



## Review Article

# An in-depth analysis of sustainable practices in vegetable seedlings nurseries: A review

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## ABSTRACT

Nowadays, sustainable and resilient cultivation techniques have significantly increased in vegetable cultivation. Thus, there is a growing demand for high-quality certified planting materials suitable for these new cultivation methods. This review aims to provide a comprehensive and in-depth analysis of recent sustainable practices in vegetable seedling nurseries. Here, we thoroughly analysed 604 articles and 3553 keywords from the Scopus database, utilizing qualitative and quantitative methods, covering the past 20 yr. We conducted a bibliometric analysis using VOSviewer software.

to identify the most relevant study topics. The design of seed trays, seed enhancement treatments, and controlled environmental conditions are crucial for generating optimal seedlings and transplants. Additionally, sustainable growing media are necessary to optimize resources and reduce input use. We identified grafting and LED lighting technology as rapidly advancing technologies in seedling production. Furthermore, applying biostimulants and beneficial microorganisms as booster agents can enhance efficiency and promote sustainable production. The findings of this study offer valuable insights into the research trends for vegetable seedlings and transplants, underscoring the imperative for adopting sustainable practices within the nursery industry.

## 1. Introduction

Using high-quality planting material in the initial phase of plant production is crucial for achieving successful crop efficiency, final yield, and product quality (Gallegos-Cedillo et al., 2024).

Using seedlings and transplants typically improves root growth, accelerates maturity, increases shoot mass, and enhances yield in vegetables compared to direct seeding. Transplanted plants exhibit more robust root growth, overall root length, and surface area. They also tend to have more extensive shoots, a higher leaf area index, and increased chlorophyll content than directly seeded plants. For example, transplanting bell peppers can improve root growth, promote early maturity, optimize shoot mass allocation, and increase fruit set and yield compared to direct seeding (Leskovar and Cantliffe, 1993). Similarly,

Leskovar and Othman (2021) compared the effects of direct seeding and transplanting on three types of globe artichoke. The results showed that transplanted plants had more robust root growth, higher shoots and yield, and more precocity. These results are consistent with those found in a study on sweet corn by Gavric and Omerbegovic (2021), which showed that transplanted plants had higher ear yields and earlier harvests than direct sowing. In summary, the transplanting method has been proven to consistently enhance plants' root and shoot characteristics and yield.

There has been a surge in consumer demand for safe vegetables in recent years, with a distinct rise in the preference for organic seedlings of popular crops. However, it is highlighted that seedlings in this category production are still in their early stages (Ronga et al., 2021). Organic vegetables must be cultivated from organic seeds or organic

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plant propagation materials. Regulations in the EU, USA and other countries require that seedlings used in organic production are produced using ecological materials and practices (Regulation EU 848/2018; USDA, 2020) (Fernández et al., 2022). Therefore, according to current regulations, seeds, fertilizers, and phytosanitary and disinfection products are used only if they have been authorized for use in organic production. Thus, in the case of countries belonging to the EU, and since it is common for organic seeds not to be available in sufficient quantities, it is possible to obtain derogations for the use of conventional untreated seeds, considering that organic seeds and vegetative plant multiplication material are not allowed from 2036 by Organic Regulation (EU) 848/2018 (Fernández et al., 2022). In addition, disinfection and phytosanitary treatments must be carried out with products or substances authorized according to Regulation (EU) 2018/848 on organic production. However, sustainable production extends beyond organic practices. The quality of the seedlings is mainly defined by the characteristics of the growing medium and their nutrition. In addition, the design and cell size dimensions of trays and transplant age impact the growth and development of seedlings and transplants. The primary material in substrates used to produce vegetable seedlings and transplants is peat. Surprisingly, this applies even to organic farming. However, peat is considered a non-renewable resource, and its use must be reduced worldwide (Gruda, 2012; Gruda et al., 2019a, 2019b; Olaria et al., 2016). Consequently, various growing media have been studied to replace peat in nurseries (Gruda and Fernández, 2022; Öztekin et al., 2017; Pascual et al., 2018). Particularly, compost and agro-industrial by-products, but also wood fibers and coir pith, can be considered potential substitutes for peat in nurseries due to their positive effects on the quality and growth of plants, their stimulant properties, and their suppressive effects on pathogenic microorganisms (Gruda et al., 2024). In addition, they improve the physical and chemical properties of growing media. Besides, the use of compost tea from various origins, microbial and non-microbial plant biostimulants and beneficial microorganisms can be used to enhance seedling nutrition, protection, and growth for the organic production of seedlings (Olaria et al., 2016; Ronga et al., 2021; Russo, 2005).

New cultivation techniques such as grafting, automatic transplanters with vision system technology, developing agricultural robots and lighting LED (Light-emitting diode) in highly controlled environments are some of the most outstanding aspects of producing vegetable seedlings. In addition, seed-enhanced treatments and certified seeds are increasingly used for nursery cultivation.

The aim of this bibliometric analysis is to provide an up-to-date overview of recent developments in the production of vegetable seedlings and transplants. This includes a comprehensive analysis of current sustainable practices in vegetable seedling nurseries.

## 2. Methods

The data pertaining to the duration of 2003–2023 were scrutinized and evaluated, retrieved from the Scopus database. Furthermore, we implemented quantitative methods to analyze the selected keywords, "organic vegetable seedling/transplants", "vegetable transplant production", "containerized transplants", "seedbed", "seedling\*", and "nursery\*" using the search field "Article title, Abstract, and Keywords", resulting in a total of 604 articles and 3553 keywords. To visualise the research trends, a bibliometric analysis was developed based on the keyword co-occurrence ratio and similarity index, with the unit of study encompassing both author and indexed keywords (Gallegos-Cedillo et al., 2024). To bolster the analysis, a thesaurus was created, while a minimum keyword occurrence threshold of eight was instituted (Chen et al., 2016; Nájera et al., 2023, 2022). In this study, we created network and overlay visualisation maps to monitor the progression of keywords used in the analysed articles and determine the most significant trends in the research area. The collected data underwent processing and analysis using the clustering algorithm of VOSviewer® software version 1.6.18.

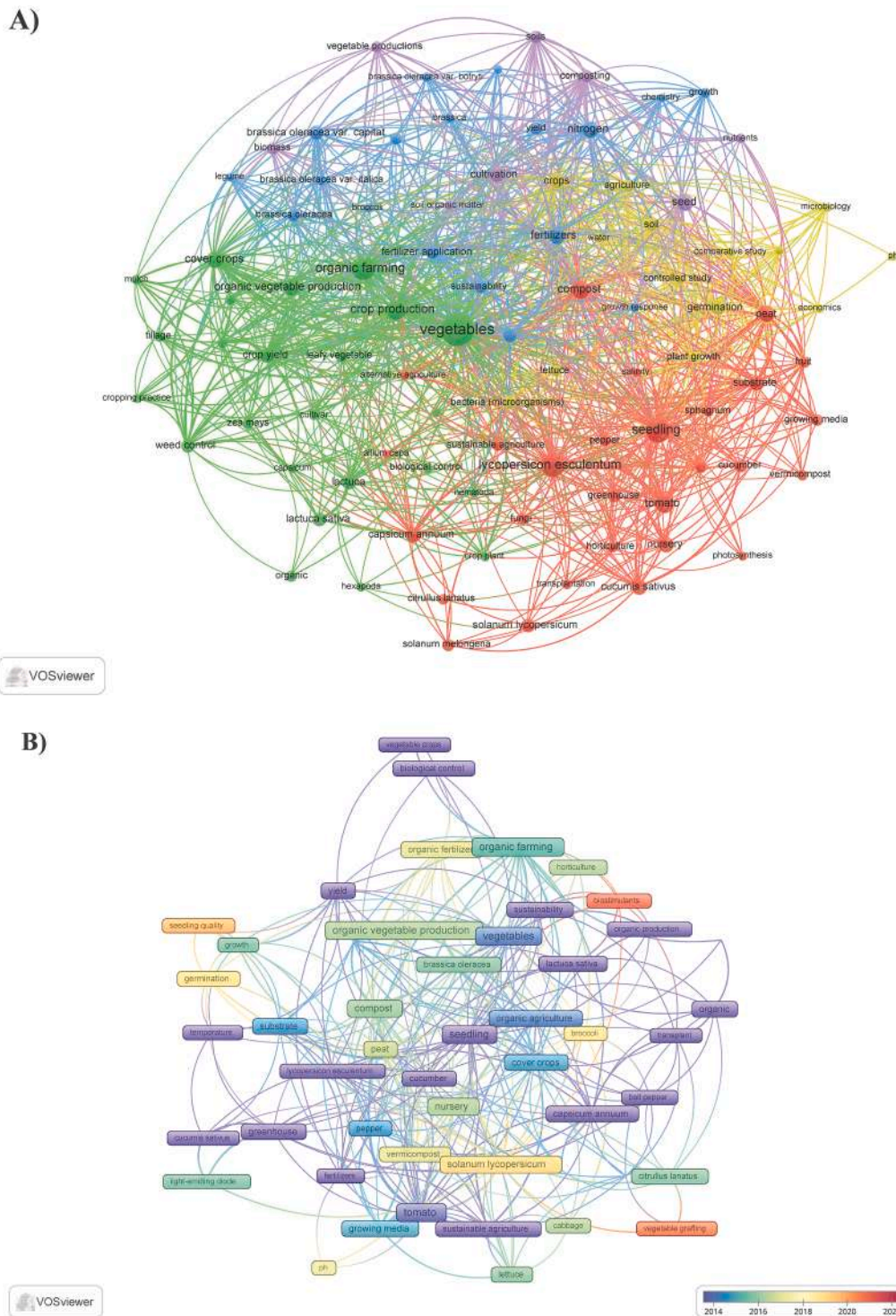
(Centre for Science and Technology Studies, Leiden University, The Netherlands) (van Eck and Waltman, 2010). From the total sample of articles ( $n = 604$ ), a representative sample was retrieved and analysed for their relevance and high number of citations in the Scopus 2023 database, a descriptive and qualitative analysis of the extracted documents to collect the data of interest and the main aspects that influence the growth and development of seedlings and their productivity.

## 3. Results

### 3.1. Bibliometric data analysis

The network visualization map showcases a representation of five clusters, each of which is uniquely identifiable by its distinct color. The map integrates indexed and author keywords (Fig. 1,A). Closely correlated articles are grouped within each cluster or line of research. For example, due to its high occurrence and total link, the topics that stand out the most in the network visualization map were seedlings, *Lycopersicon esculentum*, crop production, and organic farming (Fig. 1,A). For the studied period, cluster 1 (red colour) highlights a line of research that is aimed at the development of growing media in vegetable nurseries; in this line, the most relevant items are "compost", "peat", and "substrate". Some of the most pertinent and cited articles concerning using alternative growing media to produce vegetable transplants in nurseries (Abad et al., 2001; Herrera et al., 2008; Raviv et al., 1998; Sánchez-Monedero et al., 2004). Another new research trend includes topics such as "organic vegetable production", "organic farming", and "crop production" (cluster 2; green). Some relevant research in this cluster establishes the guidelines and regulations to produce certified transplants (Dorais, 2007; Nicola et al., 2011; Russo, 2005) and current trends and developments in organic vegetable crop production (Fernández et al., 2022). Furthermore, in cluster 3 (blue), four main research lines can be distinguished and are grouped under "fertilizer", "organic fertilizer", "fertilizer application", and "nitrogen". Several research groups are investigating some tools and strategies focused on new sources of organic fertilizer (Ronga et al., 2021; Testani et al., 2017; Tuzel et al., 2015). In this same direction, in clusters 4 (yellow) and 5 (purple), current issues related to the use of "microorganisms", "germination", "seeds", "composting", and "vegetable production" stand out. These all-innovative management approaches demonstrate the importance of natural and sustainable resource use. Likewise, some agronomic practices, such as fertilization level and the new organic sources of fertilisation, which can enhance the quality and accumulation of some compounds beneficial to human health, are included in this cluster.

