Review

Received: 7 July 2023 Revised: 4 January 2024 Accepted article published: 14 January 2024 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.13309

Analysis of global research on vegetable seedlings and transplants and their impacts on product quality

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Abstract

BACKGROUND: Previous research has established that using high-quality planting material during the early phase of vegetable production significantly impacts success and efficiency, leading to improved crop performance, faster time to harvest and better profitability. In the present study, we conducted a global analysis of vegetable seedlings and transplants, providing a comprehensive overview of research trends in seedling and transplant production to enhance the nutritional quality of vegetables.

RESULTS: The analysis involved reviewing and quantitatively analysing 762 articles and 5248 keywords from the Scopus database from 1971 to 2022. We used statistical, mathematical and clustering tools to analyse bibliometrics and visualise the most relevant research topics. A visualisation map was generated to identify the evolution of keywords used in the articles, resulting in five clusters for further analysis. Our study highlights the importance of the size of seed trays for the type of crop, the mechanical seeder used and the greenhouse facilities to produce desirable transplants. We identified grafting and light-emitting diode (LED) lighting technology as rapidly expanding technologies in vegetable seedlings and transplant production used to promote plant qualitative profile.

CONCLUSION: There is a need for sustainable growing media to optimise resources and reduce input use. Thus, applying grafting, LED artificial lighting, biostimulants, biofortification and plant growth-promoting microorganisms in seedling production can enhance efficiency and promote sustainable vegetable nutritional quality by accumulating biocompounds. Further research is needed to explore the working mechanisms and devise novel strategies to enhance the product quality of vegetables, commencing from the early stages of food production.

Keywords: bibliometric analysis; organic transplant nursey; LED lights; biostimulant; nutripriming; biofortification

INTRODUCTION

Vegetables are crucial for a balanced and healthy diet as a result of their high nutritional value, including secondary metabolites, vitamins, minerals and dietary fibre, whereas they are low in calories and fat. Their consumption has been linked to various health benefits, such as reducing the risk of chronic diseases and promoting overall well-being.[1] The positive impact on health is attributed to the range of biological substances in vegetables rather than individual elements.[2]

Vegetables can be cultivated by different propagation methods, including direct sowing of seeds (e.g. beans and peas), transplanting seedlings (e.g. lettuce, cabbage, tomatoes and peppers) or using vegetative plant parts (e.g. garlic, rhubarb, chicory and sweet potatoes). The quality of vegetable produce depends on plant genotypes, the performance of environmental conditions and applied agro-management practices.[2] Although the

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importance of genetic material on vegetable quality is acknowledged, seedlings primarily aim to enhance yield, optimise harvesting time, protect against plant diseases and mitigate abiotic stress. Using high-quality planting material in the early phase of vegetable production significantly impacts overall success and efficiency. This can lead to improved crop performance, faster time to harvest and better profitability, regardless of whether in a greenhouse or open field setting. Although the impact of seedling use on the size of the final vegetable product is widely accepted, its effect on nutritional quality remains a topic of ongoing debate because there need to be more comprehensive studies. Additionally, the long interval between transplanting and harvest may diminish the potential benefits of seedling use regarding nutritional quality. Thus, it is pertinent to ask whether the potential exists to enhance the quality of consumable vegetables during the initial phases of plant cultivation. If so, to what extent can these improvements be sustained over time?

Good production planning is necessary to coordinate with the final crop production, which includes keeping records of seeding dates, variety names, substrate types, tray types, irrigation and chemical applications.[3] The trend of commercial seedling and transplant production in highly specialised nurseries is increasing worldwide.[4] Moreover, the production of plants in vegetable nurseries plays a strategic role in the agricultural sector. It contributes to employment and local and sustainable development as a result of high labour dependence.[5,6]

The location of commercial nurseries is crucial, as long distances may preclude purchasing transplants. In addition, timely and quality of the plantlets must be ensured.[3] Therefore, optimal growth conditions should be maintained through controlled water, temperature, substrate and fertiliser operation.[3,4] This should also be respected for the new production methods, such as vertical farming. Recent trends in research on vegetable seedlings and transplants have focused on various aspects, including biotechnology, plant physiology and agronomy. For example, biotechnological techniques have been used to develop plants of agronomic interest that are more productive, more efficient in nutrient uptake, resistant to different types of abiotic stresses and biofortified.[7,8]

Moreover, researchers are exploring the potential of grafting, biostimulants and plant growth-promoting microorganisms (PGPMs) to improve the quality of planting materials. Grafting and specific rootstock/scion combinations can significantly impact the macro- and microelement profile, phytochemical composition and overall fruit quality of various vegetables.[9] Furthermore, plant biostimulants have been demonstrated to enhance the quality of plants and, additionally, the produce quality. According to recent research studies, this improvement is evident through the stimulation of the accumulation of secondary metabolites, vitamins, antioxidants and minerals.[10,11] Finally, PGPMs have demonstrated the ability to enhance nutrient uptake, improve stress tolerance and minimise plant diseases. Additionally, using PGPMs can reduce the usage of chemical fertilisers and pesticides, promoting eco-friendly vegetable production.[12-14]

Furthermore, biofortification has emerged as a novel strategy for improving the nutritional content of vegetables, making them more beneficial to human health.[15] Recent studies demonstrate that combining different approaches can often boost final vegetable nutritional and functional traits.

