*Plant Archives* Vol. 26, No. 2, 2026 pp. 3327-3341 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.2.462

# ADVANCES IN VEGETABLE NURSERY MANAGEMENT: FROM CONVENTIONAL SEEDBEDS TO SUSTAINABLE, TECHNOLOGY-DRIVEN TRANSPLANT PRODUCTION: A REVIEW

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(Date of Receiving-06-08-2026; Date of Revision-21-10-2026; Date of Acceptance-25-10-2026)

**ABSTRACT**

The quality of planting material has a significant impact on crop establishment, early development, uniformity, productivity and resource-use efficiency, making vegetable nursery management essential to effective vegetable production. Conventional soil-based seedbeds have given way to enclosed and containerised systems that offer more control over the rooting environment, water, nutrients, temperature, humidity, and light in modern nursery production. With a focus on seed quality, seed treatment, nursery architecture, plug-tray systems, growing media, sowing techniques, and early seedling establishment, this paper provides an overview of recent developments in vegetable crop nursery management. Additionally included are the effects of crop scheduling, hardening, watering, fertigation, seedling density, and environmental control on the production of robust and transplant-ready seedlings. Advanced technologies such as seed priming, biostimulants, beneficial microbes, vegetable grafting, controlled-environment production and light-emitting diode (LED) technology receive special attention. Sustainable seedling production emphasises the importance of integrated nursery health management through biological control, pest and disease monitoring, sanitation and suitable environmental management. This review also discusses new strategies for minimising plastic waste, increasing the efficiency of water and fertilizer use, lowering reliance on peat-based substrates and using automation, sensors and precision technology in nursery operations. The high initial cost, technical requirements, availability of substrate, energy consumption and demand for crop-specific management protocols limit the use of new nursery technologies, despite the fact that they can enhance seedling quality and production efficiency. Therefore, precision environmental control, sustainable growing media, biological inputs, effective resource usage and digital technology should all be incorporated into future vegetable nursery systems. In addition to increasing the economic and environmental sustainability of vegetable production systems, such integrated approaches can help produce healthy, consistent and stress-resilient seedlings.

***Key words :*** Seedling quality, Growing media, Seedling growth management, Grafted seedlings, LED lighting, Biostimulants.

## Introduction

**Importance of Nursery and Transplant Quality:** Vegetable production contributes substantially to food supply and farm income because vegetables combine high nutritional value with relatively short production periods. In commercial as well as small-scale production, however,

successful crop establishment depends greatly on the quality of the planting material. Many vegetable crops, including tomato, chilli, brinjal, cabbage, cauliflower, broccoli, lettuce, and cucurbits, are therefore raised under nursery conditions before they are transferred to the field. Raising seedlings in a nursery allows growers to manage important factors such as irrigation, nutrition, temperature, light, and plant health during the early stages of growth (Vavrina, 1998). This controlled approach can promote uniform establishment and reduce the risks associated with direct field establishment, making nursery production an increasingly important component of intensive vegetable cultivation (Balliu *et al*., 2017; Gallegos-Cedillo *et al*., 2024). A successful transplant is more than simply a seedling that has reached a suitable size. Its subsequent performance is influenced by root development, stem strength, shoot growth, leaf formation, plant compactness, and its ability to recover from transplanting stress. These characteristics develop through the interaction of genetic potential with nursery conditions and management practices. Factors such as the growing medium, container volume, irrigation and fertilisation, temperature, seedling age, and hardening practices can consequently affect transplant quality. Balliu *et al*. (2017) highlighted the importance of considering nursery practices as an interacting system rather than evaluating individual factors in isolation. Seedling age is also important, although the appropriate transplant stage differs among crops and depends on the physiological condition of the seedlings (Vavrina, 1998). Thus, producing vigorous and uniform transplants requires careful coordination of several nursery practices.

**Technological shift**

Technological advancements have transformed vegetable nursery production from conventional, labour-intensive practices towards more precise, efficient, and controlled production systems. The adoption of plug-tray technology has enabled the production of uniform and healthy seedlings within limited nursery space by providing individual rooting environments and better control over water and nutrient availability. Precision sowing, automated tray filling, and mechanised transplant handling have further improved sowing uniformity, labour efficiency, and production accuracy in commercial nurseries (Liu *et al*., 2023; Jadhav *et al*., 2025). At the same time, the use of soilless and partially soilless growing media has provided greater control over the physical and chemical properties of the root-zone environment, while increasing interest in renewable materials such as coconut coir, compost and wood fibre has supported the development of more sustainable nursery systems (Pascual *et al*., 2018; Gruda and Fernández, 2022). Protected nursery structures and controlled-environment technologies have also improved the management of temperature, humidity, light, irrigation, and nutrition, thereby enabling more consistent seedling production throughout the year. Recent developments increasingly combine these technologies with LED lighting, grafting, seed enhancement, biostimulants and beneficial microorganisms to improve transplant quality and resource-use efficiency (Gallegos-Cedillo *et al*., 2024a).

**Plug-Tray technology and Growing Media**

The introduction of plug-tray technology has brought major changes to vegetable seedling production. Individual cells provide a defined rooting space for each seedling and allow a large number of relatively uniform plants to be produced in a limited area. Cell size and container design influence root development, water and nutrient availability and the length of time seedlings can remain in the nursery. Precision sowing, automated tray filling, and mechanised handling have further improved the uniformity and efficiency of commercial transplant production (Liu *et al*., 2023; Jadhav *et al*., 2025). Growing media are equally important because they provide physical support to the seedlings while regulating the availability of water, oxygen, and nutrients around the roots. The increasing use of soilless and partially soilless substrates has provided greater control over the root-zone environment compared with conventional soil-based nursery systems. Although peat remains an important component of many commercial substrates, environmental concerns associated with peat extraction have encouraged research into alternative materials such as coconut coir, compost, and wood fibre (Pascual *et al*., 2018; Gruda and Fernández, 2022). The use of sustainable growing media is therefore receiving increasing attention in modern vegetable nursery production (Gallegos-Cedillo *et al*., 2024a).