The overlay visualisation map shows the most recent and relevant topics highlighted in orange and red (Fig. 1,B) based on the evolution of author keywords. The most prominent themes over the last decade are "germination", "organic fertilizer", "peat", "nursery", "vermicompost", "seedling quality", "vegetable grafting", and "biostimulants". Moreover, the most consolidated species are tomato, eggplant, cucumber, watermelon, lettuce, cabbage, and broccoli, which is consistent with data published by (FAOSTAT, 2023), indicating that these vegetables generate a total of almost 600 million tons of production worldwide, which may justify the interest and impact on agricultural research. Fig. 2 shows the percentage of items published from 2008 to the present in the Scopus database. The most relevant topics were organic fertilizer, compost, organic farming, and sustainable agriculture. In this sense, relatively recent trends, such as biostimulants and alternative growing media (compost and vermicompost) as transplant-strengthening agents, are gaining popularity (Paradiković et al., 2019). Furthermore, vegetable grafting is gaining more attention, as it is considered an eco-friendly technique in vegetable production (Lee et al., 2010; Nian et al., 2022). New modern systems employ supplementary lighting during some strategies such as graft production, healing, and acclimatization in a controlled environment (Kubota et al., 2019; Mitchell et al.,



**Fig. 1.** Keyword co-occurrence analysis involves two types of maps, namely network visualization and overlap maps. The former displays all the keywords over time (A), the second one contains only the keywords of the author (B). The maps utilize a range of colours to represent the diversity of thematic cluster identified, with each cluster assigned a unique colour. The five colours used are red (cluster 1), green (cluster 2), blue (cluster 3), yellow (cluster 4), purple (cluster 5).

2015; Moosavi-Nezhad et al., 2022; Soltani et al., 2023; Yousef et al., 2021b). Moreover, transplant production in plant factories or vertical farming systems has increased considerably recently (van Delden et al., 2021).

### 3.2. Main innovations in vegetable transplant production

The rapid development of cultivation techniques and mechanization

and the high demand for robust plants at a low price led to the development of extensive and specialized infrastructures known as nurseries, seedbeds, or vegetable seedlings (Kozai and Ito, 1993). The main advantages of producing seedlings in vegetable nurseries are to obtain high-quality plants with uniform characteristics, robust and developed root systems, higher field survival rates, better post-transplant adaptation and increased plant tolerance and resilience to multiple biotic and abiotic stresses (Cantliffe, 2009; Kubota et al., 2008).



Fig. 2. Research topics in vegetable production. Values are expressed as percentage (n = 604).

During 1950–1970, technological advances positively influenced aspects related to improving greenhouse structures, the development of multi-cellular containers, thermal plastic films, hybrid seeds and the rational use of water and fertilisers through fertigation. It also enhanced the sowing process and increased seed use efficiency through automated

precision seeders, standardised seedling trays and coated seeds. The establishment of these innovations package the tone for the worldwide expansion of commercial nursery transplant production in the early 1980s (Fig. 3) (Cantliffe, 2008; Gallegos-Cedillo et al., 2024). In the same years, greenhouse automation, microclimate control and soilless

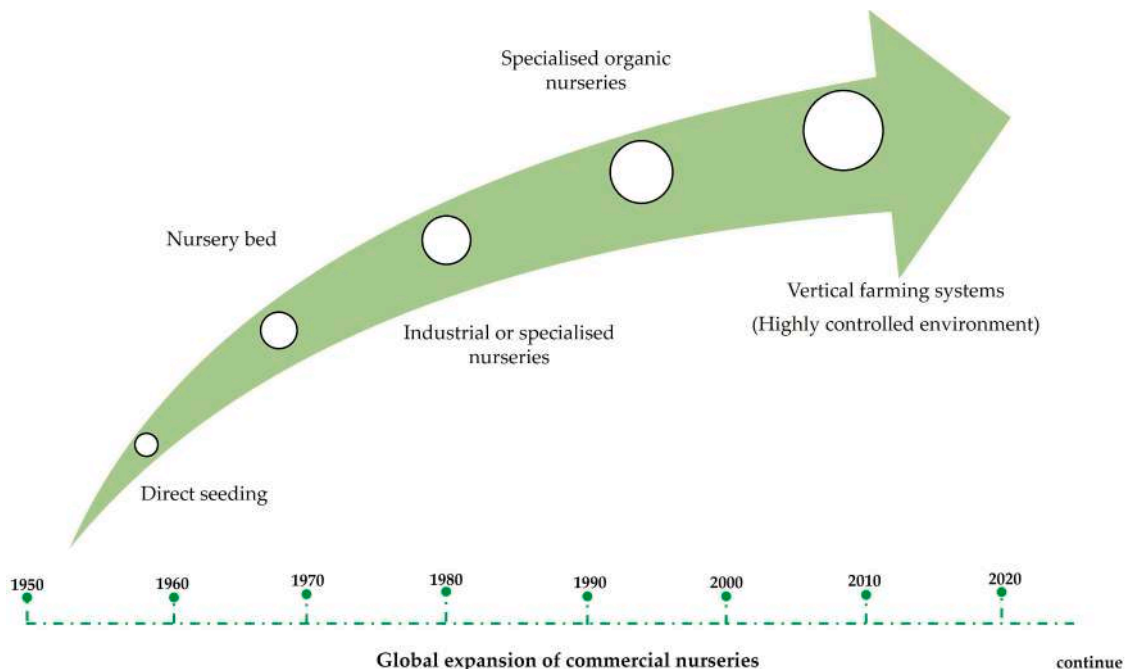


Fig. 3. Global perspective of the evolution of vegetable transplant production systems.

cultivation techniques became widespread. Subsequently, between 1990 and 2000, a change in consumer preference for organic agricultural products created the need for new production strategies to achieve the quality levels required by specific national standards. In this sense, new alternative growing media to peat were developed, and cultivation techniques such as biological control and integrated pest management were implemented, which are still current strategies. These represent significant advantages for sustainable farming, and to benefit from these advantages, farmers have, whenever possible, modified their system of production. Consequently, the demand for organic seedlings of the more widely cultivated vegetable crops has significantly increased (Chethan et al., 2022; Ronga et al., 2021).

In the contemporary era, new cultivation techniques such as grafting, automatic transplanters with vision system technology, the development of agricultural robots and lighting LED in highly controlled environments are perhaps some of the most outstanding aspects. Likewise, integrating information technologies and digitalization, such as the Internet of Things (IoT), robotics, and artificial intelligence (AI), has emerged as a pivotal component in the transformative changes within vegetable production. These cutting-edge tools are crucial in facilitating production processes' control, automation, and traceability, aligning them with sustainable agriculture principles and pursuing enhanced nutritional quality in vegetable crops. Furthermore, the transplant production chain must consider the current sustainability criteria to ensure that they maintain their high-quality attributes and that nurseries maintain their profitability (Zarbà et al., 2019).

### 3.3. Main types and characteristics of nurseries

In most regions with intensive agriculture, transplants are purchased from specialized commercial nursery companies (Gruda and Pop-simonova, 2017). However, in a low proportion, the farmer still does plant production in nursery beds or *almácigas* (for example, in some countries such as México, Argentina and Spain) (Montes, 2018; Valera et al., 2016), and in some cases, direct sowing is carried out (Caputo

et al., 2021).

The central nurseries typologies are described below.

#### 3.3.1. Nursery bed

In this system, sowing is done directly in the soil at a high density, and the seed typically receives a preventive fungicide treatment. Therefore, when the plant is ready to be transplanted, it is extracted from the soil (bare root plants). The quality and uniformity of plants in this system are subpar. The establishment rate is generally lower than in the case of seedlings produced in multicell trays due to significant damage to the root system (Balliu et al., 2017b; Cantliffe, 2008; Kumar and Raheman, 2008).

#### 3.3.2. Conventional nursery

Fig. 4, shows a schematic representation of vegetable transplant nursery facilities, in which modern greenhouses are equipped with computer-automated systems (Stanghellini et al., 2019), and overhead irrigation or sub-irrigation methods are used (McAvoy and Ozores-Hampton, 2019; Vavrina, 2002). Generally, seedling trays are placed on different growing structures, such as rails, benches, and metal wires, where seedlings are watered and fertilized through overhead irrigation systems. In contrast, in sub-irrigation systems (floating and ebb and flow systems), the trays (pots or rockwool blocks) are placed in culture ponds that are filled with nutrient solution until the substrate is wetted (at field capacity). In addition, the latter have highly efficient use of the floor space (over 90 %), and even mechanized collection is possible (Cantliffe, 2009; Wang et al., 2022).

#### 3.3.3. Organic transplant nursery

The production of seedlings in this category is relatively new (Ronga et al., 2021). The infrastructure of certified nurseries must be delimited and separated from non-organic production areas. If the infrastructure of organic and non-organic certified nurseries is shared, a protocol must be established to avoid the risk of contamination (e.g., non-organic seeds, phytosanitary treatments, etc.) (Ceglie et al., 2015; Pascual