Therefore, applying grafting, biostimulants, biofortification and PGPMs during the early stages of vegetable production results in more efficient utilisation of these techniques in a limited area with the same plant numbers.

Although vegetable seedlings and transplants are vital to horticulture and significantly improve the efficiency of agricultural practices, there needs to be a more comprehensive global analysis and study on this topic. Hence, the present study aimed to address this gap and provide an overview of recent advances, evolution, and challenges in the vegetable seedlings and transplant nursery industry. Additionally, the technical requirements for producing high-quality vegetables highlight the crucial role of research and development in this early phase of food production.

METHODS

Data for the 1971–2022 period, retrieved from the Scopus database (https://www.scopus.com), were reviewed and analysed. In addition, quantitative analyses were performed for the keywords 'vegetable transplant production', 'specialised nursery', 'organic vegetable transplants', 'seedbed', seedling* and nursery* using the search field 'Article title, Abstract, and Keywords', resulting in a total of 762 articles and 5248 keywords.

We conducted an academically driven bibliometric analysis utilising statistical, mathematical, and clustering tools to visualise the most pertinent research topics. The analysis was based on the keyword co-occurrence ratio and similarity index, with the unit of analysis encompassing both author and indexed keywords. A minimum keyword occurrence threshold of eight was established to ensure the robustness of the analysis. Moreover, we created a thesaurus file to enhance the consistency of the prominent research topics.[16,17] At the same time, an overlay visualisation map was generated to identify the evolution of keywords used in the articles analysed in the present study and the research trends. Finally, these data were processed and analysed using the clustering algorithm of the VOSviewer, version 1.6.18 (Centre for Science and Technology Studies, Leiden University, The Netherlands).[18]

From the total number of articles obtained ($n = 762$), a random and representative sample was extracted and analysed by relevance from the Scopus database. A quantitative, detailed and meticulous analysis of the articles was performed to collect the data of interest, such as the plant species under study and the specific research areas.

Surveys were conducted in various agricultural regions to address the absence of official statistics on vegetable transplant production volume and area, and input was obtained from producer groups and associations with expertise in producing vegetable transplants. Additionally, data published in articles indexed in the Scopus database were reviewed.

CLUSTERING ANALYSIS ON BIBLIOMETRIC DATA

In all the publications analysed, of the total number of keywords obtained (5248), only 131 reached the established threshold above. This set of keywords was grouped, generating five clusters in different colours in the network visualisation map (Fig. 1). Each cluster shows closely related items from the same field or line of research. According to recent reviews based on keyword analysis, the size and number of clusters can identify trends and future directions in a thematic line of research.[16,19,20] Becaue of their high occurrence and total link strength, the top-ranked keywords

