tomato (*Solanum lycopersicum*) crops.

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Abstract: A study was carried out in 2025 at the Horticulture Department of Omar Al Mukhtar University, Al Jabal Al-Khader, Libya to evaluate the impact of three different grafting dates on the survival and early growth performance of grafted seedlings of eggplant cv. Deep Purple F1 hybrid, sweet pepper cv. Bayonet, and tomato cv. Angelle. The experiment was arranged in a randomized complete block split-plot design with 4 replication, encompassing nine treatment combinations representing all possible grafting date and crop interactions. The present study clearly demonstrates that grafting success and early seedling performance of eggplant, pepper, and tomato are strongly governed by both crop species and grafting date, with the intermediate grafting stage consistently providing the most favorable outcomes. in addition, tomato and eggplant exhibited better performance than pepper across all evaluated traits.
Keywords: Self-grafting; Healing chamber; Dry weight; Fresh weight; Splice grafting

فيروزعلي أبوبكر بوعجيلة، قسم البستنة، كلية الزراعة، جامعة عمر المختار، البيضاء، ليبيا
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تأثير ثلاثة مواعيد للتطعيم على بقاء وأداء النمو المبكر للشتلات في محاصيل الباذنجان (*Solanum melongena L.*) والفلفل (*Capsicum annuum*) والطماطم (*Solanum lycopersicum*).

المستخلص : أُجريت هذه الدراسة سنة 2025 في قسم البستنة بجامعة عمر المختار، الجبل الأخضر، ليبيا، لتقييم تأثير ثلاثة مواعيد مختلفة للتطعيم على بقاء ونمو شتلات مطعمة من الباذنجان صنف "ديب بيربل" الهجين F1، والفلفل الحلو صنف "بايونيت"، والطماطم صنف "أنجيل". وقد صُممت التجربة وفق تصميم القطاعات العشوائية الكاملة مع أربع مكررات، وشملت تسع مجموعات من المعاملات تمثل جميع التفاعلات الممكنة بين موعد التطعيم والمحصول، وتُظهر هذه الدراسة بوضوح أن نجاح التطعيم وأداء الشتلات المبكرة للباذنجان والفلفل والطماطم يتأثران بشكل كبير بنوع المحصول وتاريخ التطعيم، حيث تُحقق مرحلة التطعيم المتوسطة باستمرار أفضل النتائج، بالإضافة إلى ذلك، أظهرت الطماطم والباذنجان أداءً أفضل من الفلفل في جميع الصفات التي تم تقييمها.
الكلمات المفتاحية: التطعيم الذاتي؛ حجرة الشفاء؛ الوزن الجاف؛ الوزن الطازج؛ تطعيم الوصلة.

INTRODUCTION

Vegetable grafting is widely recognized for its capacity to enhance plant growth and development, improve nutrient acquisition, and increase tolerance to salinity and temperature stress. In addition, grafting can reduce the incidence of viral, fungal, and bacterial diseases, thereby contributing to higher productivity in solanaceous and cucurbit crops across many regions, particularly under the pressures associated with intensive cultivation systems (Bie *et al*., 2017; Buojaylah *et al*, 2024; Coskun, 2023). In *Solanaceous* crops like *Solanum lycopersicum* (tomato), *Capsicum annuum* (pepper), and *Solanum melongena* (eggplant), where grafted plants show better adaptation to stress, vigor, and consistency of yield compared to non-grafted equivalents, vegetable grafting has become an essential horticultural technique for improving crop performance. In intensive agricultural systems, grafting makes it possible to combine desirable scion and rootstock features, allowing for the manipulation of plant design, resilience to biotic and abiotic challenges, and potential yield. Because of these advantages and its ability to maintain output under a variety of growing situations, vegetable grafting has been extensively used in the production of cucurbits and solanaceous crops (Kyriacou *et al.*, 2020).