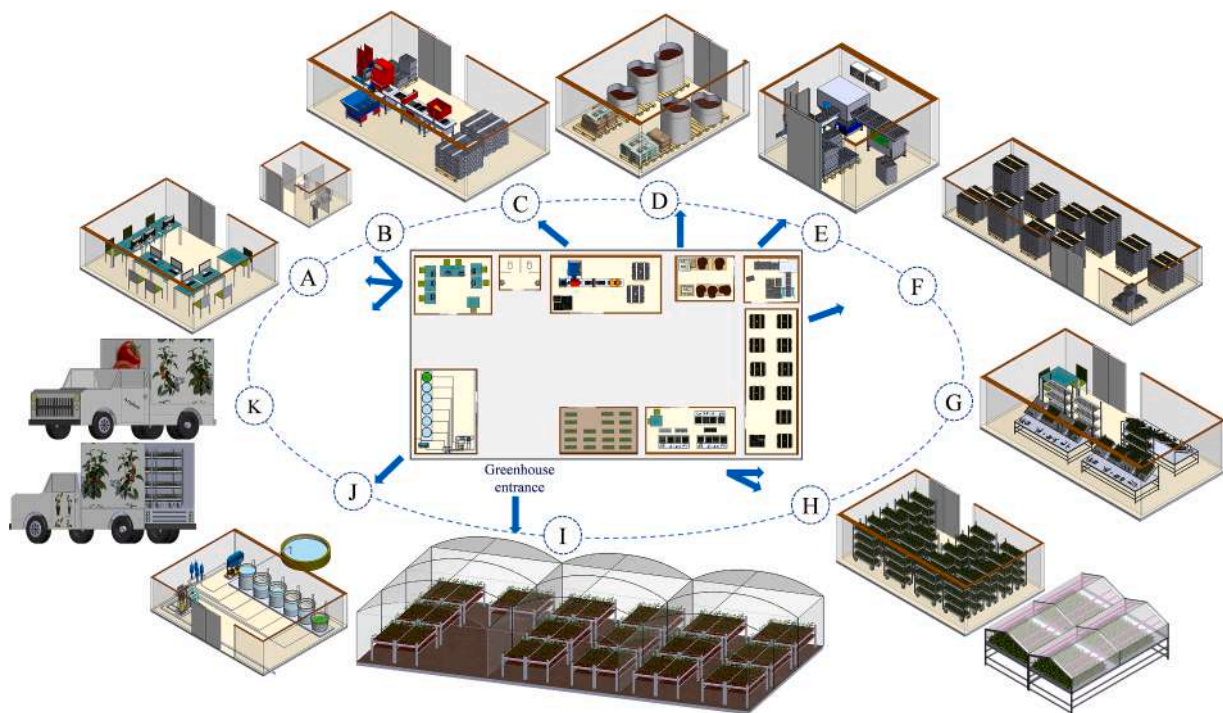


Fig. 4. Schematic representation of vegetable transplant nursery facilities: (A) Central office, (B) Toilet service, (C) Seeding area, (D) Growing media storage, (E) Tray disinfection zone, (F) Germination chamber, (G) Grafting station, (H) Healing and acclimatization section for grafting plants, (I) Greenhouse, (J) Stock nutrient solution deposits and irrigation system station, (K) Trade and transport logistics.

et al., 2018; Russo, 2005). As mentioned above, in the case of countries belonging to the European Union, disinfection and phytosanitary treatments must be carried out with products or substances authorized according to Regulation (EU) 2018/848 on organic production and labelling of organic products.

Limited organic seed availability in growing organic vegetable production leads to reliance on untreated conventional seeds from high-input systems in some countries. Despite cost-effectiveness, these conventional seeds may lack essential traits for organic systems, heightening disease susceptibility and not meeting organic production requirements (Nyochembeng, 2021).

For organic seedling production, due to the short cultivation period and the demand for specific nutrients, fertilization strategies must be adjusted. Nutrients must be totally or partially released from the organic amendments provided, and, in some cases, it is necessary to incorporate a significant proportion of base and dressing nutrients (Möller and Schultheiss, 2013). Therefore, fertilizers such as base fertilizers should be added to the substrate before sowing and/or through fertigation or foliar fertilization to supply the required nutrients during the seedling growth cycle. Mandatory fertilizers must be on the list of inputs allowed for organic production according to current regulations (Möller and Schultheiss, 2013).

Regarding sanitary management, more preventive techniques must be used than conventional ones due to the restriction on the use of pesticides once diseases appear. In this sense, the use of promoting growth and/or suppressing plant diseases (i.e. mycorrhiza, plant growth-promoting bacteria (PGPB)) is beneficial (Tüzel et al., 2020).

### 3.3.4. Vertical farming nursery systems

This type of transplant production used for plants with high nutritional and economic value in a highly controlled environment is gaining importance in the commercial nursery industry (Kubota et al., 2008; Nájera et al., 2024; 2023). Notably, it is used to acclimate plants (e.g., grafted seedlings) (Kubota et al., 2019). Also, it is possible to increase productivity per cultivation unit. Moreover, the production cycle can be shortened by 30 to 40 % compared to high-tech greenhouses (with microclimate control). Finally, producing plants free of pathogens and pesticides is enhanced (Kozai, 2020), and resource and energy efficiency are improved (Huber and Hernández, 2021; Huber et al., 2021).

### 3.4. Grafted and non-grafted vegetable transplant production

Already in 2009, the global transplant production in seedling farms was estimated at more than one trillion seedlings and transplants per year (Cantliffe, 2009). However, this estimate may be higher because this estimate did not consider the production of grafted plants. Furthermore, these estimates do not include the production of some large companies that have chosen to develop a specialised area for their transplant production to reduce production costs (Heis-Serrano, 2022). Indeed, seedling production varies widely according to agricultural areas and the level of specialization of the nursery. Between the years 2015 and 2018, China held a prominent position in the field of transplant production in Asia, exhibiting an impressive annual volume ranging from 680 to 800 thousand (Feng et al., 2015; Wang et al., 2021). Around 16 billion vegetable seedlings were grafted every year. Watermelon, cucumber, melon, and aubergine accounted for 40, 30, 20 and 15 %, respectively. For instance, Shandong was the largest vegetable-producing province in China, with more than 360 commercial vegetable transplant nurseries in this region with a production capacity of more than 6.79 billion grafted seedlings per year. Meanwhile, specialised nurseries produced over 50 million grafted seedlings annually in Wuhan, Hubei province. However, there was still scope to cover the annual demand for quality transplants of vegetable species (Huang et al., 2015). Meanwhile, in Japan and the Republic of Korea, the yearly output of plants surged to 1369 and 3417 million in 2010, respectively (Lee et al., 2010). Likewise, grafting is extensively practiced in vegetable

production. For instance, many watermelon (90–95 %) and cucumber (75 %) plants are grafted onto various rootstocks. Similarly, approximately 20–40 % and 20–55 % of tomato and aubergine plants are also subjected to grafting techniques (Kozai and Ito, 1993; Lee et al., 2010).

The largest European producing countries are Italy and Spain, which produce grafted and non-grafted plants in specialised nurseries (Colla et al., 2017; Timpanaro et al., 2018, 2015). In Spain, the annual production of plants was estimated at more than 8000 million, according to a survey of vegetable transplant producers in commercial nurseries located in different autonomous communities. According to data published by the Asociación de semilleros hortícolas (Asehor), a prominent cluster of vegetable transplant producers in the Andalusian region of Spain, the Almería province stands out for approximately 80 % of the registered nursery producers, who collectively produce an impressive annual output of 1500 to 2250 million plants, being the most cultivated species tomato, pepper, aubergine, cucumber, watermelon, zucchini, lettuce, etc. (Carmona et al., 2012; Cuadrado Gómez et al., 2005; de Pablo Valenciano et al., 2019; Gallegos-Cedillo et al., 2021; Heis-Serrano, 2022). According to data from the Autonomous Community of the Region of Murcia, over 5600 million plants are produced annually in more than 60 commercial and private nurseries with an area of 437 hectares. The most cultivated species are onion, lettuce, and broccoli, accounting for 39.3 %, 28.9 %, and 17.9 % of the volume produced.

In Italy, according to a survey carried out in 2013 on a representative sample of commercial vegetable nurseries ( $n = 10$ ) located in Sicily, the average seedling production was estimated to be between 8 and 10 million plants  $\text{ha}^{-1} \text{year}^{-1}$ . In this period, the Sicilian nurseries authorised to produce vegetable transplants were 83, and the area concerned was 110 ha (Timpanaro et al., 2015). Tomato was the most cultivated vegetable species in commercial nurseries, with an average annual production of more than 5 million plants  $\text{ha}^{-1}$  (Timpanaro et al., 2018).

In the Mediterranean countries (Italy, Spain, and Greece), the production of grafted plants in 2009–2011 was more than 90 million (Bantis et al., 2019; Bogoescu et al., 2020; Lee et al., 2010).

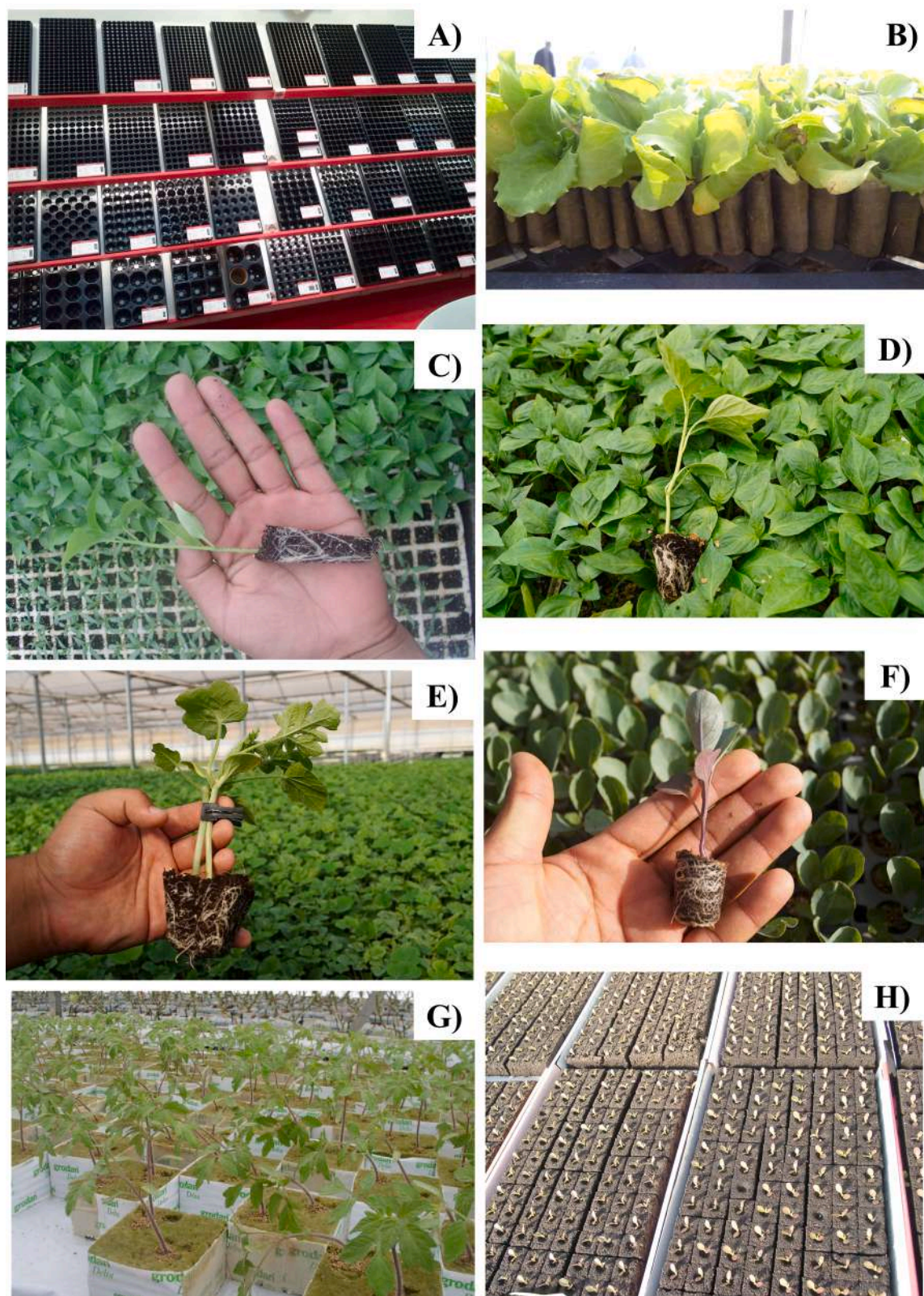
In the Netherlands, producing and trading vegetable seeds and young plants is an essential and innovative sector of the Dutch horticultural industry (Liu et al., 2015). In terms of seedling production, in past decades, the production of young tomato plants in nurseries exceeded 100 million (Klapwijk, 1986). According to data from commercial nurseries located in the Westland, one of the Netherlands' most critical protected horticultural areas, they estimate annual production of more than 2000 million plants grown in ultra-modern greenhouses (Beekenkamp Plants, 2023).