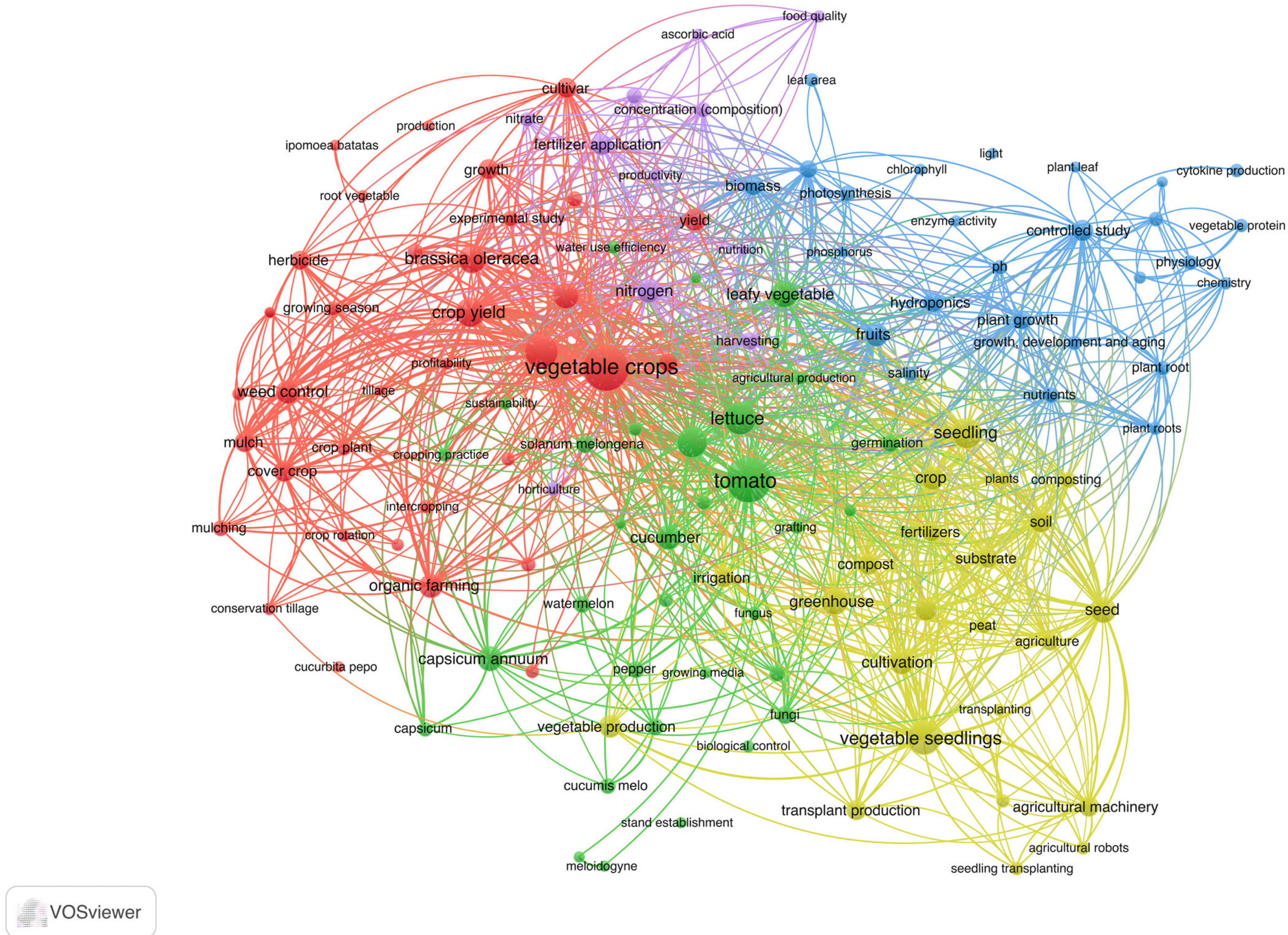

Figure 1. Network visualisation map generated from analysing the most repeated keywords in articles published from 1971 to 2022. Different colours represent the diversity of thematic clusters found and associated keywords. Red (cluster 1), green (cluster 2), yellow (cluster 3), purple (cluster 4) and blue (cluster 5).

in the present study are vegetable crop, crop production, tomato, crop yield, seedling, controlled study, vegetable seedlings and organic farming. For the studied period, different lines of research are highlighted; for example, Cluster 1 (red) with 31 items, including studies related to production techniques, transplantation and organic farming. Likewise, another line of research with 29 items (cluster 2; green) includes topics such as seedling production, controlled study, plant nutrition and plant growth. Compost, fertiliser application, irrigation and growing media were other primary descriptors used as keywords, as shown in cluster 3 (yellow). The most relevant and highest cited articles in this area are the publications of Raviv *et al.*[21] Sánchez-Monedero *et al.*[22] and Gruda and Schnitzler,[23] which develop a research topic concerning the use of compost and alternative growing media to produce vegetable transplants. Another line of research (cluster 4; purple) includes current topics such as sustainable agriculture, alternative agriculture, and water use efficiency. Indeed, they are research topics of great interest in line with new research trends for sustainable agriculture development.[24] Finally, a new approach (cluster 5; blue) highlights current issues related to the quality and nutritional composition of vegetables, where some cultural practices, such as fertilisation levels and irrigation strategies, influence the accumulation of some beneficial compounds (such as vitamin C, anthocyanins and glucosinolate profile),[25-27] as well as nitrate levels, which, in excessive intake, can be phytotoxic to human health.[28]

The overlay visualisation map shows the evolution of keywords used to describe the main content of a research study, with the most recent and relevant topics highlighted in green and yellow (Fig. 2). These keywords are agricultural robots, agricultural machinery, seed, seedling transplanting, organic farming, crop rotation, food quality, compost, peat and sustainability. In addition, other topics that have received considerable attention from 2008 to the present in the Scopus database are grafting, organic agriculture, biostimulants and light-emitting diodes (LEDs). The most cited and relevant work in this category was published by Lee *et al.*,[29] who described grafting techniques, automation, and prospects. Other examples relate to relatively recent trends, such as the use of biostimulants[30] and LED lights,[31] in which the effects on plant growth and development and their influence on improving the nutritional profile are described. Moreover, they are classified as environment-friendly agricultural practices. Figure 3 shows the temporal trend in the number of scientific articles published regarding biostimulants and LED lighting as transplant boosters and strengthening agents for vegetable cultivation. The interest in biostimulants in vegetable transplant nurseries increased over