**Seed enhancement and Early Seedling establishment**

Good nursery production also begins with high-quality seed and uniform emergence. Poor germination or uneven emergence cannot always be corrected through subsequent nursery management, making seed treatment an important part of early crop establishment. Seed priming has received considerable attention because of its potential to improve germination, emergence uniformity, and seedling vigour. Different approaches, including hydropriming, osmopriming, halopriming, nutripriming, and biopriming, have been investigated in vegetable crops. Thakur *et al*. (2022) reviewed the recent developments

in seed priming and highlighted its potential for improving the planting value of vegetable seeds. Seed enhancement can also be combined with beneficial microorganisms to support early plant establishment and improve seedling performance (Rocha *et al*., 2019; Zulfiqar, 2021).

**Protected Nursery Conditions, Grafting and Sustainable production**

Protected nursery structures allow environmental conditions affecting seedling growth to be managed more effectively. Temperature, relative humidity, light intensity, photoperiod, irrigation and nutrient availability all influence seedling architecture and physiological development. Excessive temperature and humidity may favour disease development and produce weak growth, whereas inadequate light can result in elongated and poorly developed seedlings. For this reason, greater attention is being given to microclimate management, supplemental LED lighting and controlled-environment production. Grafting has also become an important technology in vegetable transplant production, particularly for solanaceous and cucurbit crops. By combining a desirable scion with a vigorous rootstock, grafted plants can show improved tolerance to soil-borne diseases, abiotic stresses, and unfavourable root-zone conditions. Advances in grafting techniques and their mechanisation have contributed to the wider use of grafted transplants in commercial production (Lee *et al.*, 2010).

Biostimulants and beneficial microorganisms are additional approaches being explored to improve transplant quality. Beneficial fungi, microbial inoculants, and plant-derived protein hydrolysates can influence root development, nutrient uptake, and seedling vigour. Plant-derived protein hydrolysate-based biostimulants, in particular, have been shown to improve the growth, mineral accumulation, and quality characteristics of vegetable transplants (Rouphael *et al*., 2021). At the same time, modern nurseries are under increasing pressure to reduce water consumption, substrate use, plastic waste, chemical inputs and energy requirements. A recent analysis of 604 publications identified seed-tray design, seed enhancement, controlled-environment conditions, sustainable growing media, grafting, LED lighting, biostimulants, and beneficial microorganisms as important research areas in sustainable vegetable nursery production (Gallegos-Cedillo *et al*., 2024b).

These developments show that vegetable nursery production is no longer limited to raising seedlings before field planting; it has become an integrated production system in which seed quality, nursery environment, growing media, propagation technologies, plant health, and resource efficiency are closely interconnected. Accordingly, this review examines the major principles and recent developments in vegetable nursery management, with particular emphasis on nursery establishment, seedling production, environmental and nutritional management, advanced propagation technologies, plant health, seedling quality, and sustainable production practices.

**Nursery establishment and Seedling production**

The systematic integration of high-quality seeds, adequate nursery infrastructure, suitable containers, growing media, and accurate sowing techniques is essential for successful vegetable nursery production. Before being moved to the main field, the nursery environment offers young seedlings ideal conditions for germination, root development and early vegetative growth. In addition to reducing transplant shock and increasing later crop establishment and yield, proper treatment during this stage can also improve seedling uniformity. In order to efficiently produce consistent and healthy planting material, modern nursery systems are increasingly combining covered structures, plug trays, soilless substrates, and precision sowing (Balliu *et al*., 2017).

**Seed quality and Seed treatment**

The selection of high-quality seed is the first step in successful nursery production, as germination, emergence uniformity and early seedling vigour directly influence transplant quality. Nursery raising is widely used for crops such as tomato, chilli, capsicum, brinjal, cabbage, cauliflower, broccoli and onion, while selected cucurbit crops are also raised as transplants depending on the production system. Healthy seed with good germination, physiological vigour, genetic purity and freedom from seed-borne pathogens is therefore essential for obtaining a uniform nursery stand. This is particularly important with hybrid seeds, which are relatively costly and make efficient seed utilisation important, especially in crops such as tomato, brinjal, capsicum and cucurbits (Chaurasia *et al*., 2023). In commercial nurseries, uniform seed size and shape are also desirable because they facilitate precise sowing and more uniform seedling development. Seed treatment is commonly used to protect emerging seedlings from seed- and soil-borne pathogens and to support early establishment. Depending on the crop and production system, treatments may include chemical, physical and biological approaches, along with seed coating, pelleting and priming. Seed coating can also deliver protective or growth-promoting substances such as micronutrients and beneficial microorganisms. Such seed enhancement

approaches have been investigated in vegetables including tomato, pepper, onion and cucumber to improve seed handling, germination and early seedling performance (Gallegos-Cedillo *et al*., 2024).