On the other side, several large-scale commercial nurseries exist in North America. In 2019, the annual production of grafted plants was found to exceed 60 million, as per the findings of a survey conducted on 20 retail nurseries situated in Mexico, the United States, and Canada. Mexico and Canada together produce 85 % of the grafted plants. They are the leading suppliers of tomato and watermelon grafted plants in the USA (Ertle and Kubota, 2020).

### 3.5. Cultural agronomic practices and techniques

#### 3.5.1. Main drivers of seedling growth and development in vegetable nurseries

**3.5.1.1. Importance of tray morphology.** The choice of trays to be used is influenced by several factors, including the type of seedling produced, the irrigation system and the greenhouse facilities and their automation (Kubota et al., 2013). Commercial nurseries commonly use expanded polyethylene and plastic trays. Fig. 5,A shows a wide diversity of shapes, cell sizes, volumes, and materials. The number of plants per tray varies from 24 to 448, which is influenced by the cell size. Other innovative methods include biodegradable paper pot trays (Fig. 5,B) (Jang et al.,



**Fig. 5.** (A) Diversity of cultivation trays; (B) biodegradable paper pots; (C) small root ball trays ( $7\text{--}23\text{ cm}^3$ ) widely used in intensive open field production or for the processing industry; (D-E) large cell volume trays ( $43\text{--}66\text{ cm}^3$ ) mainly for greenhouse cultivation and grafting production ( $>66\text{ cm}^3$ ); (F) special small volume cells for automated transplanting; (G) rockwool cubes ( $10\text{ cm}^2$ ) used for soilless cultivation systems; (H) large volume of press pots substrate (typically  $55\text{--}72\text{ cm}^3$ ) in lettuce crops. (Fig. A and H, Gruda, private collection, Fig. B-G Gallegos-Cedillo, private collection).

2020; Kumar and Raheman, 2008). In addition, recent designs include small inner walls to facilitate the extraction and disinfection of trays and prevent mechanical damage root (Gallegos et al., 2020). Furthermore, adjusting tray size and implementing automation and mechanization in transplanting processes can be effective strategies to optimize space utilization in greenhouse areas, and the automation and mechanisation of transplanting processes (Cantliffe, 2008; Kumar and Raheman, 2008; Lee et al., 2021).

**3.5.1.2. Cells dimensions.** Containers or cells' volume and depth play a critical role in producing seedlings and transplants (Table 1), directly impacting container water capacity (CC) (Gruda and Schnitzler, 2004a, 2004b). Deep cells are less prone to becoming quickly and rapidly water-saturated, making them suitable for promoting better root growth (Gruda and Schnitzler, 2000a, 2000b). The cell volume is 4 to 171 cm<sup>3</sup>, as determined by the cell's dimensions and shape, and typically resembles an inverted truncated pyramid (Fig. 5, C–E) or circular cells for automated transplanting (Fig. 5,F). In addition, the cell height determines the substrate volume, which affects the water content of media, easily available water, and amounts of water and nutrients available to the root system (Balliu et al., 2017b; Kozai and Ito, 1992; Lee et al., 2021; Vavrina et al., 1993). In general, it has been observed that the growth, robustness, and productive potential of plants are enhanced when they are cultivated in large-volume cells (Chertok et al., 2020; Lee et al., 2021; OMAFRA, 2022). The reduced density of plants per tray results in a decrease in competition for light and an increase in the availability of water and nutrients (Gruda and Schnitzler, 2006a; Leskovar, 2020). The results underscore the significance of employing suitable tray characteristics in nursery cultivation to optimize crop yield and promote successful plant development through effective utilization of substrate, water, and nutrients. Thus, carefully considering container/cell geometry is essential for sustainable vegetable seedlings and transplant production.

### 3.5.2. Transplant age

The time needed to produce a high-quality transplant in a vegetable nursery is relatively short, depending on the species grown, the season of the year and the specific temperature and lighting conditions. Generally, most crops are ready to be transplanted for about 4 to 6 weeks after sowing, considering both the economic benefits for the commercial vegetable growers (Aznar-Sánchez et al., 2020; Cantliffe, 2008; Vavrina and Orzolek, 1993). Table 1 specifies reference values (weeks) for a marketable transplant according to season and plant density per tray for

different vegetable species in commercial nurseries of southeastern Spain (typically in cold greenhouses). For example, transplants produced in summer can be ready for transplanting 1 to 2 weeks earlier than those made in winter. This advance in precocity is probably due to better-growing conditions, such as higher solar radiation and photoperiod and warmer temperatures inside the greenhouse. On the other hand, Vavrina (1998), in her review, gives the guideline age ranges for different groups of plant species families. For instance, Alliaceae crops require 10–12 weeks, while Solanaceae and Cucurbitaceae crops need 5–7 and 3–4 weeks respectively for optimal transplant age. However, when transplanting into the final field is not possible, the time of the plants in the nursery is usually extended (Bantis et al., 2019; Vavrina, 1998). Nevertheless, one of the most common causes of buttoning in some crops, such as cauliflower, is using seedlings that are too old when transplanting. On the other hand, there are certain crops whose productivity increases steadily with the age of their transplant (Leskovar, 2020). In central and northern Europe, it is a common practice for commercial nurseries to utilize sizeable containers to prolong the growth period of plants, thereby yielding larger plants. This technique consists of additional transplanting of plants grown in small containers into larger ones (e.g., pot 9 cm diameter, giant cell volume (171 cm<sup>3</sup>), and rockwool cubes (10 cm<sup>2</sup>) (Fig. 5,G)), before transplanting into the field (Pascual et al., 2018). Placing a system of stakes (plastic or natural canes) is necessary for this plant to prevent it from falling during each watering or handling.

The larger substrate volume of press pots (typically 55–72 cm<sup>3</sup>) (Fig. 5,H) offers advantages over other systems, such as multi-cell trays, including greater flexibility for transplanting and promoting more robust root growth in the field, leading to shorter cultivation times. Press pots are a high-tech production chain component involving substrate production, fully automated press pot manufacturing in plant nurseries, and specialized, high-performance equipment for planting (Laun et al., 2021).

### 3.5.3. Growing media used in vegetable transplant nurseries

The utilization of growing media in horticulture has undergone a historical transformation, exhibiting distinct phases across different countries. Before the 1950s, gardening soil was the predominant substrate. However, in the 1950s, there was a notable shift towards the popularity of peat-based substrates, solidifying their dominance by the 1960s. The trend in horticulture that began at that time is continuing today. Peat continues to be the primary material in the seedlings and transplant industry. Mineral wool was introduced in the late 1970s,

**Table 1**

Time required in weeks and number of cells per tray for a marketable vegetable transplant grafted and non-grafted. Estimated times based on data from commercial nurseries of southeastern Spain.

Non-grafted	Number of cells per tray	Number of weeks Growing season		Grafted	Number of cells per tray	Number of weeks Growing season	
		Winter	Summer			Winter	Summer
Tomato	78 (staggered)	6	4	Tomato	150	9	8
	150	6	5	Tomato (clipped)	150	10	9
Tomato (clipped)	117	8	6	Aubergine	150	8	6
Pepper	96	9	6	Cucumber	70	5	4
	104	8	5	78 (staggered)	5	5	4
150	8	6	150		7	6	
Aubergine	78	6	4		Melon	24	8
Cucumber	150	6	5	54	8	7	
	78 (staggered)	4	2	70	8	7	
Melon	96	4	3	Watermelon	24	9	8
	150	4	3		40	8	8
Watermelon	78 (staggered)	6	6	54	10	8	
	96	6	5				
Zucchini	150	6	5				
	150	5	4				
	78 (staggered)	3	2				
	104	2	1.5				
	150	2	1.5				

particularly in Western Europe, to cultivate soilless vegetables in protected environments (Gruda, 2022). The same material is used for their seedlings and transplants.

Nowadays, commercial nurseries use a range of organic and inorganic substrates for growing plants. These include materials such as peat, coir pith, compost, and wood fibres for producing seedlings to be planted in open fields. Peat-based substrates are the most widely used growing medium for both the volume of growing media and the number of seedlings produced from them (Abad et al., 2001; Laun et al., 2021). Although the root volume per seedling cell is relatively low, the cumulative impact is substantial. Depending on the plant type and quantity, the growing media needed for seedlings and transplants could constitute up to 20 % of horticultural media. Given that peat is a non-renewable resource, even if only a portion of the whole, it is prudent to consider substituting it with renewable and regenerative alternatives such as agricultural and forest resources and wastes.

To effectively handle substrates, it is essential to have a comprehensive understanding of their physical properties, including bulk density or volume weight, total porosity, and water-holding capacity. Moreover, it is equally essential to comprehend their chemical properties, such as the mineral content and cation exchange capacity, as well as their biological properties, such as N immobilization and microbial activity. This knowledge enables informed decision-making and ensures optimal growing conditions, crucial for achieving the final product's high yield and quality (Gruda, 2022). The importance of culturally adapted guidelines across diverse substrates cannot be overstated. Full realization of the benefits associated with substrates and cultivation procedures is contingent upon strict adherence to these guidelines. This adherence, in turn, guarantees the successful cultivation of plants. The physical, chemical, and biological growing media properties should align harmoniously with the water and fertilizer supply, prevailing climate conditions, and the unique requirements of the plants to facilitate optimal growth (Gruda et al., 2001; Gruda and Schnitzler, 2006b). Hence, cultural practice errors, such as a shortage of irrigation and fertigation, harm the growth rate and quality of seedlings and transplants because of the relatively low volume of substrate used in trays (Carmona et al., 2012; Gruda, 2019). Knowing the physical properties of the growing media, such as water holding capacity and changes following the water retention curves (Gruda and Schnitzler, 2000a, 2000b), can serve as a tool within irrigation strategies to optimize water use efficiency (Beaulieu et al., 2022). Also, it is possible to develop or formulate sustainable substrates and reduce agrochemical use by considering the fertility, salinity, and pH levels without affecting the quality of transplants (Zamparo et al., 2021). As we become more aware of the impact of climate change and the importance of conserving natural resources, there has been a growing interest in sustainable production methods. Thus, to meet the criteria of the circular economy, various materials have been developed, tested, and evaluated to identify suitable alternatives to peat for use in mixtures (Ceglie et al., 2015; Laun et al., 2021; Pascual et al., 2018; Scotti et al., 2020). However, many are only used locally without the potential to replace peat satisfactorily (Gruda, 2019). Compost, agro-industrial by-products, coir pith, and wood fibers are potential substitutes for peat due to their favorable properties. Some of these materials, such as compost and wood fibers, are also known to have suppressive effects on pathogenic microorganisms. Wood fibers and coir can improve the physical properties of growing media, while compost can provide minerals when blended with peat (Pascual et al., 2018; Ronga et al., 2021; Scotti et al., 2020). For instance, Laun et al. (2021) found that up to 30–50 % of peat could be replaced by raw materials such as wood fiber, coir pith, and compost amended with clay to produce press pots with similar stability to standard one. The study also revealed that approximately 95 % of all seedlings could be transplanted successfully into the field. Coir pith is a waste material that shows potential as a growing medium for seedling production without primary environmental and economic concerns (Kingston et al., 2017; Raviv et al., 2019). For instance, Martins et al. (2023)

reported on using coir-based growing media combined with municipal solid waste compost and biochar, blended with peat for lettuce seedling production. Previous studies have demonstrated the successful production of lettuce seedlings using 100 % wood fibers within a soilless culture system (Gruda et al., 2001; Gruda and Schnitzler, 2006b).