Graft union development and subsequent performance of plants are significantly influenced by the changing dynamics time of grafting, particularly the seedling stage at which grafting is carried out. In order to guarantee ideal tissue contact and vascular reconnection at the union connection, grafting demands not only physiological compatibility between the scion and rootstock but additionally exact coordination of seedling development. The effectiveness of vascular integration and the survival percentage of grafted plants are strongly influenced by the developmental stage of seedlings at grafting, including true number of leaves and stem diameter, according to studies conducted in tomato and other agricultural crops (Martínez-Ballesta *et al*., 2010).

Vegetable seedlings of the Solanaceae family should be grafted when their stem diameter is between 1.5 and 2 millimeters, which is typically when they have two or three true leaves. Depending on the growth conditions and circumstances, tomatoes and eggplant are often ready two to three weeks after seeding. Compared to tomatoes, peppers often develop more slowly and may require longer time to achieve the required stem diameter (Guan and Hallett, 2016; Kubota *et al*., 2008). This carefully selected timing also reduces transplant handling and dealing stress and streamlines nursery operations, thereby enhancing seedling survival throughout the healing period (Johnson *et al.*, 2011).

The developmental stage of the plant and stem thickness at the time of grafting play critical roles in the anatomical and physiological mechanisms involved in graft union formation. Grafting too early, when tissues are still immature, can hinder proper xylem development and limit the establishment of effective water transport. In contrast, grafting at a later stage may decrease the natural flexibility and regenerative capacity of young tissues, ultimately lowering the likelihood of successful graft union formation (Hartmann *et al*., 2011; Lee, 1994).

Although grafting time is widely acknowledged as a key determinant of graft success, systematic comparative studies among solanaceous crops are still scarce, especially those that control for genetic background through self-grafting. The use of self-grafting—where both scion and rootstock belong to the same species or cultivar—allows researchers to isolate the effect of timing by minimizing variability arising from interspecific incompatibility or rootstock influences. Evidence from pepper indicates that postponing grafting can lead to inadequate xylem differentiation at the graft junction, highlighting the close relationship between developmental stage and effective vascular reconnection. Therefore, investigating the effects of grafting time under controlled self-grafting conditions is critical for delineating the ontogenetic window that maximizes union success and subsequent growth outcomes across these solanaceous crops. Such knowledge is essential not only for refining nursery protocols but also for enhancing the reproducibility of experimental grafting studies that seek to attribute performance differences specifically to timing effects rather than to rootstock genetics or incompatibility phenomena. The objective of this study was to evaluate the influence of three grafting dates on self-graft survival and subsequent seedling growth in eggplant, pepper, and tomato.

MATERIALS AND METHODS

Study Design and Treatment Arrangement: A study was carried out in 2025 at the Horticulture Department of Omar Al Mukhtar University, Al Jabal Al-Khader, Libya (Latitude: 32.7627° N, Longitude: 21.7551° E), to evaluate the impact of three different grafting dates on the survival and early growth performance of grafted seedlings of eggplant cv. Deep Purple F1 hybrid, sweet pepper cv. Bayonet, and tomato cv. Angelle (Syngenta, Cairo, Egypt). The main plot factor consisted of three grafting dates, with grafting performed on vegetable seedlings at 17 (19 October), 23 (25 October), and 32 (3 November) days after sowing. The sub-plot factor comprised the *Solanaceous* vegetable crops: eggplant, sweet pepper, and tomato. Seedlings were sown on 2 October in trays containing peat moss. Details about peat moss analysis are presented in Table 1. The experiment was arranged in a randomized complete block design with a split-plot layout, encompassing nine treatment combinations representing all possible grafting date and crop interactions, and each treatment was replicated four times to enhance the reliability of the results.

Table: (1). Peat moss characteristics and properties.

Measurements	Values
Organic Matter (%)	85–98
E.C (Mmhos/ cm)	0.2–1.0
Moisture (%)	40–60
pH	5.5–6.5
(%)Organic carbon	40–50
(%) Total nitrogen	0.5–1.0
C:N ratio	50:3

Seedlings were self-grafted using the splice method and subsequently maintained in a healing chamber for nine days. Self-grafting was performed to reduce the risk of genetic incompatibility and to ensure precise alignment between the scion and rootstock, thereby minimizing potential negative effects on graft survival. Grafting operations were carried out between 8:30 AM and 11:30 AM, a period associated with lower transpiration rates and reduced water stress, following the recommendations of Rivard and Louws (2006).