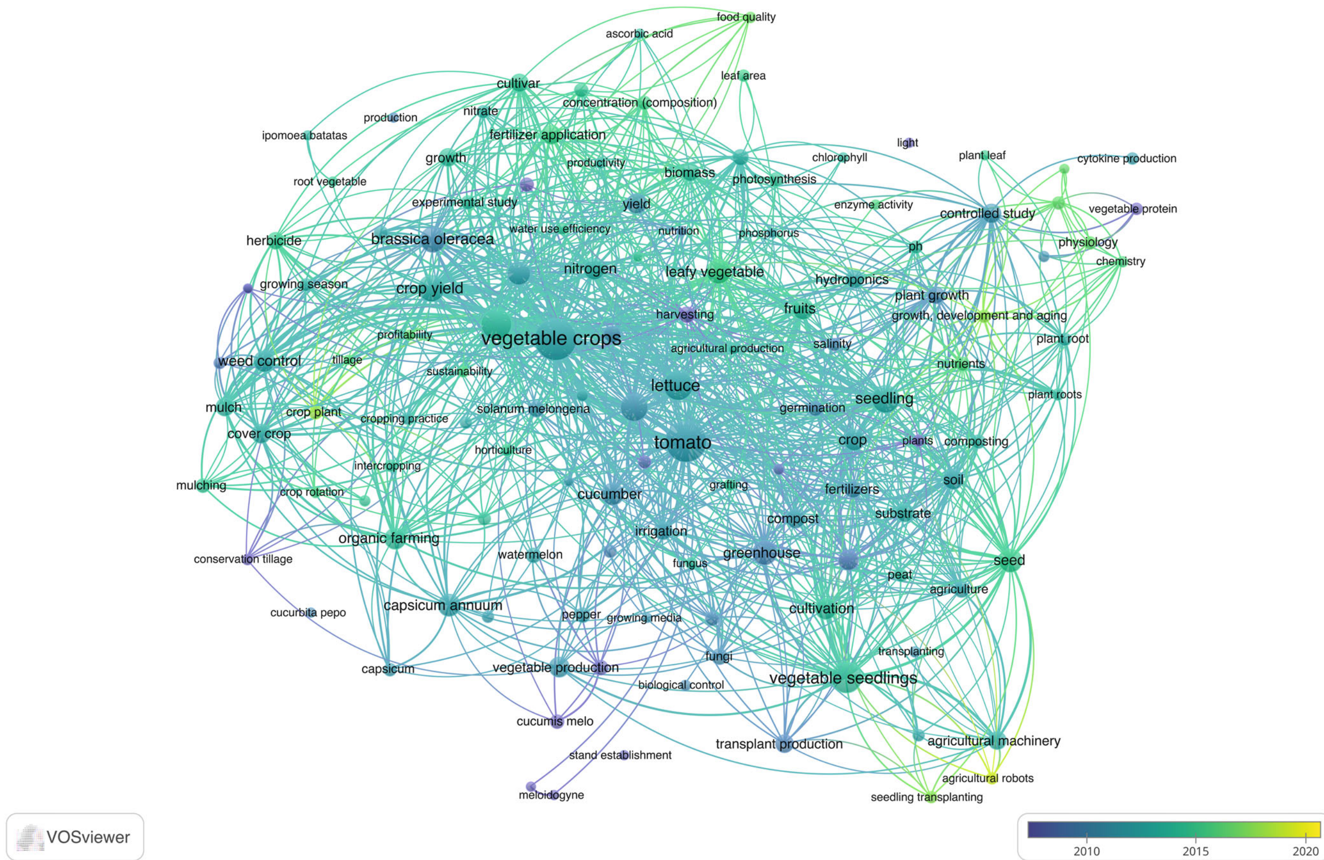

Figure 2. The overlay visualisation map shows the evolution of research keywords over time based on the average publication year. Earlier research topics are coloured purple, and more recent items are shown in green and yellow.

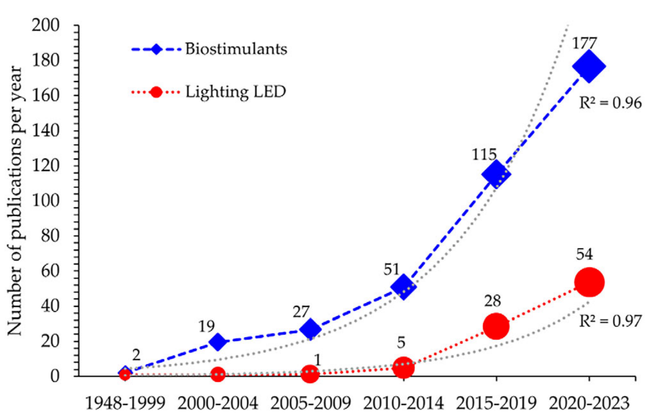

Figure 3. Temporal trend in the number of scientific articles published regarding biostimulants and light-emitting diodes (LED) lighting in vegetable nurseries.

time, as demonstrated by the increasing number of scientific articles, particularly in the last 8 years (Fig. 3), with a total percentage of 68% and a peak in the previous 3 years of 177 records per year. In the same way, the adoption of LED lighting as a cultivation technique shows a positive exponential trend ($R^2 = 0.97$), with a 90.8% increase in the number of articles published in the last 5 years (Fig. 3). This may be because plant production in highly controlled environments has increased dramatically.[32] Supplemental lighting with light LED has been adopted in cultivation techniques such as grafting, healing and acclimatisation strategies.[33,34]