#### 3.5.4. The challenges of new materials

Incorporating new materials as substitutes for peat in container substrates can pose challenges related to phytotoxicity and other harmful issues. It is recommended to conduct bioassays to assess these challenges. The growing media industry frequently employs Chinese cabbage to assess germination rates in bioassays (Gruda et al., 2008). Nonetheless, tomatoes and lettuce, known for their sensitivity to germination and radicle growth, are also suitable candidates for such investigations. Gruda et al. (2009) conducted bioassays with tomato and lettuce seeds and three plant experiments involving marigolds (*Tagetes erecta* L.). The performance of marigold plants was similar to the bioassays with tomatoes and lettuce. While extrapolating the results directly to actual growing conditions is challenging due to various variables, including interference with nutrients and different plant species, conducting bioassays is advisable. Also, from a sustainable perspective, it is advisable to carry out these small trials rather than invest time and resources in complex experiments only to conclude that a particular material may not be recommended for use in growing media due to potential toxicity or other harmful issues. The latest may include nutrient imbalances, water retention alterations, microbial activity changes, aeration impacts, and/or potential degradation over time. Different methodologies, such as Simplex-centroid design (Ceglie et al., 2015) and Taguchi method (Tietjen et al., 2022) have been devised and assessed to recognize and aid in the decision-making process for the appropriate choice of substrate or mixture alternatives to peat.

#### 3.5.5. Is the reuse of growing media feasible?

Seedlings and transplants represent the final product's future (Gallegos-Cedillo et al., 2024), playing a crucial role in the initial phases of vegetable production, substantially influencing crop performance's overall success and efficiency. Their significance lies in accelerating the time to harvest and enhancing profitability and product quality (Gallegos-Cedillo et al., 2024). The critical stage involves a high level of risk, necessitating a secure growing medium. Furthermore, the small size of the cells leaves little space for stress relief. Additionally, ensuring food safety can be difficult when reusing the growing media. Thus, the literature's scarcity of information on reusing substrates for seedling and transplant production is not unexpected. Contrastingly, the reuse of growing media, in general, has garnered increasing attention recently (Diara et al., 2012; Machado et al., 2023; Vandecasteele et al., 2020). Adopting circular economy principles holds the potential to instigate transformative changes in this regard. Realizing this potential, however, requires the development of innovative technologies. These technologies should address challenges such as preventing pest and disease issues, facilitating the monitoring, calculation, and utilization of mineral nutrient levels, and ensuring plant growth when utilizing previously used substrates.

#### 3.5.6. Growth control and hardening methods

The suitability of seedlings for shipping and transplanting usually requires growth control. As for shipping, growth control is essential to optimize the use of the space and avoid possible damage to the plants. As for transplanting, it is necessary to ensure good-quality plants against transplantation stress since the environmental conditions are harsher than those to which the transplants were exposed during propagation (Balliu et al., 2017a) and avoid this manner of slow and non-uniform field establishment (Agehara and Leskovar, 2014). Transplants should generally have well-balanced shoot and root development (Kubota et al., 2013), implying both morphological and critical physiological changes. However, excessive hardening should be avoided as it may exhaust the

plant's energy reserves.

Different methods can be implemented for hardening. Plant growth regulators (PGRs) appeared to be the most interesting because of their ease of application, relatively low cost, and effectiveness. One common PGR for hardening seedlings is abscisic acid (ABA), a naturally occurring hormone in plants that promotes stress responses and growth inhibition (Leskovar, 2020). Also, Gibberellin inhibitors such as daminozide, paclobutrazol, and uniconazole have been commercially used to produce compact plants (Gibson and Whipker, 2001) due to their long-term growth inhibitory effects (Cantliffe and Soundy, 2000). However, these methods are currently in disuse, mainly due to environmental regulations that limit and eliminate the use of PGRs in the agricultural field. In addition to using PGRs, several alternative methods can be employed. For example, physical methods (including mechanical conditioning such as brushing, shaking, and vibration by wind or forced aeration), which are automated stimulation techniques that can reduce stem elongation by stimulating ethylene production (Kubota et al., 2013), which in turn inhibits cell elongation and promotes stem thickening (Agehara and Leskovar, 2014). Brushing can also positively affect root growth in cauliflower, celery, and lettuce (Schrader, 2000). Likewise, a low intensity brushing at an early growth stage can be recommended to improve the quality of melon seedlings and their growth after transplanting (Ayastuy et al., 2011). Nonetheless, damage can occur in Cucurbits because of their stem's fragility (Schrader, 2000). Moreover, their commercial application is limited because of the high costs of automation and labour (Latimer, 1998). Alternatively, methods of control of climatic variables (mainly lighting and the difference between day and night temperatures, known as DIF) are used. For instance, low DIF can promote stem reduction, helping to keep the seedlings more compact without using PGRs (Moe and Heins, 1990). Finally, other hardening methods are through the regulation of water supply (Kubota et al., 2013) and fertigation (Cantliffe and Soundy, 2000; Melton and Dufault, 1991) or a combination of them (Pardossi et al., 1988). For example, Kozai and Ito (1993) hardened tomato seedlings, lowering the temperature, reducing the amount of irrigation water, and modifying the fertilizer composition (high  $K^+$  and low N). They applied this combination approximately one week before shipping without decreasing the quality of the seedlings.

### 3.6. Seeding process and germination conditions

Improved seeds are widely used in commercial nurseries to improve germination and emergence uniformity. Also, automatic seeders with high adaptability and sowing efficiency are necessary. For example, cylindrical and drum vacuum seeders are the most widely used in the vegetable transplant industry. Additionally, seed-enhanced treatments such as pelleting, priming, and seed coating are extensively employed in nurseries that specialize in vegetable transplant production to enhance the efficiency of mechanised sowing operations (Pedrini et al., 2020; Taylor, 2020). Using microorganisms, such as *Rhizobium*, *Trichoderma*, *Pseudomonas* and *Bacillus*, as a seed coating treatment for vegetables is a sustainable strategy with great potential in organic and conventional nurseries (Rocha et al., 2019). Positive plant improvements, such as vigour, enhanced tolerance, and resistance to pathogens, have been reported by decreasing insecticides and fungicides (Chakraborty and Dwivedi, 2021; Jijeesh et al., 2022; Marthandan et al., 2020; Pereira et al., 2022; Raj et al., 2019). Seed priming is a pre-sowing technique that involves controlled hydration conditions to promote uniform and speedy germination. The use of seed priming technology can significantly enhance plant responses at physiological, biochemical, and molecular levels, ultimately leading to improved crop productivity (Thakur et al., 2022). However, the process of treating seeds can lead to a reduction in their quality after storage due to the fact that such seeds are typically not used immediately, thus accelerating the ageing and decreasing the longevity of the seeds. Environmental factors such as storage temperature and moisture content influence them negatively.

An innovative approach has been identified; whereby seed treatments may exert an influence on the nutritional characteristics of the crop through biofortification. This biofortification process can be initiated in the seeds via nutripriming, which involves soaking the seeds in a nutrient-based solution prior to planting (Bhardwaj et al., 2022; Farooq et al., 2019; Lutts et al., 2016). The implementation of nutripriming practice has the potential to serve as a helpful intervention to alleviate malnutrition through various means (Veena and Puthur, 2022). Alternatively, it is possible to increase the concentration of essential elements within plants (Bukhari et al., 2021).

The reference values for temperature, relative humidity (RH) and estimated germination times for the main vegetable crops are given in Table 2. For example, the optimum temperature for Solanaceae and vine crops is between 25 and 28 °C, and relative humidity is around 75–85%. The optimum temperature for lettuce and cole crops is 15–18 °C and slightly lower relative humidity (60–80%). Daily monitoring of the germination chamber is recommended to optimize the growth of young seedlings, considering both the date of sowing and the estimated time of emergence. In addition, as outlined in Table 2, this will serve as a guideline to determine the precise moment the trays should be removed from the chamber and transferred to the greenhouse to initiate the vegetative growth phase, during which the seedlings will rely on external sources for sustenance. In addition, it is recommended to inspect 10% of the total volume of trays of each consignment (Valera et al., 2002) to prevent the beginning of plant emergence, which impacts the quality of the plantlets and their commercial value (Cuadrado Gómez et al., 2005).

### 3.7. Irrigation systems used in vegetable nurseries

Irrigation in vegetable transplant nurseries is essential to obtain plant quality and uniformity (Lieth and Oki, 2019; Raviv et al., 2019). The most widespread systems are aerial and localized irrigation. The most used aerial irrigation systems are hand watering, boom, mist, and sprinkler systems (Lieth and Oki, 2019). The principle is based on the uniform distribution of water in rain, localized micro-droplets or fine mist that reduces the temperature and increases the relative humidity level in the plant environment (van Os et al., 2019; Zhang et al., 2022). Mist and fog systems are widely used in nurseries (e.g., propagation benches and growing benches). In fog systems, droplets smaller than 40 µm remain suspended in the air, while droplets > 40 µm tend to deposit and condense as water on the foliage surface and throughout the root zone (Hartmann et al., 2010). This effect improves water efficiency and quadruples the rooting percentage (80%) compared to the mist system (Tetsumura et al., 2017).

For example, microtubing and in-line systems are highly efficient, minimise leaching, and use up to 70% less water than other irrigation systems (Martí, 2005). In addition, they are commonly used in crops where sprinkler irrigation affects foliage and commercial plant quality (Marfà et al., 2012). Daugovish et al. (2012) compared the impact of spray and drip irrigation and found that drip irrigation can reduce the incidence of fungal diseases on plant leaves in nurseries.

Sub-irrigation is a highly efficient alternative to traditional irrigation methods. It is also known as zero run-off irrigation. The most used sub-irrigation systems are ebb-and-flow and flooded floor systems. Cantliffe (2009) stated that commercial vegetable nurseries in those floating systems have high water use efficiency, in addition to the decrease in the dose of fertilizers (30–50%), leaching and labour (Nemali, 2016). Nevertheless, they can be quite challenging mainly because of the initial installation cost and technological suitability of the greenhouse (Paudel et al., 2016). In these systems, the use of pesticides and the presence of foliar diseases decrease as compared with the traditional overhead irrigated systems (Leskovar et al., 1994; Wang et al., 2022).