**Nursery structures and Tray systems**

In the delicate early phases of vegetable development, nursery structures offer a regulated environment. Seedlings can be raised in open nurseries, shade-net houses, naturally ventilated polyhouses, insect-proof net houses (40-50 mesh), or fully controlled greenhouses, depending on the climate and production goals. In addition to lowering exposure to severe rainfall, wind and temperature swings, protected structures can help improve irrigation management and plant protection. Crop, season, local climate and production scale should all be taken into consideration while selecting a structure. Because lowering vector access can assist reduce disease pressure, insect-proof structures are especially helpful for crops vulnerable to viruses spread by insects. In protected nurseries, adequate ventilation is crucial since high humidity can encourage damping-off and other illnesses. Benches or elevated platforms can enhance air circulation and lessen direct contact between containers and contaminated surfaces, and nursery floors should have sufficient drainage. Because they enable individual seedlings to grow in distinct rooting cells, plug trays have grown in importance within commercial vegetable nurseries. This makes it possible to generate a large number of seedlings in a comparatively small area and lessens root damage when transplanting. For cucurbit crops, where traditional bare-root nursery production might result in significant root disruption during transplanting, plug-tray nursery technique has been effectively applied in India (Singh *et al*., 2007a). Vigorous cucurbit seedlings for off-season culture have also been made possible by the use of cocopeat, vermiculite, and perlite in plug trays. Nursery performance is significantly influenced by cell shape and volume. Smaller cells boost production density and minimise substrate requirements, but they may inhibit root growth when seedlings remain in the nursery for lengthy durations. (Singh *et al*., 2007b) showed that the quality of tomato seedlings grown in soilless media can be affected by both cell size and shape. Instead of choosing trays only based on the number of cells per tray, their approach emphasised the significance of matching tray shape with crop requirements. Root architecture can also be influenced by container design. In their evaluation of various container geometries for tomatoes, peppers, and cucumbers, (Gallegos *et al*., 2020) discovered that containers with internal vertical walls reduced mechanical issues related to root spiralling while increasing root surface and biomass. Therefore, root formation and post-transplant adaptability may be enhanced by such designs. Another significant advancement is the mechanization of nursery sowing. Placing individual seeds by hand requires a lot of effort, especially at times when nursery production is at its highest. Precision sowing has the ability to increase nursery capacity while lowering labour needs. Gaikwad and Sirohi (2008) designed a low-cost pneumatic plug-tray seeder for tomato and capsicum and reported more than 90% single-seed placement under appropriate operating circumstances.

**Growing Media and substrates**

The growth medium regulates the availability of water, air, and nutrients surrounding the root system while also giving the growing seedling mechanical support. Sufficient water-holding capacity, air-filled porosity, drainage, low bulk density, proper pH, optimum electrical conductivity and adequate structural stability are all desirable characteristics of a nursery substrate. It should also be devoid of important plant diseases, phytotoxic substances and weed seeds. Due to its advantageous physical characteristics and generally consistent performance, peat has long been utilized extensively in commercial vegetable nurseries. However, significant study into alternative substrates has been prompted by environmental issues associated with peat exploitation. Because substitute materials can differ in porosity, water retention, bulk density, nutritional content, and biological stability, replacing peat is technically difficult (Ceglie *et al*., 2015). Thus, a lot of attention has been paid to coconut coir, compost, wood-derived materials, vermicompost, bark, rice husk, and processed agricultural residues. Due to its physical, chemical, and biological characteristics that are pertinent to nursery production, coir dust has been assessed as a growing-medium component (Prasad, 1997). Their appropriateness is determined not only by the material itself, but also by how much of it is added to the finished substrate. For instance, (Abdel-Razzak *et al*., 2019) discovered that adding very small amounts of compost made from tomato waste to peat-vermiculite combinations enhanced seedling morphology and germination in tomato, pepper, cucumber and summer squash. However, higher proportions weren't always better, highlighting the need of substrate composition optimisation. Another possible alternative to peat is spent mushroom substrate. In their evaluation of weathered spent mushroom substrate (SMS) for tomato and cucumber seedling production (Zhang *et al*., 2012) discovered that, when compared to the traditional peat–perlite control, certain combinations containing vermiculite

**Table 1 :** Major growing media used for vegetable seedling production.

| Growing medium | Major characteristics | Potential advantages | Important considerations |
|---|---|---|---|
| **Peat** | High water-holding capacity and good porosity | Uniform and widely standardized | Sustainability concerns and cost |
| **Cocopeat/Coir** | Lightweight, porous and renewable | Good aeration and water retention | High Na and K – requires washing and calcium buffering |
| **Perlite** | Lightweight and highly porous | Improves drainage and aeration | Low nutrient-holding capacity |
| **Vermiculite** | High water and nutrient retention | Useful for germination and early growth | Excessive proportions may reduce aeration |
| **Green-waste compost** | Nutrient-rich organic material | Recycles organic residues | Maturity and EC must be monitored |
| **Tomato-waste compost** | Nutrient-containing organic residue | Partial peat replacement possible | Optimum proportion is crop dependent |
| **Spent mushroom substrate** | Organic and relatively porous | Potential peat substitute | Composition varies with source |
| **Wood/bark-based materials** | Fibrous and structurally stable | Can reduce peat dependence | Nitrogen immobilization may occur |
| **Rice husk/rice-husk compost** | Lightweight and locally available | Improves aeration and recycling | Physical properties vary with processing |
| **Vermicompost** | Nutrient-rich and biologically active | Can improve seedling growth at suitable rates | Excessive proportions may increase EC |
| **Mixed substrates** | Combination of complementary materials | Allows optimization of water, air and nutrients | Requires formulation and quality testing |

**Source:** Compiled from Barrett *et al.* (2016), Pascual *et al.* (2018) and Abdel-Razzak *et al.* (2019)". Rows on spent mushroom substrate, green-waste compost, wood/bark and rice husk are based on Zhang *et al.* (2012), Meng *et al.* (2018), St. Martin *et al.* (2014) and Tietjen *et al.* (2022).