Grafting Method Conducted in the Study: In the present study, self-grafting was adopted to achieve uniform stem diameters, thereby isolating the assessment to the influence of the three predetermined grafting times. Successful graft union development depends on precise cambial alignment and intimate contact between the vascular tissues of both the scion and the rootstock. Consequently, comparable stem thickness between the two components at the grafting stage is required. Seedlings were grafted using the splice grafting approach described by Johnson *et al*. (2011). Rootstock and scion plants received irrigation 12–24 h prior to the operation, while watering was intentionally withheld immediately before grafting. Because grafting clips were reused, they were carefully washed and sterilized before application. To enhance humidity conditions, the interior walls of the healing chamber were misted several hours ahead of grafting. Cutting was performed with sanitized, sharp razor blades, and frequent hand disinfection was maintained using antibacterial soap or alcohol-based sanitizer.

At the first grafting time, seedlings had reached the two- to four-true-leaf developmental stage, which is considered optimal for grafting success. All grafting operations were conducted during the early morning hours to minimize transpiration rates and limit water stress in freshly grafted plants. During the procedure, each stem was cut at an angle of approximately 45° just beneath the cotyledons using a sharp razor blade. The exposed surfaces of the scion and rootstock were subsequently matched and fastened with a silicone grafting clip to maintain firm and accurate tissue contact.

Post-Grafting Healing and Acclimation of Seedlings: The healing phase for grafted seedlings began immediately after grafting, with the grafting day defined as the first day. After the operation, the healing chamber was kept completely closed, and the seedlings were left untouched for the rest of the first day as well as the entire second day. To facilitate a progressive adjustment to laboratory conditions, the chamber was opened for gradually longer intervals: 5 min on the third day, 30 min on the fourth day, 1 h on the fifth day, 3 h on the sixth day, between 4 and 6 h on the seventh day, and between 6 and 8 h on the eighth day. On the ninth day, seedlings were taken out of the healing chamber at 1:00 PM and relocated to a laboratory bench, where they remained until the conclusion of the experiment. Throughout the nine-day recovery period, air temperature and relative humidity inside the chamber were continuously recorded to maintain conditions conducive to successful graft union development.

Data Analysis: All data were analyzed using analysis of variance (ANOVA) in JMP software (version 11.0 for Windows; SAS Institute, Cary, NC). Homogeneity of variances was evaluated using Levene's test, while normality was assessed with the Shapiro–Wilk test (W > 0.80). Treatment means were separated using the LS Means Student's test at a significance level of $\alpha = 0.05$.

RESULTS

The analysis of variance revealed that crop species, grafting date, and their interaction significantly influenced most of the measured seedling traits (Table 2). Crop species had a highly significant effect on survival percentage ($P = 0.004$), seedling height ($P = 0.003$), stem diameter ($P = 0.004$), number of leaves per plant (P = 0.028), seedling fresh weight ($P = 0.001$), and seedling dry weight ($P = 0.002$), indicating substantial interspecific variability in grafting response.

Grafting date also exerted a significant effect on all evaluated parameters. Survival percentage, seedling height, stem diameter, leaves per plant, fresh weight, and dry weight were all significantly influenced by grafting timing ($P \leq 0.002$), highlighting the critical role of grafting date in determining graft success and subsequent seedling growth.

The interaction between crop species and grafting date was significant for survival percentage ($P = 0.019$), seedling height ($P = 0.036$), stem diameter ($P = 0.032$), and seedling fresh weight ($P = 0.017$), suggesting that the effect of grafting date varied among crop species for these traits. In contrast, the interaction effect was not significant for the number of leaves per plant ($P = 0.433$) and seedling dry weight ($P = 0.11$), indicating a more consistent response across crops and grafting dates for these parameters.