**Table 2**  
Recommended temperature and relative humidity conditions for vegetable transplants.

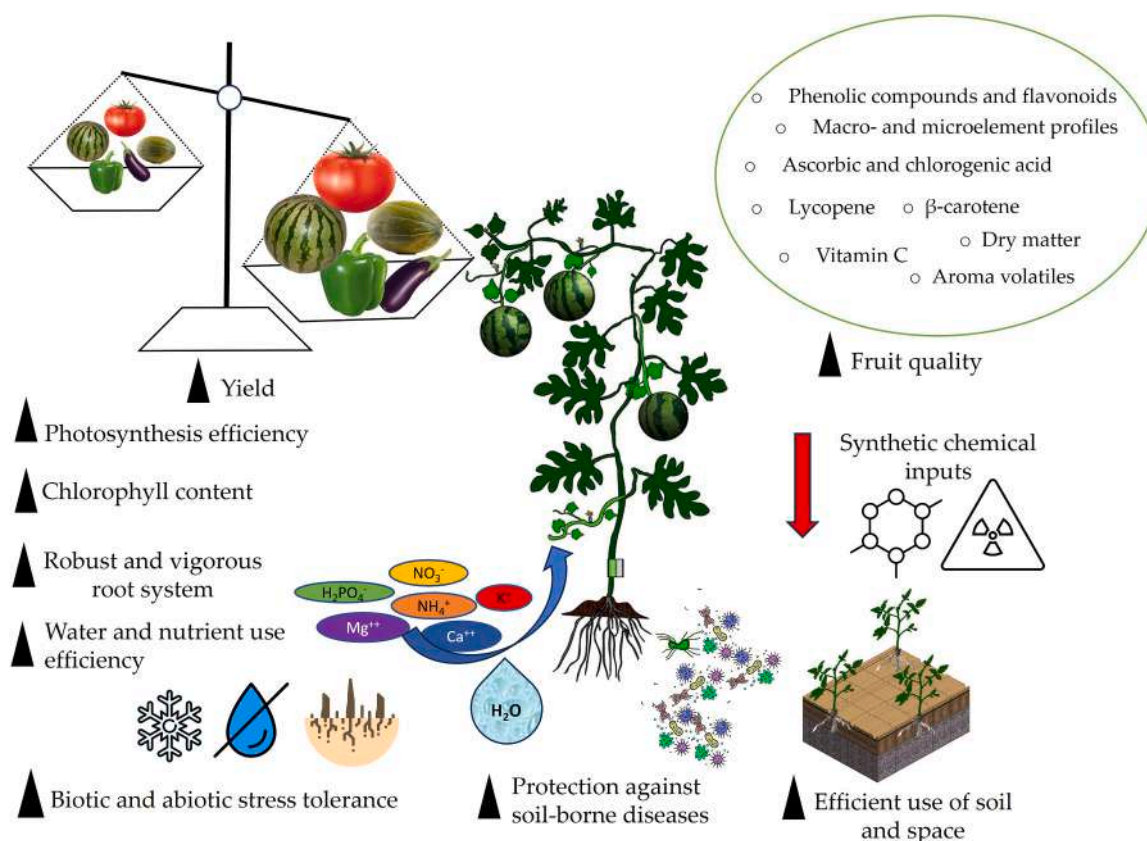
Crop	Germination chamber period Temperature (°C)			RH (%)	Days to germination	Greenhouse period Temperature (°C)	
	Minimum	Optimum	Maximum			Day	Night
Tomato	21	22	24	85	3–4	18–24	16–18
Pepper	26	27	28	75	4–6	18–24	16–18
Aubergine	20	25	35	85	3–5	21–27	18–21
Lettuce	5	15	25	85	2	13–18	10–13
Broccoli	5	23	25	60–80	2–4	16–21	10–16
Onion	18	21	24	85	3–4	16–18	13–16
Celery	5	20	30	85	7	24–16	16–18
Vine crops	24	27	30	80	2–3	21–24	12–18
Melon	15	28	35	75	3	21–24	16–18
Cucumber	15	28	35	80	2–3	21–24	18–21
Watermelon	15	25	30	85	3	21–27	18–21
Squash	15	28	30	60–80	3	21–24	16–18
Zucchini	10	25	30	60–80	2–3	21–24	18–21
Cole crops	18	21	25	60–80	3–4	16–21	10–16
Cauliflower	5	25	35	60–80	2–5	16–21	10–16
Green bean	10	20	30	60–80	2	21–28	16–18
Leek	7	15	25	75	10–14	13–14	24
Pea	15	18	20	60–80	5		
Artichoke	25	28	30	60–80	5		
Spinach	5	22	30	60–80	2		
Radish	5	15	30				
Carrot	5	18	30				
Chicory	15	22	30				

Adapted from (Balliu et al., 2017b; Cuadrado Gómez et al., 2005; Maynard and Hochmuth, 2007; Valera et al., 2002; Villarnau and González, 1999).

### 3.8. Grafting an eco-friendly and sustainable approach

Grafting is an environmentally friendly, sustainable approach to reduce plant disease, increase the yield and improve produce quality by reducing synthetic chemical inputs in vegetables (Fernández et al., 2022). The time needed to obtain seedlings ready to be grafted will

depend on the nursery’s climatic conditions. Generally, rootstock seeding is carried out 2–5 days before scion seeding (Colla et al., 2017), although this period could shorten in warm conditions. After grafting, the plants need to be healed and acclimated. For successful healing, the most critical process of grafting propagation is necessary to control temperature, relative humidity, and light conditions (Kubota et al.,



**Fig. 6.** Main morphological and physiological advantages of grafted vegetables.

2017). Although there are conflicting temperature recommendations for temperature healing from different scientists and growers related to the type of healing conditions used, the most common range is between 25 and 28 °C for 5–7 days (Colla et al., 2017; Kubota et al., 2017; Mensuali-Sodi et al., 2018). Concerning relative humidity, maintaining high values and near saturation is recommended to minimize the cuticular transpiration of grafted plants (Kubota et al., 2017). Finally, newly grafted plants must be placed in darkness or heavy shade conditions for 1–3 days following grafting. However, because light can influence the healing process, some authors have recently evaluated the effect of different light spectra on this process, obtaining differing results according to each genotype combination and spectrum used (Bantis et al., 2021; Li et al., 2015). After the callus has formed and the wounded surfaces are healed, plants may be put under relative humidity-decreasing conditions to acclimatize fully to the ambient environment inside the nursery (Mensuali-Sodi et al., 2018).

At present, the technique of grafting is predominantly employed in Cucurbitaceae and Solanaceae plant families, and it is spreading rapidly across the globe (Fernández et al., 2018). Grafting involves combining plants of the same or different species, such as tomato with tomato, or tomato with eggplants (Abdelmageed and Gruda, 2009). The main morphological and physiological advantages of the grafted plants are detailed in Fig. 6. The benefits of this technique include increased growth and root system development, leading to improved resource efficiency (e.g., water, nutrients) (López-Marín et al., 2013). Additionally, increased resilience to biotic and abiotic stress scenarios enhances the photosynthetic efficiency and chlorophyll content (Martínez-Ballesta et al., 2010). Likewise, improved protection against soil-borne diseases and soil depletion caused by successive cropping activities (Lee et al., 2010). In addition, speciality crops such as globe artichoke and green bean have been successfully grafted onto specific rootstocks with promising results (Koren et al., 2017), remarkably to reduce the incidence of soil-borne diseases, such as *verticillium* in globe artichoke and *fusarium* and nematodes in green bean (Mensuali-Sodi et al., 2018). This particular approach has garnered extensive usage within the agricultural domain, with the primary objective being to optimize both the quantity and caliber of fruit produced (Colla et al., 2017).

The most common vegetable grafting methods are shown in Fig. 7. Tongue approach grafting, also known as side-by-side grafting, is principally used in cucurbits (mainly watermelon), where both the scion and rootstock retain their root system during graft union formation (Fig. 7, A–B). In watermelon and melon, aside from the tongue approach graft,

the frequently used grafting methods include hole insertion (Fig. 7,C), side insertion (Fig. 7,D) and one cotyledon (Fig. 7,E), in which only the root system of the rootstock is retained. Furthermore, the slant-cut graft for cucumber, melon, and watermelon (Fig. 7,F) was developed especially for robotic grafting. On the other hand, cleft grafting (Fig. 7,G–H) and tube grafting (Fig. 7,I–J) are the most widely used methods for grafting tomato, pepper, and aubergine plants. It is also used in cabbage crops (Fig. 7,K) as a potential tool to improve cabbage head quality (Chen et al., 2019). Finally, pin grafting is commonly employed for tomato and pepper plants (Fig. 7, L–M). This technique involves using a ceramic or acrylic pin to enhance the union between the scion and the rootstock.

Fig. 8 provides a summary of the benefits associated with the primary rootstocks used in vegetable crop production. For an updated and comprehensive list of rootstock varieties used in commercial Solanaceous and Cucurbitaceous crop production, reference could be taken to (Colla et al., 2017; Mensuali-Sodi et al., 2018; Roskopf et al., 2017). Sometimes, obtaining a favorable graft using robust rootstocks, such as *Cucurbita maxima* x *C. moschata*, can be a challenging task. To overcome this hurdle, it is recommended to employ the stenting method, which entails executing the cutting and grafting procedures concurrently (Kroin, 2016). Notwithstanding the efficacy of this technique, a significant limitation is the exorbitant cost of grafted seedlings which can be primarily attributed to the labor-intensive nature of the operation. Consequently, high-performance universal grafting machines (robots) are increasingly used to reduce the workload in nurseries and improve grafting productivity (Pardo-Alonso et al., 2019; Yan et al., 2022). These innovations are anticipated to enhance the efficiency and accuracy of the grafting, augment crop yields, and decrease labour expenses for the nursery transplant industry.