or perlite provided excellent or better seedling growth. Circular nursery production can also benefit from composted industrial and agricultural waste (Meng *et al*., 2018). Assessed spent mushroom substrate (SMS) and composted biogas residue (digestate) as growth media for tomato and pepper seedlings. Although variations in pH, electrical conductivity, porosity, and nutrient availability showed the need for careful formulation, certain compost-based combinations provided seedling development that was either equal to or better than peat-based controls. Compost stability and maturity are especially crucial. After being incorporated into the substrate, immature compost may include phytotoxic chemicals or undergo microbial breakdown, which could immobilise nutrients. When evaluating green-waste composts as substrates for tomato and sweet pepper seedlings, (St. Martin *et al.*, 2014) stressed the significance of determining compost maturity. Instead of finding a single, all-purpose peat substitute, more recent methods have concentrated on optimising mixes. (Tietjen *et al.*, 2022) showed that mixes of green compost, bark compost, sawdust, and rice husks may significantly reduce peat in press-pot substrates, however nitrogen immobilization had to be taken into account. When comparing commercially available and farm-prepared substrates for organic seedling culture, (Divéky-Ertsey *et al.*, 2022) equally emphasised the significance of physical and chemical substrate features. Additionally, formulations created especially for mechanised transplanting have been the focus of recent substrate research. According to Han *et al.* (2022), the proper addition of peat-based materials to regional nursery soils enhanced root-lump strength and seedling growth, two traits crucial for automated handling and transplanting. In order to replace peat in transplant production, other organic materials, such as compost made from Posidonia, have also been studied (Parente *et al.*, 2014).

### Sowing and Seedling establishment

After filling the tray and preparing the substrate, seeds should be evenly distributed within each cell and coated with the proper amount of fine substrate. Inadequate aeration can hinder germination and raise the risk of seedling infection. Therefore, the substrate should

be sufficiently moist during planting but not stay saturated. In order for seedlings to emerge within a limited time window, the sowing technique should result in uniform spacing and depth. During germination, water management should be consistent and mild. Without displacing seeds or compacting the surface, moisture can be maintained using a fine mist or appropriate overhead irrigation. Irrigation should be modified based on crop, substrate, weather and seedling progress after emergence. While insufficient moisture might result in uneven emergence and poor establishment, excessive watering can lower the amount of oxygen available in the root zone. According to recent nursery research, good establishment depends more and more on combining substrate management, tray design, and seed quality rather than handling each element separately. Global research trends show that in contemporary vegetable transplant production, seed improvement, tray design, and regulated environmental conditions are closely related (Gallegos-Cedillo *et al*., 2024).

**Seedling Growth management**

Environmental factors, water availability, nutrient supply, plant density and developmental stage all interact to control seedling growth in the nursery. For compact, robust and physiologically balanced transplants that can quickly establish following field planting, proper treatment during this time is crucial. Weak, elongated, or poorly rooted seedlings can be caused by excessive irrigation, nutrient imbalance, insufficient light, or an unsuitable temperature. Thus, while preserving a suitable root-to-shoot balance and transplanting quality, nursery management should strive for slow, steady and comparatively stress-free growth (Balliu *et al*., 2017).

**Temperature, Humidity and Light**

One of the main environmental variables influencing biomass buildup, leaf expansion, root development, and seed germination is temperature (Park *et al*., 2022). Plant morphology and physiological activity can be significantly altered by departures from the typical temperature range for each vegetable crop's ideal seedling growth. Cool-season crops like cabbage, cauliflower, broccoli and lettuce typically demand colder nursery conditions than warm-season vegetables like tomato, pepper, eggplant, cucumber and melon. Large temperature swings should be avoided if feasible since they may also result in uneven growth. Because seedlings need enough radiation for photosynthesis and optimal development, light availability is equally crucial. Reduced biomass, weak tissues, and excessive stem elongation can all result from insufficient light (Gallegos-Cedillo *et al*., 2024). Both light intensity and spectral composition can be adjusted with controlled lighting. Modifying LED light conditions can affect seedling morphology and subsequent development after transplanting, according to research on tomatoes and cucumbers (Liu *et al*., 2023). For controlled nursery production, light should be evaluated using photosynthetic photon flux density (PPFD), daily light integral (DLI) and photoperiod rather than light intensity alone. Across studies on vegetable seedlings, PPFD values of approximately 145–200 µmol $m^{-2}$ $s^{-1}$ and photoperiods of 12–18 h $day^{-1}$ are frequently reported, although the optimum combination varies with crop and developmental stage (Gallegos-Cedillo *et al*., 2024). The cucumber seedlings' development and physiological traits have also been demonstrated to be impacted by LED spectral composition (Hamedalla *et al*., 2022). Crop-specific responses to light quality vary. According to Javanmardi and Emami (2013), tomato and pepper transplants' stem diameter, plant height, leaf growth and eventual productivity were all impacted by combinations of red and blue LED light. Far-red-enriched LED lighting has also been studied more recently as a way to regulate the morphology of seedlings in a number of vegetable crops (Hwang *et al*., 2020). These results suggest that light management can be utilised to control transplant quality and plant architecture in addition to increasing biomass.

**Irrigation and Fertigation**

For seedlings to continue growing, water control is essential. Sufficient moisture is needed for seed imbibition and germination right after sowing, but too much water might lower the substrate's oxygen availability and raise the possibility of damping-off. Plant size, substrate properties, radiation, temperature and atmospheric demand should all be taken into consideration while adjusting irrigation as seedlings grow. Because individual cells in plug trays have very small amounts of substrate and might dry quickly, uniform watering is especially crucial. In addition, excessive irrigation may result in poorly aerated root-zone conditions and nutrient leaching. In controlled nursery systems, the relationship between light and nutrient content is very crucial. Both LED light spectrum and nutritional solution strength have an impact on plant growth, photosynthetic parameters, and nutrient uptake in tomato seedlings, according to recent research, underscoring the necessity of controlling these variables jointly rather than separately (Nasiri *et al*., 2025). More generally, in vegetable production systems, precise fertigation can decrease needless fertiliser losses while increasing nutrient-use efficiency (Das *et al*., 2026).