Results in Table 2 demonstrates that crop species and grafting date are major determinants of grafting success and early seedling performance, with significant main and interaction effects observed for most evaluated traits. The significant effect of crop species on survival percentage and growth parameters reflects inherent physiological and anatomical differences among species that influence graft compatibility, vascular reconnection, and post-grafting recovery. Variability in stem diameter, seedling height, and biomass accumulation among crops has been widely attributed to differences in cambial activity, wound-healing capacity, and translocation efficiency following graft union formation.

The strong influence of grafting date on all measured parameters underscores the importance of optimal environmental and developmental conditions at the time of grafting. Grafting performed at appropriate seedling stages likely coincided with favorable stem diameters, active cambial growth, and balanced source–sink relationships, thereby enhancing callus formation and vascular differentiation. Suboptimal grafting dates may have exposed seedlings to physiological stress or developmental asynchrony between scion and rootstock, resulting in reduced survival and suppressed growth. These findings are consistent with previous reports indicating that grafting timing plays a critical role in determining graft union success and subsequent seedling vigor (Hartmann et al., 2011; Han et al., 2025; Wang et al., 2024).

The significant interaction between crop species and grafting date for survival percentage, seedling height, stem diameter, and fresh weight indicates that crop responses to grafting timing are species-dependent. This suggests that optimal grafting windows vary among crops, likely due to differences in growth rate, stem lignification, and sensitivity to environmental conditions. For some crops, delayed or early grafting may disrupt vascular continuity or prolong healing, whereas others may exhibit greater plasticity and tol erance across grafting dates. The absence of a significant interaction effect for leaf number and dry weight suggests that these traits are less sensitive to crop-specific responses to grafting timing and may be more strongly regulated by inherent growth patterns and biomass partitioning mechanisms.

The significant effects observed for fresh weight, but not dry weight, in the crop × grafting date interaction imply that water relations and tissue hydration were more responsive to grafting conditions than structural biomass accumulation. Fresh weight is often influenced by short-term physiological status, including water uptake and transpirational balance, which can be directly affected by graft union functionality during early establishment. In contrast, dry weight accumulation reflects longer-term carbon assimilation and structural growth, which may require extended time beyond the early seedling stage to exhibit pronounced interaction effects.

Overall, the results highlight the necessity of optimizing grafting date according to crop-specific growth dynamics to maximize graft survival and seedling quality. The observed differences emphasize that standardized grafting schedules may not be universally applicable across crops and should be adjusted based on species characteristics and developmental stage. These findings have practical implications for commercial grafted seedling production, as fine-tuning grafting timing can improve uniformity, reduce seedling losses, and enhance early plant vigor.

Table: (2). Overall probability values for crop, grafting date and interaction between them[z].

Treatment	Survival %[y]	Seedling ht (cm)	Steam Diamm (mm)	Leaves/ Plant	Seedling Fresh Wt. (g)	Seedling Dry Wt. (g)
Crop	0.004	0.003	0.004	0.028	0.001	0.002
Grafting Date	0.002	0.001	0.001	0.002	0.002	0.001
Crop × Grafting Date	0.019	0.036	0.032	0.433	0.017	0.11

[z]All data were subjected to analysis of variance using ANOVA in JMP (version 11.0 for Windows; SAS Institute, Cary, NC).[y]Survival was assessed through visual evaluation of scion leaf and stem turgidity using a 0–3 rating scale, where 0 indicated fully turgid leaves and stems, 1 represented more than 50% flaccidity, 2 indicated more than 70% flaccidity, and 3 denoted complete wilting. Only plants assigned a rating of 0 were classified as having survived.