### 3.9. Supplemental lighting LED as a novel technology in vegetable transplant production

The production of vegetable in plant factories, also known as enclosed and controlled cultivation chambers, offer a suitable environment for growing transplants, is experiencing exponential growth in the agriculture industry (Nájera et al., 2023, 2022). This production system is viewed as a favourable option to acquire high-quality young plants. Its proficiency in using natural resources, especially in the face of climate change, is noteworthy (Borrelli et al., 2020; Kozai and Niu, 2020). Furthermore, it enhances the nutritional value of healthy products. Supplementary lighting is used in modern nurseries for various

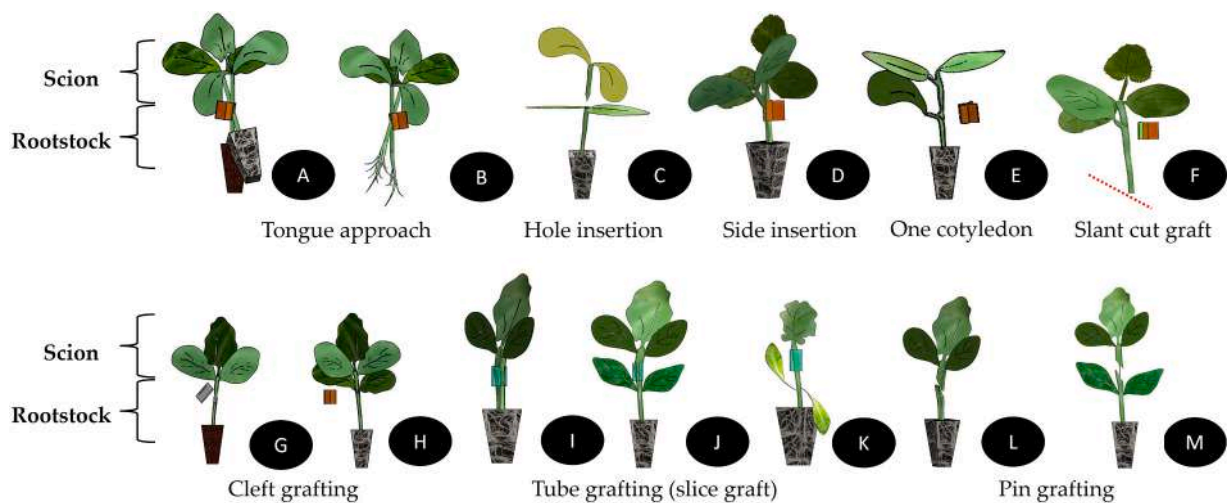


Fig. 7. Herbaceous grafting: (A–B) Tongue approach; (A) Scion and rootstock root systems are retained with root ball and (B) bare root during the grafting process; (C) Hole insertion; (D) Side insertion; (E) One cotyledon (only the rootstock root system is retained); (F) Slant cut grafting (without root system); Cleft grafting (G–H) Under and on the rootstock cotyledons; (I–J–K) Tube grafting; (L–M) Pin grafting under and on the rootstock cotyledons.

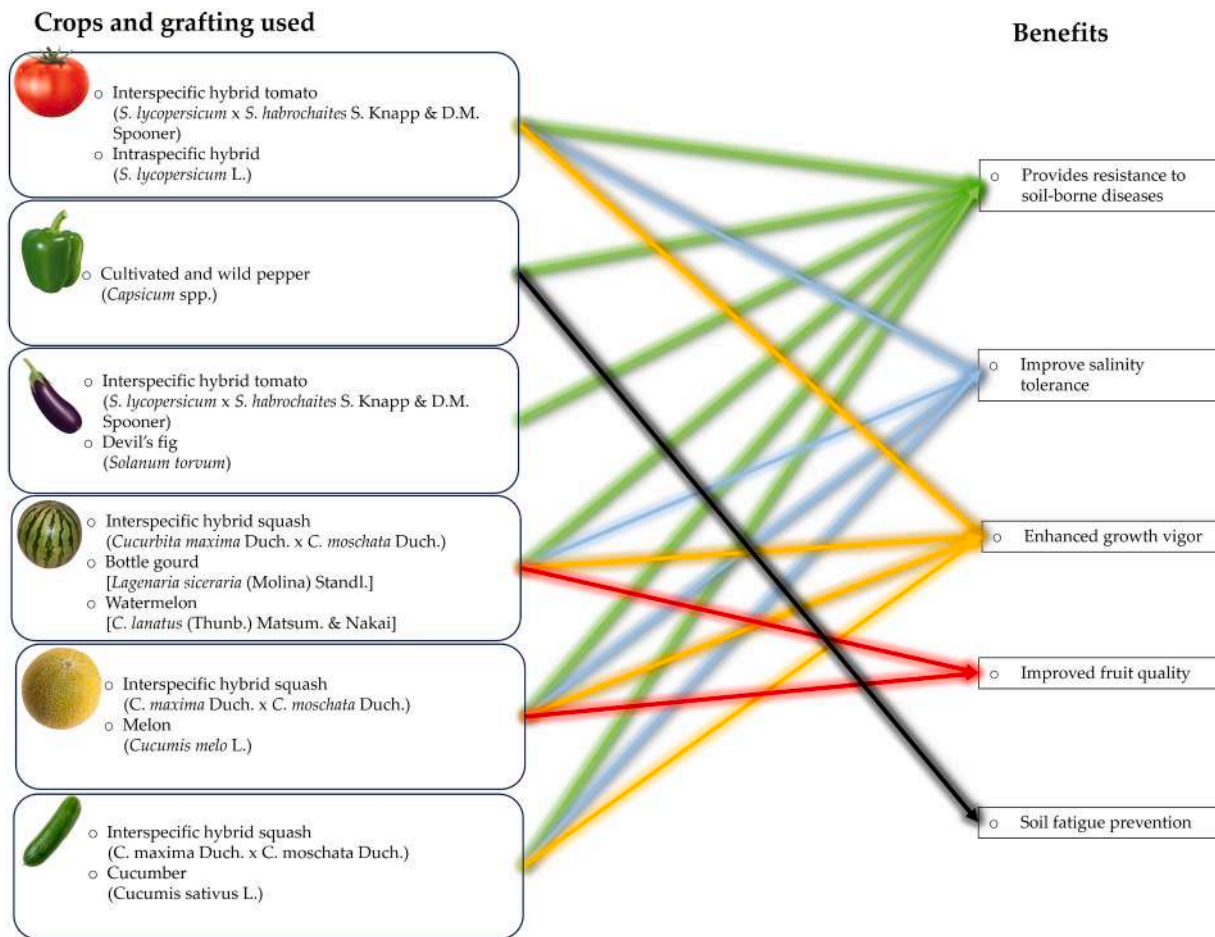


Fig. 8. Primary rootstocks in vegetable crop production and their advantages. Adapted from (Mensuali-Sodi et al., 2018; Gallegos-Cedillo et al., 2024).

procedures, including grafting production, healing, and acclimatization strategies. Light performs an essential role because it can influence hormonal regulation and tissue regeneration, which is of great significance for the development and growth of grafted seedlings (Li et al., 2015). For example, it has been studied that graft healing in tomato plants with the green spectrum has improved, and it may be because green light regulates the gene expression of some proteins or enzymes that positively influence the graft healing process and the functioning of the roots (Li et al., 2021). Likewise, plant hormones such as auxins are involved in the growth of plant vascular tissue that is synthesised in the plant, and turn, light is a factor involved in the lateral transport of hormones within the plant so that light can influence the availability of auxins (Yousef et al., 2021b). In recent years, the effect of LED lights on the development of plants has been studied (Fig. 9,A), both in culture chambers and greenhouses or tunnels (Fig. 9,B), experiencing benefits in the growth and morphology of seedlings according to the different spectra used, or even the combination of these, and the benefit precisely in grafting (Fig. 9,C). Nguyen et al. (2014) can have up to 50 % differences in seedling survival between a plant factory structure with artificial LED lights (indoor) and a conventional tunnel system. Fig. 9,B (chamber) shows the design of a plant factory that makes maximum use of space and resources and is like the structure of vertical farming crops, where the involvement of technologies is the protagonist, being one of the most innovative systems in recent years (Bie ZhiLong et al., 2017). However, in organic transplant nurseries, it is a little-studied system. The racks with independent sections and equipped with lights (Fig. 9,B) are essential complements to the light chambers, as they allow the seedlings to receive sufficient artificial light and effectively penetrate

the plants; the racks have spacings between one base and another of 40 to 60 cm (Benke and Tomkins, 2017), making the system even more efficient. One of the most frequent and most widely used infrastructures in seedlings worldwide are conventional greenhouses or growing tunnels (Moosavi-Nezhad et al., 2022), which, in comparison to controlled chambers, are less efficient and have a higher plant mortality rate (Colla et al., 2017). In addition, it has been studied that healing is improved under controlled conditions with  $150 \text{ mol m}^{-2} \text{ s}^{-1}$  illumination, and the connection between the scion and the rootstock is better than under greenhouse or tunnel conditions (Jang et al., 2014).

Concerning the spectral range employed, the absorption peaks most frequently used fall within 450–495 and 620–750 nm using a blended spectrum of Blue and Red LED lamps, respectively. In some studies, incorporating and specifying spectra has led to the conclusion that LED lamps have a positive impact on plant dry weight (Marcelis et al., 1998; Stanghellini et al., 2019) and photosynthetic activity (Yousef et al., 2021a).

### 3.10. The use of beneficial probiotic microorganisms

The use of sustainable production tools such as biostimulants and beneficial micro-organisms has witnessed a steady rise over time. Notably, the scholarly discourse on biostimulants has surged in the last five years, with the number of published papers reaching approximately 885 articles—a marked increase compared to the 255 articles published during the period of 2010–2014 (Gallegos-Cedillo et al., 2024). Fig. 10 summarises different cultivation strategies and strengthening agents for sustainable vegetable transplant production. Pre-sowing seed and

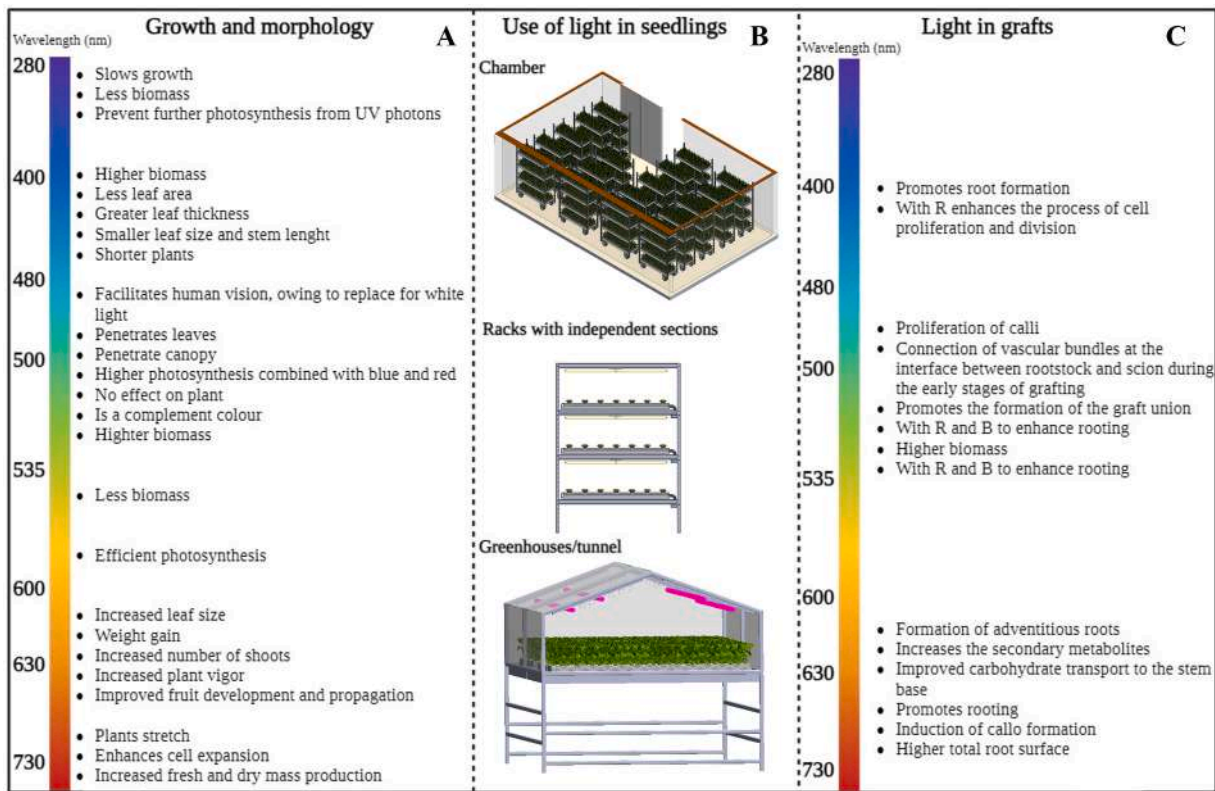


Fig. 9. Schematic representation of the spectral benefits in seedlings and transplants production (A), systems used in seedlings with lighting (B) and the benefits of LED light in the grafting of vegetable plants (C).