**Seedling Density and Crop scheduling**

The quantity of light, water, and nutrients accessible to individual plants is determined by seedling density. Although high-density production produces more seedlings per unit nursery area, it may lead to higher stem elongation and competition for light. Although low density increases the amount of infrastructure and substrate needed for each seedling, it typically offers more room for individual plant development (Gallegos-Cedillo *et al*., 2024). Crop species, tray geometry, production duration and environmental factors all affect the ideal density. When light becomes scarce, closely spaced seedlings may produce weaker stems and smaller leaves (Singh *et al*., 2007a). Therefore, maintaining consistent canopy development and lowering excessive humidity around plants require enough spacing. Because seedlings must reach the proper physiological stage by the planned field-transplanting date, crop timing is equally crucial. While very early seedlings may have inadequate reserves and underdeveloped root systems, older seedlings may become root-restricted and too elongated. Crop-specific timetables that coordinate sowing date, nursery length, environmental conditions, and anticipated transplanting date are becoming more and more common in modern nursery systems. For commercial production, when a lot of seedlings must be prepared for field planting in a short amount of time, this kind of scheduling is very crucial.

**Hardening and Transplant Readiness**

The process of gradually acclimating nursery-grown seedlings to the predicted climatic conditions following transplantation is known as hardening. Compared to plants growing in open fields, seedlings grown in enclosed environments typically have less wind movement, more constant temperatures, regulated humidity, and consistent water supplies. Thus, abrupt exposure to field conditions may result in diminished growth, leaf wilting, and transient water stress. Before transplanting, hardening often entails a controlled decrease in irrigation and a progressive increase in ventilation and sun exposure. The goal is to increase the seedling's ability to withstand changes in the environment after planting rather than to put it under extreme stress. In order to avoid overly soft vegetative growth, nutrient management may also be modified during the last nursery stage. Therefore, the last management step that prepares nursery-grown seedlings for a smooth transition to the production environment is proper hardening.

**Advanced Nursery Technologies**

Conventional seedling production is gradually giving way to technology-based techniques in modern vegetable nurseries, which offer more control over plant growth, uniformity, and transplant quality. The efficiency and dependability of nursery operations can be increased by using cutting-edge techniques including vegetable grafting, controlled-environment production, LED illumination, automated grafting, healing chambers, seed priming and biostimulant application. When high-quality transplants are needed for hydroponics, protected growing, and intensive vegetable production systems, these technologies are especially crucial (An *et al*., 2021).

**Vegetable grafting and Grafted Seedling production**

One of the most significant cutting-edge techniques employed in vegetable nurseries, especially for tomatoes, eggplants, cucumbers, watermelons, and melons, is grafting. This method combines a desirable scion with a rootstock that has characteristics including enhanced root vigour, tolerance to salinity or temperature stress, and resistance to soil-borne diseases. Thus, grafted seedlings can combine the robust root system and stress tolerance of the rootstock with the desirable fruit traits of the scion (Kubota *et al*., 2008). In commercial grafted seedling production, rootstock and scion seedlings are typically raised separately, then grafted, healed, and acclimated. Because incompatibility can lower graft success and subsequent plant performance, choosing compatible rootstock–scion pairings is crucial. In intensive production systems, where cultivating the same vegetable crop repeatedly raises the risk of soil-borne illnesses, grafting has become especially crucial (Lee and Oda, 2002). During graft recovery, the nursery environment is crucial. To avoid excessive water loss from the graft union while permitting a progressive restoration of photosynthetic activity, temperature, relative humidity, light intensity, and ventilation must be carefully regulated. Additionally, studies on cucumber seedlings have demonstrated that photosynthesis, growth, and graft-take % are influenced by light intensity and relative humidity during healing and acclimatization (Jang *et al*., 2011). Commercial nurseries have created robotic and semi-automatic devices that can more consistently cut and align scion and rootstock. These technologies have the potential to increase the productivity of large-scale grafted-seedling production while lowering labour needs (Bogoescu *et al*., 2020; Zhou *et al*., 2023).

**LED Lighting and Controlled-environment Nurseries**

The ability to precisely control light intensity, photoperiod, and spectrum composition has made light-emitting diode (LED) technology a crucial part of contemporary vegetable nurseries. In contrast to

traditional lights, LEDs can offer certain mixes of blue, red, green and far-red wavelengths, giving farmers the ability to control the morphology and physiological development of seedlings. Vegetable seedlings' reactions to artificial light vary depending on their species, cultivar, and spectral makeup. Tomato leaf area, biomass, chlorophyll concentration, plant compactness and overall seedling quality can all be affected by combinations of blue and red light. In plant factories and other controlled-environment systems, LED systems are also helpful for creating sturdy and small transplants. When properly integrated with the current light environment, supplemental far-red-enriched LED lighting can alter seedling morphology and enhance growth characteristics (Hwang *et al*., 2020). When there is not enough natural sunshine or when nursery output needs to continue all year round, the technology is especially helpful. Artificial illumination, however, necessitates careful environmental control. In tomato seedlings, physiological conditions like intumescence may be exacerbated by high humidity and low UV light. In tomato seedlings grown under LED lighting, Kubota *et al*. (2017) showed that controlled UV-B exposure can reduce intumescence damage. More recently, grafted tomato and pepper seedlings have been studied in LED healing chambers; photoperiod control affects intumescence development as well as graft establishment (Yun *et al*., 2025). Due to its spectrum flexibility, energy economy, and capacity to control plant development, LED lighting has grown in importance in controlled-environment horticulture (Morrow, 2008).