The grafting date significantly influenced the survival rate of eggplant, pepper, and tomato seedlings (P = 0.002, 0.005, P < 0.0001, respectively) (Table 3). For eggplant, the intermediate grafting date resulted in the highest survival rate of 94%, which was significantly higher than both early (82%) and late (80%) grafting dates. Similarly, pepper seedlings exhibited the highest survival rate at the intermediate grafting date (83%), significantly surpassing early (65%) and late (60%) grafting. Tomato plants also showed a superior survival rate of 91% when grafted at the intermediate stage, compared to 78% for early grafting and 73% for late grafting. Moreover, significant differences in seedling height were observed across different grafting dates for all three crops (P = 0.001, 0.003, $P < 0.0001$, respectively). Eggplant seedlings achieved their maximum height of 16.8 cm with intermediate grafting, which was significantly greater than early (14.5 cm) and late (14.1 cm) grafting. Pepper seedlings followed a similar trend, with intermediate grafting yielding the tallest plants at 15.6 cm, compared to 12.8 cm for early grafting and 12.1 cm for late grafting. Tomato seedlings also demonstrated optimal growth in height (18.5 cm) when grafted at the intermediate date, significantly outperforming early (16.2 cm) and late (15.4 cm) grafting.

The stem diameter of eggplant, pepper, and tomato seedlings was significantly affected by the grafting date ($P = 0.003$, 0.017, $P < 0.0001$, respectively). Eggplant exhibited the largest stem diameter of 3.9 mm at the intermediate grafting date, which was significantly thicker than early (3.3 mm) and late (3.1 mm) grafting. Pepper seedlings showed a stem diameter of 2.7 mm with intermediate grafting, which was significantly larger than late grafting (2.3 mm) but not significantly different from early grafting (2.6 mm). Tomato seedlings displayed the thickest stems (3.7 mm) when grafted at the intermediate date, significantly exceeding early (3.1 mm) and late (2.8 mm) grafting. In contrast to the other parameter, the number of leaves per plant for eggplant ($P = 0.224$), pepper ($P = 0.077$), and tomato ($P = 0.119$) did not show statistically significant differences across the different grafting dates. The number of leaves remained relatively consistent regardless of whether grafting occurred early, intermediately, or late.

Overall, tomato and eggplant exhibited better performance than pepper across the evaluated traits. Both crops showed higher survival rates and greater vegetative vigor, as indicated by increased seedling height and stem diameter. In contrast, pepper consistently displayed lower survival and weaker growth characteristics. Differences among crops were less pronounced for the number of leaves per plant, which showed similar values across all three species.

The findings consistently demonstrate that the intermediate grafting date significantly optimizes several key growth parameters across eggplant, pepper, and tomato seedlings, including survival rate, seedling height, and stem diameter. This suggests a critical window for grafting that maximizes plant vigor and establishment. The superior performance observed at the intermediate grafting stage can be attributed to several physiological and environmental factors. At this stage, the rootstock and scion are likely at an optimal developmental phase, characterized by active cambial activity and sufficient carbohydrate reserves, which are crucial for successful graft union formation and subsequent growth (Lee, 2006, Lee *et al*., 2010). Early grafting may expose young, less developed seedlings to stress, which leading to decrease survival rates and reduced growth. Conversely, late grafting could involve more lignified tissues, which are less amenable to successful union formation, or expose the plants to less favorable environmental conditions for establishment, thereby hindering growth and survival (Davis *et al*., 2008).

The significant improvements in survival rate with intermediate grafting highlight its importance for successful crop production. A higher survival rate directly translates to better stand establishment and potentially higher yields. The consistent positive effect across all three Solanaceous crops (eggplant, pepper, and tomato) suggests a general principle that could be applied to other grafted vegetable crops, emphasizing the importance of timing in horticultural practices. Similarly, the enhanced seedling height and stem diameter observed with intermediate grafting indicate a more robust and vigorous plant development. Taller seedlings with thicker stems are generally more resilient to transplant shock and adverse environmental conditions, and they tend to establish faster in the field, leading to earlier and potentially higher yields. This improved vegetative growth is likely a direct consequence of a well-formed graft union that facilitates efficient water and nutrient uptake from the rootstock to the scion, promoting overall plant development. Interestingly, the number of leaves per plant did not show significant variation across different grafting dates for any of the tested crops. This suggests that while grafting date profoundly impacts survival and overall plant architecture (height and stem diameter), the initiation and development of leaves might be less sensitive to the timing of the grafting process within the tested range. It is possible that leaf development is more genetically predetermined or influenced by factors other than the immediate success of the graft union, such as overall photosynthetic capacity or nutrient availability that might not be differentially affected by grafting date in terms of leaf count. In conclusion, the results underscore the critical role of grafting date in optimizing the early growth and establishment of grafted eggplant, pepper, and tomato seedlings. The intermediate grafting date consistently provided the most favorable conditions for survival, height, and stem diameter, indicating a balance between seedling maturity and environmental suitability. Future research could explore the specific physiological mechanisms underlying these observations, such as hormone signaling and gene expression patterns during graft union formation at different developmental stages.