A BRIEF HISTORY AND A GLOBAL PERSPECTIVE OF VEGETABLE TRANSPLANT PRODUCTION SYSTEMS

The technique of producing transplants of vegetable species in highly qualified nurseries has acquired relevance and gradual evolution. In the mid-twentieth century, the most widespread plant production method was through *almácigas* or nursery beds,[35,36] until the first large-scale plant production systems were developed using cell containers, trays or pots of different sizes and substrates as growing media.[37-39] However, it was not until the 1970s that nurseries and large-scale commercial sales of plants saw global expansion. Figure 4 shows the main changes that have taken place in vegetable transplant production over the years, where the adoption of technological innovations has allowed the development of specialised industrial nurseries and increased efficiency in the agricultural production chain. Primarily, it was driven by the advantages of obtaining high-quality plants with uniform characteristics, robust root systems and increased tolerance to biotic and abiotic stresses, making them ideal for field or greenhouse transplantation.[40,41] Likewise, the problems associated with cryptogamic soil diseases[42] and the high value of the hybrid seed used have promoted commercial nurseries.[6]

One of the significant challenges of modern vegetable transplant nurseries is the production of quality plants, which depends

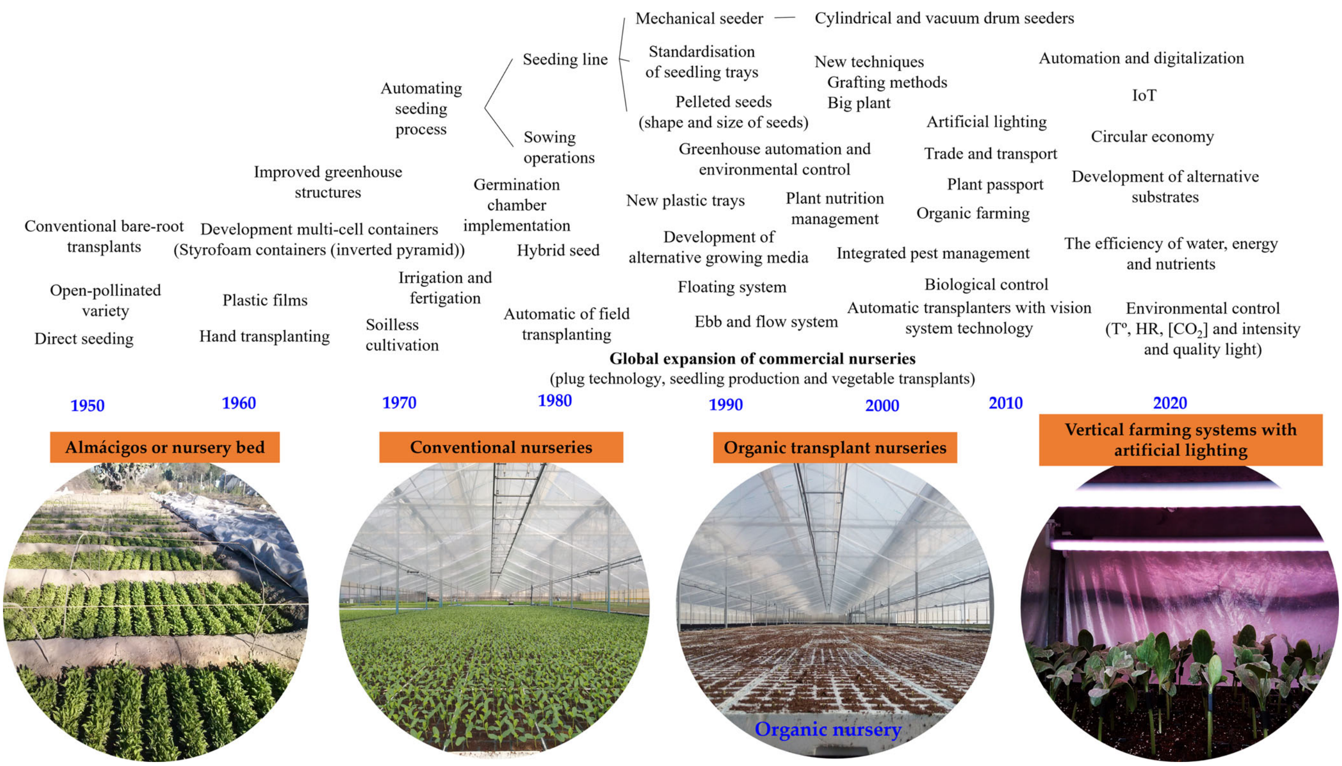

Figure 4. Timeline and main innovations in the industry specialising in the production of vegetable transplants.

to a great extent on the experience and agronomic management of the nursery that produces them.[43-45] In this regard, recent articles provide a detailed review of more than 10 indicators of plant quality in vegetable nurseries.[46-48] Finally, the implementation of a circular economy and sustainability criteria in the transplant production chain, without diminishing the high attributes of plant quality, health and profitability, is an excellent challenge for the nursery company.[49,50]