**Healing Chambers, Plant Factories and Nursery Automation**

Maintaining water balance and promoting the development of functional vascular connections between rootstock and scion are made easier by high relative humidity, moderate temperatures, and carefully controlled lighting. LED-based healing chambers are appropriate for commercial grafted seedling production because they offer more control over photoperiod and light quality. By combining artificial lighting, temperature control, humidity management, fertigation, and environmental monitoring into a single production system, controlled-environment plant factories expand on this idea. Mechanisation is also becoming more and more linked with grafting technology. LED lighting has also been studied recently during the healing process of grafted vegetable seedlings, suggesting that it may play a part in enhancing the graft-healing environment (Koukounaras *et al*., 2023). These technologies lessen reliance on external weather conditions and enable the year-round production of consistent seedlings. In order to boost productivity and lessen production limitations, grafting nurseries in Korea have developed using grafting robots, artificial light plant factories, LED healing chambers, and enhanced production facilities (An *et al*., 2021). Another significant advancement in contemporary nurseries is automation. Repetitive tasks like cutting, placing, and attaching rootstock and scion can be completed by automated or semi-automatic grafting systems. According to (Bogoescu *et al*., 2020), robotic grafting can decrease labour requirements while increasing operational efficiency and grafting quality. The necessity for mechanisation to address the high labour requirement associated with traditional grafted-seedling production has also been brought to light by extensive nursery experiments (Zhou *et al*., 2023). Graft healing can also be combined with advanced lighting. In double-root-cutting tomato seedlings, green light supplementation has been studied as a way to improve graft-union formation and root regeneration, showing that spectral manipulation can be used for both general seedling growth and specialised graft-healing operations (Li *et al*., 2021).

**Seed Priming and Bio-stimulant-based technologies**

Another significant strategy for raising nursery performance is the use of seed improvement technology. In order to start the physiological processes involved in germination without permitting radicle emergence, seed priming entails carefully hydrating seeds prior to sowing. In plug-tray nurseries where uniform emergence is crucial, proper priming can enhance germination uniformity, emergence speed and seedling establishment. The use of biostimulants in nursery production as supplements or substitutes for traditional inputs is growing. Seaweed extracts, protein hydrolysates, humic compounds, advantageous microbes and other physiologically active materials are among them. Their use may promote photosynthetic activity, root growth, nutrient-use efficiency, and stress tolerance (Malik *et al*., 2021). Plant-based biostimulants can enhance the nutritional qualities and quality of vegetable transplants and may help them establish better after transplanting. (Rouphael *et al*., 2021). The potential of natural extracts as growth-promoting agents was demonstrated by (Moncada *et al*., 2022), who discovered that Ecklonia maxima extracts might affect the growth of lettuce and tomato seedlings under nursery circumstances. Biostimulants based on seaweed have been directly tested. During the formation of vegetable transplants. In vegetable nurseries, microbial and cyanobacterial technologies are also developing. In tomato and spinach, cyanobacterium-based seed priming has been studied. Certain cyanobacterial treatments enhanced a number

**Table 2 :** Major seed priming methods used in vegetable crops.

| Priming method | Priming agent | Vegetable crop examples | Typical duration | Major effects |
|---|---|---|---|---|
| Hydro-priming | Water | Tomato, cucumber, okra | 6–24 h, depending on crop and seed | Faster and more uniform germination, improved seedling establishment |
| Osmo-priming | Polyethylene glycol (PEG) or other osmotic solutions | Tomato, pepper, cucumber | Usually several hours to 1–2 days, depending on osmotic potential and crop | Improves germination uniformity and seedling performance, particularly under stress |
| Halo-priming | Inorganic salts such as $KNO_3$, KCl or $CaCl_2$ | Tomato, pepper, spinach | Several hours to about 24 h, depending on concentration and crop | Enhances germination, seedling vigour and stress tolerance |
| Nutri-priming | Nutrient solutions containing N, P, K or micronutrients | Tomato, chilli, cabbage | Several hours to 24 h, depending on nutrient concentration | Improves nutrient availability, germination and early seedling growth |
| Bio-priming | Beneficial microorganisms such as *Trichoderma* spp. and *Bacillus* spp. | Tomato, cucumber, chilli | Usually several hours to 24–48 h, depending on inoculant and protocol | Enhances seedling vigour and may improve resistance to seed- and soil-borne pathogens |

**Source:** Priming duration is protocol- and crop-dependent; values should not be treated as universal recommendations. The classification and general effects are supported by Thakur *et al*. (2022) and Zulfiqar (2021).

of seedling growth parameters, which in turn affected crop performance (Nivedha *et al*., 2024). By integrating biological nutrition and growth-promoting mechanisms with seed modification, these methods can help create more sustainable nursery systems. In general, cutting-edge nursery technologies shouldn't be seen as stand-alone treatments. When complementary technologies are combined, like as grafting with LED healing chambers, automated grafting with controlled conditions, or seed priming with biostimulant-based nursery management, they reach their full potential. Producing consistent, robust, and physiologically prepared transplants, while increasing labour productivity, resource efficiency and sustainability should be the goal.

**Nursery health and Sustainable management**

Successful vegetable production starts with healthy seedlings since issues that arise during the nursery stage might persist after transplanting and lower crop establishment and productivity. Sanitation, adequate feeding and irrigation, disease-free planting materials, efficient pest control, and suitable environmental conditions are all important for nursery health. Reducing chemical inputs, recycling organic materials, conserving water, and preserving the biological health of the growing medium are additional goals of sustainable nursery management (Gallegos-Cedillo *et al*., 2024).