The grafting date significantly influenced the seedling fresh weight of eggplant, pepper, and tomato (P = 0.009, 0.016, 0.037, respectively) (Table 4). For eggplant, the intermediate grafting date yielded the highest fresh weight of 9.6 g, which was significantly greater than both early (7.4 g) and late (7.0 g) grafting dates. Similarly, pepper seedlings exhibited the highest fresh weight at the intermediate grafting date (6.5 g), significantly surpassing early (4.9 g) and late (4.6 g) grafting. Tomato plants also showed a superior fresh weight of 8.9 g when grafted at the intermediate stage, compared to 6.6 g for early grafting and 6.3 g for late grafting. In addition, significant differences in seedling dry weight were observed across different grafting dates for all three crops (P = 0.007, 0.004, 0.002, respectively). Eggplant seedlings achieved their maximum dry weight of 1.22 g with intermediate grafting, which was significantly greater than early (0.94 g) and late (0.69 g) grafting. Pepper seedlings followed a similar trend, with intermediate grafting yielding the highest dry weight at 0.77 g, compared to 0.52 g for both early and late grafting. Tomato seedlings also demonstrated optimal dry weight (1.14 g) when grafted at the intermediate date, significantly outperforming early (0.83 g) and late (0.69 g) grafting.

Table: (3). Effect of grafting date on survival rate, seedling height, stem diameter, and Leaves/ Plant of eggplant, pepper, and tomato.

Crop^{z}	Grafting Date			
	Survival Rate			
	Early Grafting Date	Intermediate Grafting Date	Late grafting Date	*P*- values
Eggplant	82 b^{y}	94 a	80 b	0.002
Pepper	65 b	83 a	60 c	0.005
Tomato	78 b	91 a	73 c	<0.0001
	Seedling Height (cm)			
Eggplant	14.5 b	16.8 a	14.1 b	0.001
Pepper	12.8 b	15.6 a	12.1 b	0.003
Tomato	16. 2 b	18.5 a	15.4 c	<0.0001
	Steam Diameter (mm)			
Eggplant	3.3 b	3.9 b	3.1 b	0.003
Pepper	2.6 a	2.7 a	2.3 b	0.017
Tomato	3.1 b	3.7 a	2.8 c	<0.0001
	Leaves/ Plant			
Eggplant	3.1	3.3	3.2	0.224
Pepper	2.9	3.0	2.9	0.077
Tomato	3.2	3.3	3.3	0.119

^{z}All data were subjected to analysis of variance using ANOVA in JMP (version 11.0 for Windows; SAS Institute, Cary, NC).^{y}Means followed by a different letter within sampling date are significantly different at P < 0.05.

Eggplant exhibited the highest seedling biomass, recording greater fresh and dry weights compared with tomato and pepper. Tomato showed intermediate biomass accumulation, whereas pepper consistently had the lowest fresh and dry weights among the three crops. These results indicate that eggplant had the strongest biomass development during the seedling stage, followed by tomato, while pepper showed comparatively weaker growth performance.

The consistent observation that the intermediate grafting date significantly enhanced both seedling fresh and dry weights across eggplant, pepper, and tomato aligns with the findings for survival rate, seedling height, and stem diameter from previous analyses. This robust pattern underscores the critical importance of optimal timing in the grafting process for promoting vigorous early plant growth. The increased fresh and dry biomass at the intermediate grafting stage suggests a more efficient physiological integration between the rootstock and scion, leading to superior resource acquisition and utilization.

