

Determinate and indeterminate tomatoes also differ in how density should be optimized across seasons and systems. For determinate cultivars in a closed hydroponic gravel-film system, spring/summer marketable yield improved at 20~25 plants/m², whereas in summer/fall 10 plants/m² was more cost-effective because higher density no longer increased yield under lower radiation. In a spring film greenhouse, the indeterminate hybrid Tobolsk F1 reached maximum yield at 3.5 plants/m², consistent with breeder recommendations centered around 2.5~3.5 plants/m² for indeterminate types under those conditions (Sievidov and Sievidov, 2020). Under summer heat in NFT hydroponics, cultivar choice also determined whether high density was useful: the heat-tolerant cultivar benefited from denser planting, while Jaguar was uneconomical because blossom end rot sharply reduced marketable yield (Ayarna et al., 2021). In organically grown hydroponic tomato under abiotic stress, grafted 'Velocity F1' at 3.5 plants/m² outperformed the denser 5.5 plants/m² treatment, showing that the optimum for vigorous indeterminate material under stress can shift downward rather than upward (Figure 3) (Dash et al., 2023).

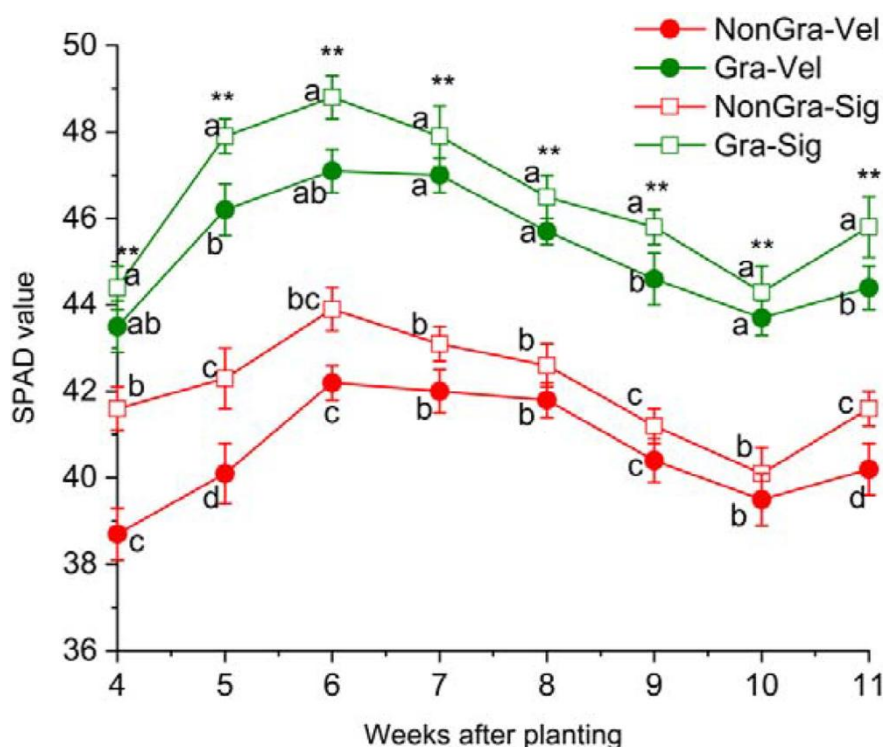


Figure 3 Effect of grafting and cultivar on the soil plant analysis development value of tomato (Adopted from Dash et al., 2023)

Image caption: Vertical bar represents the SE; Dissimilar letters on the line graph show statistical differences, the same letters show statistical similarities according to Tukey's honest significant difference test at $P < 0.05$. NonGra-Vel=nongrafted 'Velocity F1'; Gra-Vel=grafted 'Velocity F1'; NonGra-Sig=non-grafted 'Sigma F1'; Gra-Sig=grafted 'Sigma F1'; Significant at $P < 0.01$ (Adopted from Dash et al., 2023)

5.2 Density optimization strategies under protected cultivation conditions

Under protected cultivation, density optimization is best treated as a balance between maximizing yield per area and avoiding the fruit-size, quality, and stress penalties of chronic overcrowding (Caradonia et al., 2023; Karpe et al., 2024). In greenhouse soilless culture in Golestan, increasing density to 3.5 plants/m² increased yield per square meter in all three hybrids tested, supporting denser planting than the commonly used 2~2.5 plants/m² (Dash et al., 2023). In a separate hydroponic greenhouse study, the highest total yield, 22.61 kg/m², was obtained at 11.1 plants/m² with two bunches per plant, showing that optimal density in protected systems depends on pruning intensity and planned sink load as well as spacing itself (Cardoso et al., 2018). In spring film-greenhouse production, 3.5 plants/m² was likewise optimal for Tobolsk F1, while in closed hydroponic determinate tomato the best density shifted with season because high density was less beneficial under shorter days and lower radiation (Sievidov and Sievidov, 2020).