**Sanitation and Disease management**

One of the most significant illnesses impacting vegetable nurseries is damping-off. *Pythium*, *Phytophthora*, *Rhizoctonia* and *Fusarium* are among the soil-borne fungi and oomycetes frequently associated with damping-off. Before emergence, the disease can cause seed degradation, or after emergence, it can cause immature seedlings to collapse due to lesions near the soil line. Disease development is facilitated by high wetness, limited air circulation, poor drainage, and overcrowding. Therefore, in commercial nurseries, strict sanitation is crucial. Benches, irrigation equipment, tools, and seedling trays should all be cleaned and sanitised in between production cycles. Reusing contaminated growth media and plant detritus requires appropriate treatment. The initial inoculum is further decreased by using certified seed and substrates free of pathogens. Because viruses can spread through contaminated trays, equipment, irrigation water, workers, and plant wastes, proper sanitation is especially crucial. In areas with high disease pressure, soil and substrate disinfestation may also be utilised. Research in vegetable nurseries has shown that damping-off is reduced once nursery beds are solarised (Mercure, 2024; Raj *et al*., 1997). Because extended wetness of the growing media promotes damping-off, water control is equally critical. Poor drainage and excessive irrigation lower the amount of oxygen available around roots and foster the growth of pathogens. Therefore, rather than adhering to a set schedule, irrigation should be modified based on crop stage, weather, substrate characteristics and water-holding capacity. In

vegetable nurseries, biological methods utilising Trichoderma and Pseudomonas species have also shown promise for reducing damping-off pathogens and enhancing seedling health (Choudhary *et al*., 2019; Hlokwe *et al*., 2020; Kumhar *et al*., 2022).

**Biological Disease control**

A key element of long-term nursery health management is biological control. Through competition, antibiosis, mycoparasitism, and the stimulation of plant defensive responses, beneficial microbes including *Bacillus, Pseudomonas* and *Trichoderma* can reduce soil-borne diseases. Additionally, using these organisms can enhance seedling vigour and root development. Early studies showed that *Rhizoctonia solani* induced damping-off in lettuce seedlings might be biologically controlled by *Trichoderma harzianum*. By means of mycoparasitism and antibiotic activity, the antagonistic fungus decreased illness (Wilson *et al*., 1988). Formulations containing *Trichoderma* could lessen damping-off in vegetable seedlings, according to later studies conducted in greenhouses (Lewis *et al*., 2001). Additionally, the use of biological control agents in commercial nurseries has been studied. When applied to cucumber and pepper seedlings, *Trichoderma harzianum* increased development and vigour while lowering disease pressure, proving that biological agents can offer advantages beyond direct pathogen suppression (Inbar *et al*., 1994). *Bacillus subtilis, Trichoderma* spp., and *Pseudomonas fluorescens* have been tested in Indian vegetable nurseries to control damping-off in solanaceous crops. When combined with proper irrigation, growing conditions and cleanliness, these biocontrol agents/ treatments can be a component of integrated nursery disease-management programs (Tripathi *et al*., 2022). To avoid depending just on pesticides, integrated pest management (IPM) should incorporate chemical, biological, cultural, and preventive methods. Pest pressure can be decreased by keeping an eye on pest populations, eliminating sick seedlings, using insect-proof buildings, sticky traps and biological management. Chemical pesticides, if necessary and legally approved for the crop and nursery usage, should be administered according to label guidelines and integrated with non-chemical approaches. To lower disease incidence and preserve healthy vegetable seedlings, integrated disease management integrates preventive, cultural, biological, and other suitable strategies (Pandey *et al*., 2016).

**Water, Nutrient and Environmental resource management**

Sustainable nursery production requires effective management of nutrients and water. Due to their limited root volume, seedlings are vulnerable to both excessive watering and a lack of water. While insufficient irrigation results in wilting and inhibits root growth, over irrigation can lead to nutrient loss, poor aeration, and disease development. Water-use efficiency can be increased via drip irrigation, micro-irrigation, and carefully controlled misting systems. Since high salinity can negatively impact vegetable plants, water quality should also be taken into account. Compared to mature plants, seedlings are typically more vulnerable to salt stress in their early stages of development. With potential advantages for seedling growth and vigour, microbial biostimulants have been studied as a way to increase tomato and lettuce transplants' tolerance to saline irrigation water (Miceli *et al*., 2021). Crop requirements and the growing medium's nutritional condition should be the basis for nutrient management. While poor feeding results in weak and chlorotic seedlings, excessive fertilisation can enhance electrical conductivity and harm roots. In order to minimise nutrient losses, controlled fertigation can supply nutrients in small amounts based on crop demand. Reducing reliance on non-renewable growth media is another aspect of sustainable nursery management. Because of its advantageous physical and chemical characteristics, peat has historically been utilised extensively; nevertheless, worries about its effects on the environment have prompted research into substitute substrates. When their physical stability, salinity, pH and nutritional qualities are appropriately controlled, compost, vermicompost, agro-industrial leftovers, wood-based materials, and other renewable resources can partially replace peat. Circular resource management is further supported by the use of organic wastes as nursery substrates. For instance, tomato waste compost has been tested as a partial replacement for peat in the production of vegetable seedlings; in the right amounts, seedling germination and morphology are improved (Abdel-Razzak *et al*., 2019). In a similar vein, arbuscular mycorrhizal fungi in combination with substrates derived from date palm trash have demonstrated promise for the sustainable development of lettuce seedlings (Dhen *et al*., 2019).