CURRENT SITUATION OF VEGETABLE TRANSPLANT PRODUCTION WORLDWIDE

Vegetable transplant production varies widely according to agricultural areas and level of specialisation. Globally, vegetable transplant production is estimated at more than one trillion plants annually.[51] However, this estimate may be higher as a result of the recent trend towards using grafted transplants as a sustainable cultivation strategy. Figure 5 shows an overall estimate of the volume of transplant production of the main vegetable crops in countries with intensive horticultural systems. For example, in Asia, China led transplant production with an annual volume exceeding 680 000 billion for 2015–2018.[52,53] Additionally, the amount of grafted vegetable plants is about 16 billion annually.[54] On the other hand, in Southern European countries, the largest producing countries in the Mediterranean are Italy and Spain, with solid horticulture vocation, where grafted and non-grafted plants in specialised nurseries are produced similarly.[29,55] In Spain alone, more than 8000 billion plants are produced annually.[5,56-58] On the other side, in North America, the annual production of grafted plants was more than 60 million in 2019,[59] In Mexico and Canada alone, an approximate production volume of 30 and 20 million grafted plants was recorded, respectively. In addition, they are the leading suppliers of grafted plants to the USA. For example, Canada exports about half of its tomato and watermelon production 100% grafted. Meanwhile, Mexico exports only 1.7% of grafted tomato plants, probably because of US import regulations.[60]

CULTIVATION TECHNIQUES: GENERAL TOPICS

Importance of the design of trays used in a nursery

The design and choice of a seed tray play an essential role in the vegetable transplant production industry. There is a wide diversity of shapes, cell sizes, volumes, colours and materials. It must also be inexpensive, durable and reusable.[38] The choice of seed tray depends mainly on the plantlet type, the mechanical seeder and the greenhouse facilities (e.g. the type of benches and fertigation system used).[3] The size of the trays used in the nurseries is variable and ranges between 20 and 40 cm in width, between 56 and 70 cm in length, and between 2.5 and 5 cm in depth. Expanded polyethylene and rigid plastic trays are the most widely used by commercial vegetable transplant producers. Additionally, flexible plastic trays are used for mechanical transplanting. In addition, a flexible outer plastic tray can be placed in the trays to facilitate the extraction of plants and disinfection of trays. Furthermore, it has small inner walls, which decreases mechanical damage to the root and prevents root spiralling.[61] Another novel method for transplant production is the paper pot tray, generally made from recycled paper.[62,63]

Cell size dimensions

Cell volume (cm^3) and number of cells per tray (plant density per tray) are two factors that influence plant quality in a wide range of vegetable species. Table 1 shows the cell size, dimensions and density of the trays used for different vegetable species.