Fresh weight is a direct indicator of water content and overall plant size, while dry weight reflects the accumulation of organic matter through photosynthesis and nutrient uptake. The simultaneous increase in both parameters at the intermediate grafting date implies that these seedlings are not only larger but also possess a greater accumulation of structural and metabolic compounds. This enhanced biomass production is crucial for successful transplanting and rapid establishment in the field, as seedlings with higher fresh and dry weights typically have better reserves to cope with environmental stresses and initiate faster growth post-transplant.

The reduced fresh and dry weights observed in early and late grafting dates, particularly in late grafting, could be attributed to several factors. Early grafting might occur when the seedlings are too immature, lacking sufficient physiological development or carbohydrate reserves to support the stress of grafting and subsequent growth. Conversely, late grafting might involve more mature, lignified tissues that are less conducive to forming a strong and efficient graft union, thereby impeding the transport of water and nutrients essential for biomass accumulation. Furthermore, environmental conditions at very early or very late grafting dates might be less favorable for rapid growth and establishment compared to the intermediate period.

These results collectively reinforce the concept of a critical developmental window for grafting, where the physiological state of both the rootstock and scion, coupled with conducive environmental conditions, maximizes the benefits of grafting. The enhanced fresh and dry weights are indicative of a healthier, more robust seedling, which is a prerequisite for improved yield and quality in grafted vegetable production systems. Future research could delve into the biochemical and molecular mechanisms underlying the superior biomass accumulation at the intermediate grafting stage, such as gene expression related to photosynthesis, nutrient transport, and stress response.

Table: (4). Effect of Grafting Date on Seedling Fresh and Dry Weight of Eggplant, Pepper, and Tomato.

	Grafting Date[z]			
	Seedling Fresh Wt. (g)			
Crop	Early Grafting Date	Intermediate Grafting Date	Late grafting Date	*P*- values
Eggplant	7.4 b[y]	9.6 a	7.0 b	0.009
Pepper	4.9 b	6.5 a	4.6 b	0.016
Tomato	6.6 b	8.9 a	6.3 c	0.037
	Seedling Dry Wt. (g)			
Eggplant	0.94 b	1.22 a	0.69 c	0.007
Pepper	0.52 b	0.77 a	0.52 b	0.004
Tomato	0.83 b	1.14 a	0.69 c	0.002

[z]All data were subjected to analysis of variance using ANOVA in JMP (version 11.0 for Windows; SAS Institute, Cary, NC).[y]Means followed by a different letter within sampling date are significantly different at $P < 0.05$.

CONCLUSION

The present study clearly demonstrates that grafting success and early seedling performance of eggplant, pepper, and tomato are strongly governed by both crop species and grafting date, with the intermediate grafting stage consistently providing the most favorable outcomes. Significant main and interaction effects indicate that grafting responses are species-dependent and highly sensitive to timing, reflecting underlying physiological and anatomical differences among crops. Across all evaluated traits, including survival percentage, seedling height, stem diameter, and biomass accumulation, the intermediate grafting date resulted in superior seedling vigor, indicating the existence of an optimal developmental window in which cambial activity, carbohydrate availability, and vascular reconnection are maximized. In contrast, early grafting likely exposed physiologically immature seedlings to stress, while late grafting involved more lignified tissues with reduced graft union efficiency. The consistent enhancement of both fresh and dry weights at the intermediate stage further underscores improved water relations, nutrient transport, and assimilate partitioning following successful graft union formation. Collectively, these findings highlight the necessity of tailoring grafting schedules to crop-specific growth dynamics rather than adopting uniform practices. Optimizing grafting date is therefore a critical management strategy for improving survival, uniformity, and quality of grafted seedlings, with direct implications for efficient commercial seedling production and improved field establishment in solanaceous vegetable crops.

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Author contributions: Fayrouz Buojaylah conceived and designed the study, analyzed the data, and drafted the manuscript. Alsunousi Masoud contributed to the study design and data collection. Fatma Mohamed participated in data collection. All authors approved the final manuscript.

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