**Sustainable Nursery systems and Quality assurance**

Integrating environmental, biological and financial factors is necessary for sustainable nursery management. The goal is to create production methods that reliably produce healthy, uniform, and transplant-ready seedlings while making effective use of water, nutrients, energy, and growing materials rather than just lowering chemical inputs. By using compost, compost teas, beneficial microbes, and plant biostimulants, organic and biological

methods can help achieve this goal. Because the root environment affects the availability of water and nutrients as well as the interactions between seedlings and helpful or pathogenic microbes, root-zone management is especially crucial (Ronga *et al*., 2021). In addition to offering an alternative to traditional peat-based media, recycling municipal and agricultural organic leftovers into nursery substrates can lower trash disposal needs. Regular monitoring of seedling height, stem diameter, root growth, leaf colour, root-to-shoot balance, disease incidence, and uniformity should all be part of quality assurance. Additionally, seed lot, sowing date, substrate composition, irrigation, fertilization, pest and disease observations, and transplant date should all be recorded in nursery records. These records make it easier to trace and assist in determining which management techniques are to blame for uneven or subpar seedling performance. Preventive interventions should therefore be the first step in an integrated nursery health program. The fundamental preventive framework consists of disease-free seed, sanitised trays, pathogen-free substrate, suitable plant density, regulated irrigation and sufficient ventilation. Chemical interventions should only be used when necessary and in accordance with authorised guidelines; biological control agents and biostimulants can then be added where suitable. In general, biological regulation, monitoring, prevention, and effective resource utilisation are all part of sustainable nursery management. In addition to lowering preventable losses of water, nutrients, growth media and pesticides, this strategy enhances seedling health. In intensive vegetable production, where many seedlings are grown in very small areas and minor management improvements can have significant cumulative effects, the shift to sustainable nursery systems is especially pertinent (Gallegos-Cedillo *et al*., 2024).

**Constraints and Future prospects**

Although, emerging technologies offer considerable opportunities for improving vegetable nursery management, their adoption is associated with several practical and sustainability-related challenges. The extensive use of plastic trays, containers, films, and other nursery materials may increase plastic waste, creating a need for durable, reusable, recyclable, or biodegradable alternatives (Nambuthiri *et al*., 2015). The incorporation of sensors, automated equipment, and precision-based technologies can improve the monitoring and management of environmental and nutritional conditions; however, their implementation often involves high initial investment, specialized technical knowledge, maintenance requirements, and operational costs. Energy demand is another important consideration, particularly in nurseries relying on automated or controlled environmental systems, and greater emphasis should therefore be placed on energy-efficient technologies and renewable energy sources. The availability, affordability, consistency, and sustainability of suitable growing substrates can also restrict the adoption of advanced nursery practices, especially where locally available materials are limited (Kaptein *et al*., 2019). Furthermore, the effectiveness of precision and automated systems depends on crop-specific management strategies because different vegetable crops have distinct requirements for water, nutrients, temperature, humidity, and light. Future research should therefore focus on developing integrated nursery production systems that combine resource-efficient technologies, sensor-based monitoring, automation, sustainable growing media, biological inputs, and precise water and nutrient management. Such integration could help reduce material and energy losses, improve resource-use efficiency and support the production of uniform, vigorous and stress-tolerant seedlings, while enhancing the long-term economic and environmental sustainability of vegetable nurseries (Iddio *et al*., 2020; Aurdal, 2025).

## Conclusion

Vegetable nursery management plays an important role in producing healthy, uniform and transplant-ready seedlings. Seed quality, suitable growing media, appropriate tray size, balanced irrigation and nutrition, environmental regulation, hardening and effective plant health management together determine seedling quality and subsequent crop establishment. Modern practices such as seed priming, biostimulants, grafting, biological control and controlled-environment production can further improve seedling vigour and uniformity when applied according to crop requirements. Sustainable nursery production should focus on efficient use of water, nutrients, growing media, energy and other inputs while maintaining good sanitation and plant health. The future development of vegetable nurseries will depend on combining practical horticultural practices with suitable technologies such as automation, sensors and precision management. These technologies should be selected according to their economic feasibility, environmental benefits and suitability for individual crops. An integrated and crop-specific approach will be important for producing reliable, healthy and resilient vegetable transplants under changing production conditions.

**Constraints and Future Prospects**

Although, modern nursery technologies can improve seedling quality and production efficiency, their adoption

is still limited by several practical constraints. The initial cost of protected structures, plug trays, automated equipment, sensors and controlled-environment systems can be high, particularly for small and medium-scale nurseries. The economic benefit of adopting such technologies therefore depends on nursery size, crop value, production scale and the expected improvement in seedling quality.

Energy consumption is another important concern in controlled nursery systems. LED lighting and plant factory systems provide better control over light and seedling growth, but their electricity requirements can increase production costs. Future systems should therefore focus on energy-efficient lighting, appropriate photoperiods and light intensity and the use of renewable energy where feasible. Similarly, repeated use of plastic trays and other nursery materials can contribute to plastic waste. Durable reusable trays, recyclable materials and biodegradable alternatives should be evaluated according to their cost, performance and environmental impact. Precision irrigation is another area with considerable potential for future nursery production. Sensors for monitoring substrate moisture, temperature, humidity and electrical conductivity can help improve irrigation and fertigation decisions and reduce unnecessary water and nutrient application. However, sensor-based systems need proper calibration and simple operating procedures to make them practical for routine nursery use.

Artificial intelligence and digital tools may further support nursery management through environmental monitoring, prediction of seedling growth, disease detection and irrigation scheduling. However, their usefulness will depend on the availability of reliable data and crop-specific models. At present, management recommendations are often generalised across crops, whereas tomato, chilli, capsicum, brinjal, cole crops and cucurbits differ in their requirements for temperature, light, irrigation, nutrition, cell volume and transplant age. Future research should therefore develop crop-specific nursery protocols and validate them under different production environments.

Overall, future vegetable nursery systems should aim for a balance between technological development, economic feasibility and environmental sustainability. Rather than adopting technology simply because it is available, nurseries should select practices that provide measurable improvements in seedling quality while reducing unnecessary use of water, nutrients, energy, growing media and plastic materials.

**Author contributions :** All authors contributed to the conceptualisation, literature collection, writing, review and editing of the manuscript. All authors read and approved the final manuscript.

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