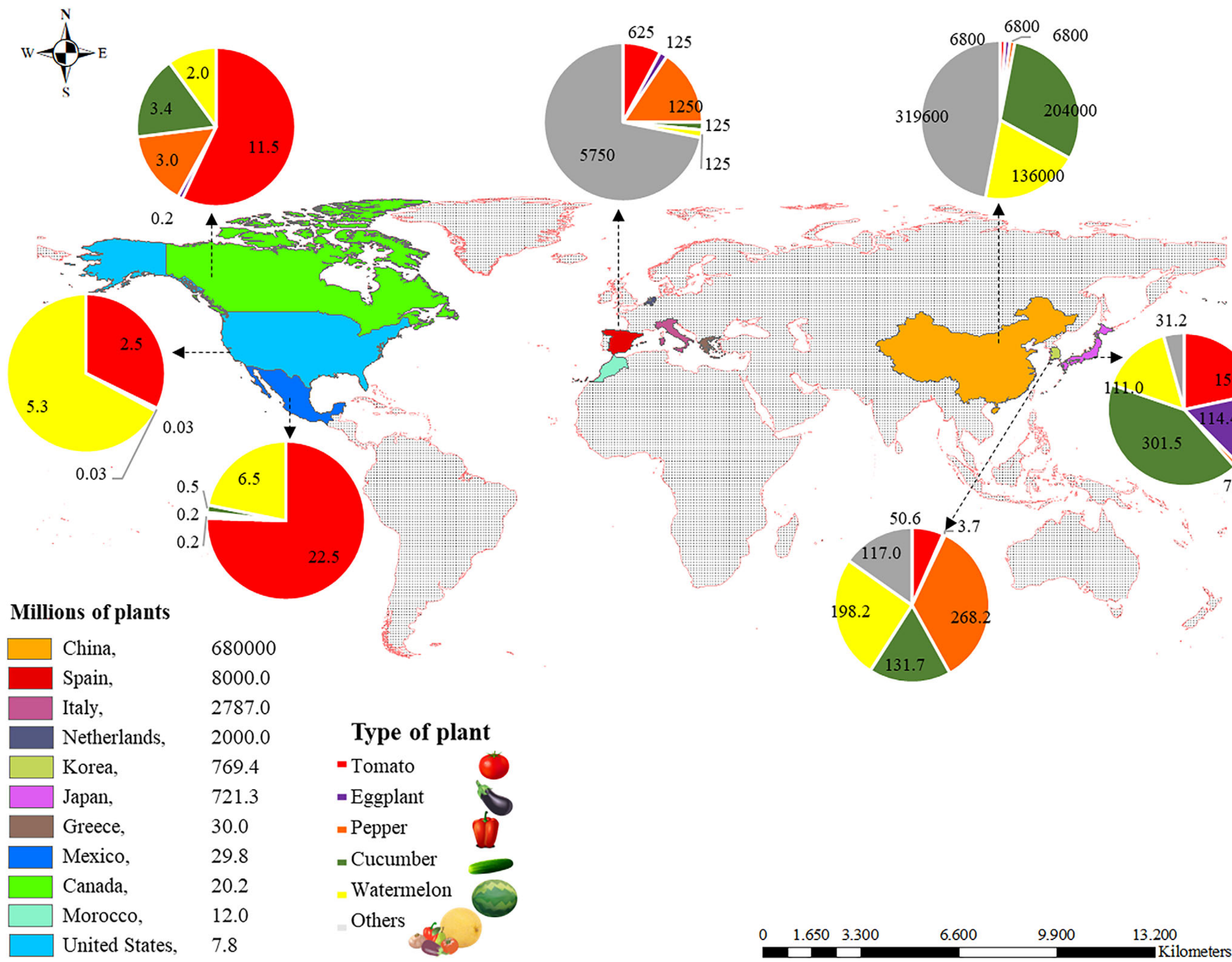

Figure 5. Vegetable transplant production and global distribution.

Table 1. Density and cell volume in different cultivation trays commonly used in the transplant production industry

	Solanaceous crops (tomato, pepper, and aubergine)						Vine crops (cucumber, melons, squash and watermelon)			Brassica crops (broccoli, cabbage and cauliflower)		Bulb crops (leeks and onions)			Leaf vegetables (basil, chard, lettuce and spinach)			
																		
Number of cells per tray	24	50	72	128	200	288	50	72	128	128	200	200	288	448	72	128	200	253
Cell volume (cm^3)	171	66	43	23	11	7	66	43	23	43	11	11	7	4	43	23	11	7

Note: Adapted from previous studies.[64,65]

Transplants of species such as tomato, aubergine, cucumber and watermelon are produced in large cell volume trays mainly for greenhouse cultivation and grafting production (e.g. 43–66 cm^3). However, when the production is intensive in open fields (for the processing industry), trays with small cells are used (e.g. 7–23 cm^3) (Table 1). Similarly, cabbage, vegetable and bulb production are preferred in trays with small-volume cells, as transplanting with automated planters is possible.[66] According to Leskovar,[67] the growth and development of transplants can be regulated through the container cell size or volume, having a proportional relationship between cell volume and plant growth rate. In this sense, plants grown in large volume cells show better growth, robustness, and higher productive potential,[64,68,69] probably as a result of the more significant amount of substrate for root development, the greater availability of water and nutrients, and the lower competition for light because of the low density of plants per tray. Thus, other factors, such as irrigation and root development of seedlings in wood fibre substrates, may contribute to the successful growth of lettuce seedlings and subsequent yield in the field.[70] These findings highlight the importance of using appropriate tray features in nursery production to maximise yield and ensure successful crop growth by efficiently using resources such as substrate, water and nutrients. Therefore, it could be concluded that the appropriate container geometry can promote root development, reduce transplant shock and improve the overall quality of the seedlings.

Transplant age

The time required to produce a quality plant in a vegetable nursery is relatively short. Vavrina[71] reported that the age of transplants could have a variable impact on crop productivity, owing to the diverse range of cultivation techniques and methods employed. For instance, Cucurbitaceae crops perform best when transplanted at 3–4 weeks, whereas Solanaceae tend to have an optimum transplant age of 5–7 weeks and Alliaceae typically require a longer transplant age of 10–12 weeks.[71] It is essential to consider both the economic benefits of commercial vegetable production and the quality of plantlets when determining the appropriate transplant age for different crops.[48,51,72,73] However, the quality must be considered because it has more influence on crop productivity than the age of the transplant.[74] As a rule, vegetable growers prefer young, actively growing transplants with high-quality standards.[71,75]

By contrast, some research suggests crop productivity increases linearly with transplant age.[67] Extending the growing cycle of plants using larger containers to produce larger plants (also called big or jumbo plants) is a widespread growing technique in commercial nurseries in central and northern Europe. For example, a large tomato plant can reach a height of about 30–40 cm with one or two stems, and even the first flower truss has developed.

Growing media

The vegetable nursery industry considers a wide diversity of substrates. Various organic (e.g. peat, coconut fibre) and inorganic [e.g. perlite (B12 0–5 mm), pumice, vermiculite, rockwool] substrates or their mixtures are used in the commercial nursery industry.[76] For example, peat is the most widely used growing medium in producing vegetable seedlings and transplants.[77,78] Moreover, according to Regulation (EU) 2018/848 on organic production and labelling of organic products, its use is also allowed in organic nurseries. However, because of the increasing concern about climate change and the conservation of natural resources and sustainable production, different methodologies have been developed and evaluated to identify and facilitate the choice of substrate or mixtures alternatives to peat.[49,78-80] Recent reviews discuss the physical, chemical and microbiological characteristics of different growing media, organic amendments, compost and agro-industrial residues extensively as an alternative to peat use, with significant emphasis on the production of vegetable seedlings and transplants in organic nurseries.[43,81,82] To this end, the use of sustainable and low environmental impact growing media, with an emphasis on optimising resources (such as water and substrates) and reducing the use of inputs (such as chemicals and fertilisers), without negatively impacting the economic efficiency of the transplant production industry, is becoming increasingly crucial in line with the current circular economy approach.