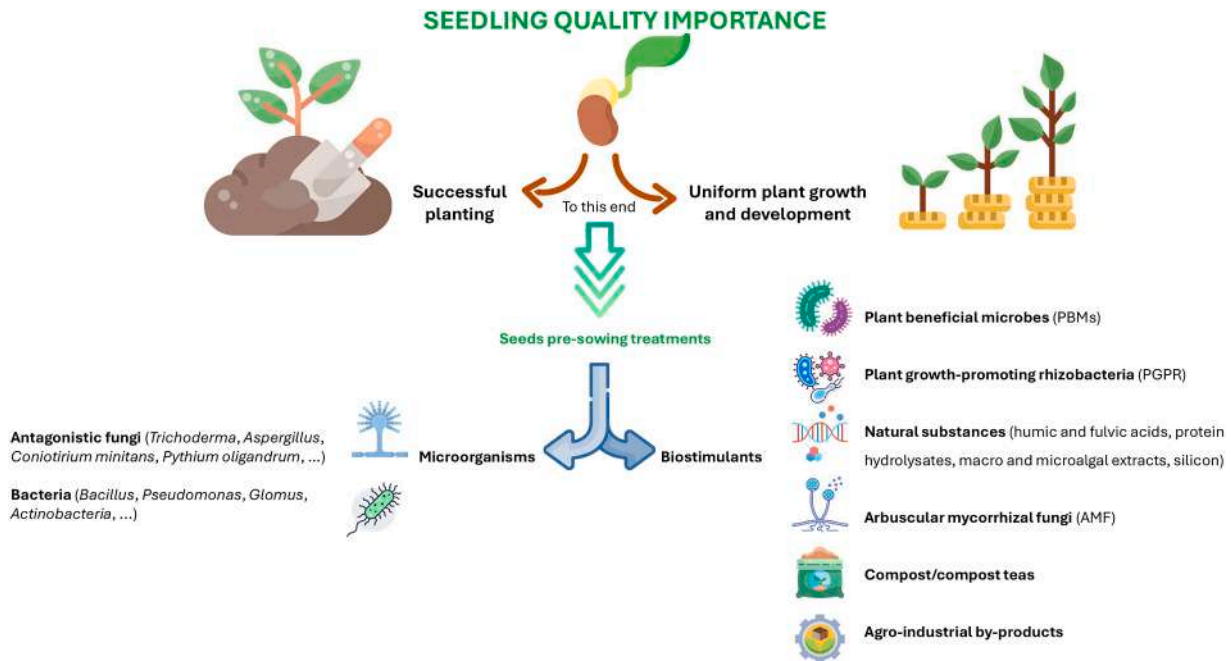


Fig. 10. Strengthening agents for sustainable vegetable transplant production. Created with [www.flaticon.com](http://www.flaticon.com).

seedling treatments with biostimulants and microorganisms have generated significant interest due to their excellent efficacy and environmental benefits (Cardarelli et al., 2022; Dasgan et al., 2023b; 2023a). The primary focus within the nursery sector has recently been on the application of sustainable production tools, particularly concerning plant growth, biomass production, pathogen incidence, dry matter

content, effects on root characteristics and various facets related to the enhancement seedling quality (Gallegos-Cedillo et al., 2024; Ronga et al., 2021). In addition, the use of low and high molecular fractions (LMF and HMF, respectively) were used, for instance, for eggplant cultivation to enhance enhanced seed germination and seedling growth, regarding fresh and dry weight (Kaniyassery et al., 2024). Other aspects

are related to the use of humic and fulvic acids (Bettoni et al., 2014; Zhang et al., 2021), macro and microalgal extracts (Hernández-Herrera et al., 2014; Puglisi et al., 2020), protein hydrolysates (Rouphael et al., 2021), arbuscular mycorrhizal fungi (AMF) (Baum et al., 2015; Comite et al., 2021). Furthermore, compost and its by products, are reported as a viable alternative approaches (Rouphael and Colla, 2020). However, it is recommended to consider the current Regulation (EU) 2019/1009, governing the promotion and sale of fertilizing products in the European Union, which also encompasses the microbial biostimulants containing Arbuscular Mycorrhizal Fungi (AMF) and plant growth-promoting rhizobacteria (PGPR).

Recent studies have shown that using AMF and PGPR on vegetable seedlings can enhance plant biometric traits, vegetable nutrient quality, and resistance to abiotic and biotic stress (e.g. salinity stress) (Bettoni et al., 2014; Mohamed et al., 2016; Ren et al., 2019).

Gustab et al. (2024) studied the impact of multi-bacterial inoculation on the growth of the seedlings of some Brassicaceae species in the greenhouse. The authors stated that the bacterial inoculum may substitute fertilization for Brassica seedlings. The efficacy of this substitution depends on the plant species, and using all four bacterial strains together was essential for a positive effect. Some applications may have physiological implications in impact phytopathogens ameliorating the adverse effects of some phytopathogens, such as the use of calcium-mobilizing biostimulants applied in hydroponic nutrient solutions, to mitigate tip burn in butterhead lettuce, apart from increasing fresh weight and dry mass (Biradar and Meng, 2024).

Due to the ongoing evolution of modern horticulture, the selection of vegetable species and their integration with diverse cropping factors, such as hydroponic systems and LED lamps, is constantly changing. As a result, the use of biostimulants is also adapting to align with these emerging trends. For example, it has been observed that a high red/far-red ratio promotes root colonization of *Serratia plymuthica*, a PGPR (Guo et al., 2024).

Some fungi strains, such as *Trichoderma harzianum*, *T. saturnisporum*, are used as biological control agents to improve the quality of seedlings and fruit quality, owing to their biostimulant activity and suppressive effects (Pascual et al., 2017; Yu et al., 2024). For example, Rasool et al. (2024) reported that substrates inoculated with bacterial and fungal strains (*Trichoderma* spp. and *Enterobacter* MN-17) had the highest germination percentage and earliest mean germination from marigold and zinnia. Likewise, bacteria and biochar may be used to mitigate the effects of salinity on *Prosopis koelziana* seedlings (Saadatfar et al., 2024).

Another category of biostimulants is compost and its by-products, such as compost “tea” and vermicompost “tea” (Villego et al., 2020). It has been observed that the growth-promoting may be associated with the release of extracellular microbial signals/nutrients and/or the nutrient availability of the applied vermicompost tea, rather than the microbial biomass itself (Javanmardi et al., 2024).

Finally, the digested deriving from agro-industrial by-products could be used as sustainable fertilizer for seedling production (Nkoa, 2014), as during anaerobic digestion, NPK is retained into the liquid phase (Aso, 2021). Some authors such as (Lencioni et al., 2016; Yagüe and Lobo, 2020), have reported that liquid digestate may be used on horticultural crops to stimulate a low concentration of seed germination. In contrast, Ronga et al. (2018) used liquid digestate as fertilizer for the soilless production of baby-leaf lettuce. In addition, the solid-state digestate has been used as a peat replacement for sage (Greco et al., 2021) and basil and peppermint cultivation (Ronga et al., 2018). Finally, livestock blood has been identified as a potential source of sustainable fertilizer for organic seedling production (Ronga et al., 2021). However, its suitability for use as a fertilizer is subject to verification of food safety concerns.

### 3.11. Seedlings, sustainability, and climate-smart agriculture

One of the biggest challenges we will face in the future is

undoubtedly the impact of climate change (Bisbis et al., 2019). According to Reed et al. (2022), the influence of climate change is projected to exert a more pronounced effect during the early phases of plant development, particularly in germination and seedling establishment, in contrast to the later adult stages. Consequently, there is a great need for intelligent production practices to manage and alleviate the impact of climate change effectively (Gruda et al., 2021). Climate-smart agricultural practices are a multifaceted paradigm that encompasses various dimensions. In the realm of seedling and transplant production, this entails carefully selecting climate-resilient varieties that showcase superior performance, especially in early growth stages. Deploying controlled environment structures is highly advisable, providing a protective shield for seedlings against adverse impacts from extreme weather events and temperature fluctuations. Additionally, exploring novel growing media characterized by superior water retention and optimal aeration for seedlings holds promise for promotion to drought conditions. Incorporating microorganisms and biostimulants can significantly contribute to sustainably enhancing resilience (Dasgan et al., 2022; Ikiz et al., 2024; Kilic et al., 2023). Furthermore, precision irrigation systems optimize water use and harmoniously adjust water supply with plants' discerned needs and prevailing environmental conditions. The analysis of weather data, coupled with soil moisture sensors and advanced tools integrated into robotic and AI decision-making processes, facilitates nimble and informed modifications to production practices in response to the fluctuations of climate conditions. Lastly, a critical facet of this comprehensive approach involves well-trained agricultural practitioners equipped with a proactive stance and skills to meet the nuanced demands of climate-resilient seedling production. Therefore, adopting climate-smart agricultural practices can help promote sustainable seedling and transplant production, thereby enhancing agricultural productivity and food security in the face of climate change. The seedling industry should also be prepared to accommodate the introduction of new crops in different locations while honoring consumer preferences (Hong and Gruda, 2020).

## 4. Conclusions

Research on vegetable seedlings and transplants is rapidly evolving, and new trends are constantly emerging. The study sheds light on the increasing importance of sustainable practices in the horticultural industry and the rapid expansion of new technologies. It also identifies several critical practical issues and research topics, including seed tray design, sustainable growing media, seed-enhanced treatments and germination conditions, grafting, irrigation methods, LED lighting technology, biostimulants and beneficial microorganisms as booster agents that can enhance efficiency and promote sustainable production. Finally, it provides an in-depth analysis and insight into developing sustainable and efficient vegetable transplant production systems nowadays. Future research in sustainable vegetable seedling production is anticipated to prioritize alternative growing media, biological control with an emphasis on biostimulants, circular economy practices, climate-adaptive seedlings, and advanced automation.

## CRedit authorship contribution statement

**Victor M. Gallegos-Cedillo:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Cinthia Nájera:** Writing – review & editing, Writing – original draft, Resources. **Nazim S. Gruda:** Writing – review & editing, Supervision, Conceptualization. **Angelo Signore:** Writing – review & editing, Writing – original draft. **Jesús Gallegos:** Writing – review & editing, Writing – original draft, Visualization. **Roberto Rodríguez:** Writing – review & editing, Writing – original draft. **Jesús Ochoa:** Writing – review & editing, Writing – original draft. **Catalina Egea-Gilabert:** Writing – review & editing, Writing – original draft. **Juan A. Fernández:** Writing – review & editing,

Writing – original draft, Conceptualization.

## Declaration of competing interest

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

## Data availability

Data will be made available on request.

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