

significant density $\times$ nitrogen interaction for fruit volume and fruit weight, confirming that density recommendations should be linked to fertilizer regime rather than chosen independently (Aminifard et al., 2012).

Recent irrigation studies reinforce that the best density is the one matched to a specific water-delivery system. Under automated protected cultivation, sensor-based irrigation at 75% available soil moisture combined with 125% recommended fertilizer produced 60,089 kg/ha and the highest water and nutrient use efficiencies (Ningoji et al., 2024). In precision-fertigated chili pepper, higher densities up to 106,666 plants/ha increased total yield and improved WUE, NUE, and PUE, but double drip lines raised yield while reducing water use efficiency, showing that irrigation layout can shift the agronomic optimum for density (Susila et al., 2025).

6.3 Precision technologies

Precision agriculture offers a way to regulate planting density more dynamically by linking stand establishment, canopy monitoring, and input delivery to spatial variability within the crop. In greenhouse pepper, sensor networks and machine-learning-based control systems are being developed to improve decision-making, resource use, and sustainability, while fertigation regimes tailored to crop response already improve productivity under monitored microclimate conditions (Fadare et al., 2025). More broadly in vegetable systems, integrating weather stations, soil sensors, and remote sensing into decision-support systems helps farmers evaluate crop growth, yield potential, and resource use, which is directly relevant for refining density management over time (Chaudhari et al., 2024).

Remote sensing and automation are especially useful for translating density management from fixed spacing recommendations into site-specific regulation. Remote sensing in precision agriculture supports crop monitoring, irrigation management, nutrient application, and yield prediction, and UAV platforms are increasingly favored because they provide high-resolution imagery needed for practical management decisions (Sishodia et al., 2020). In parallel, automated seeding and transplanting systems can improve the uniformity of plant spacing and reduce labor costs, which makes them a practical tool for achieving target pepper populations more accurately than manual establishment (Chaudhari et al., 2024).

7 Case Study: Effects of Different Planting Densities on Pepper Yield Formation

7.1 Experimental background and planting density treatments

Pepper density case studies have been conducted across open-field, greenhouse, protected organic, and soilless production systems, and they consistently use multi-level density gradients to quantify how stand structure affects yield formation. In protected organic sweet pepper, experiments compared three genotypes at 2, 4, 6, and 8 plants/m² in a duplicated randomized complete block design, while bell pepper trials in Canada tested 1.4, 1.9, 2.8, 5.6, and 11.1 plants/m² under mulch and row-cover conditions to capture both density and microenvironment effects (Silva et al., 2021). These designs are useful as case-study models because they span both moderate and very high densities and therefore allow identification of the point where greater land occupancy ceases to improve biological or commercial performance.

Other studies show that density treatments are also shaped by establishment method and local production practice. In field-grown sweet pepper, four spacing combinations—20 $\times$ 50, 30 $\times$ 50, 20 $\times$ 100, and 30 $\times$ 100 cm—were combined with nitrogen treatments, whereas direct-seeded paprika pepper was thinned to a very broad density range from 13,333 to more than 500,000 plants/ha, enabling evaluation of both yield and color responses under commercial-scale plant populations (Figure 2) (Aminifard et al., 2012). Together, these case studies show that meaningful density evaluation in pepper requires treatment ranges wide enough to detect not only yield increases at low-to-moderate crowding but also the threshold where competition begins to offset further gains.

7.2 Responses of growth characteristics and yield components

Across case studies, increasing planting density generally shifts pepper growth toward greater population productivity but weaker individual plant performance. In sweet pepper, higher density reduced vegetative and reproductive traits at the plant level, including lateral stem number, leaf dry matter, fruit volume, fruit weight, and yield per plant, even though total yield per hectare increased (Aminifard et al., 2012). A similar pattern was