SEEDING PROCESS METHODOLOGY

Seed-enhanced treatments

Uniform and high-quality seeds are indispensable to guarantee a high germination rate and plant quality and increase the efficiency of the sowing process in vegetable nurseries. However, there is a great diversity of seeds (with different dimensions, forms, textures and germination types) that are not protected or coated, which makes mechanised sowing operations in nurseries or direct sowing in the field difficult.[83] Therefore, pelleting, priming and seed coating in vegetable transplant nurseries are widely used.[84] For example, seed pelleting is mainly carried out on small and irregular seed species such as lettuce, herbs, onion, leek and carrot. Applying a thick layer of pelleting material facilitates seed handling and uniformity, increasing efficiency in the automated sowing process.[85] In addition, some seeds, such as celery, have germination and conservation problems, which can be solved by priming.[86]

Furthermore, seed coating treatments deliver compounds and protective agents (e.g. micronutrients, germination promoters, growth regulators and symbiotic microorganisms) that improve seed and plant performance.[87] Several studies reported better growth and vigour[88-90] and enhanced tolerance to drought and heat stresses.[91,92] However, another critical aspect regards the effect that seed treatments may have on some nutritional characteristics of the crop through biofortification that can be initiated in the seeds via the nutripriming process, namely the soaking of seeds in a solution containing nutrients, before planting.[93-95] Indeed, nutripriming practice may be helpful in several ways, to alleviate malnutrition[96] or to enrich the concentration of valuable elements in plants.[97]

Using PGPMs as a seed coating treatment for vegetables, such as tomatoes, peppers, onions and cucumbers, is a sustainable strategy with great potential in the organic and conventional/integrated nursery industry.[98] Furthermore, seeds coated with PGPM could improve seed germination ratio, seed vigour, seedling emergence and resistance to pathogens, with reduced use of insecticides and fungicides. The most prominent microbial inoculants are *Rhizobium*, *Trichoderma*, *Pseudomonas* and *Bacillus*. Moreover, some seeds must be hydrated under controlled conditions before sowing to homogenise and accelerate the germination process, known as priming. Different invasive and non-invasive methods of seed priming offer several advantages, such as homogenising germination, improving seedling vigour, reducing plant establishment time and enhancing the production of quality plants.[99] Also, seed priming technology enhances a diverse range of physiological, biochemical and molecular responses in plants, can confer a beneficial effect on plant emergence under environmental stress, pathogen resistance (pesticide use is reduced) and improves field performance.[100] However, it can accelerate seed ageing and decrease seed quality after storage, as treated seeds are usually not used immediately. The longevity of primed seeds is influenced by environmental factors such as storage temperature, moisture content and seed quality.

GRAFTING AND ITS INFLUENCE ON PLANT QUALITATIVE PROFILE

Currently, grafting in vegetables is primarily used in Cucurbitaceae and Solanaceae species. It is rapidly spreading and expanding worldwide.[101] The grafting combination could be intraspecific; for example, tomato/tomato or interspecific, for example, tomato/aubergines.[102] The initial objective of this technique was to achieve protection against soil-borne diseases and soil fatigue provoked by successive cropping.[29] However, presently, this technique has been widely used to improve yield and fruit quality under both biotic and abiotic stress conditions.[60] In addition, grafted plants provide a robust and vigorous root system, which improves soil, water and fertiliser use.[103] Lastly, grafting is an environmentally friendly technique suitable for organic vegetable production by reducing chemical inputs in cropping systems.[104]

An explication of the most common methods for grafting vegetables (splice, tongue or approach, cleft, pin and hole insertion), comparing their main features and the vegetable species in which they may be used, have been reported in some studies.[60,105,106] However, sometimes it is difficult to achieve a good graft with some cultivars when vigorous rootstocks are used (i.e. *Cucurbita maxima* × *Cucurbita moschata*). In this particular scenario, it is advisable to utilise the stenting technique, where cutting and grafting are performed simultaneously.[107] However, one major drawback of this technique is the high price of grafted seedlings caused mainly by the labour intensive required for this operation. Yan *et al.*[108] and Pardo-Alonso *et al.*[109] stated that improving machine vision, artificial intelligence and automation technology will be crucial for developing high-performance universal grafting robots.[110] These advancements are expected to increase efficiency and precision in the grafting process, improve crop yields, reduce labour costs and enhance the nutritional quality of vegetables. The main rootstocks used in vegetable crop production and the advantages of their use are summarised in Table 2. An updated list of rootstock varieties for commercial solanaceous and cucurbit crop production can be found in Rosskopf *et al.*[106]

Rootstock genotypes and specific rootstock/scion combinations influence macro- and microelement profiles and vegetable phytochemicals. For example, grafting mini watermelon 'Ingrid' onto the interspecific pumpkin hybrid 'PS1313' increased K and Mg concentrations in the pulp.[111] Additionally, melon cultivar 'Khatooni' grafted onto 'Ace' and 'Shintoza' rootstocks showed increased N, P and K concentrations.[112] According to Consentino *et al.*[113] grafting of 'Birgah' eggplant onto *Solanum torvum* rootstock significantly increased protein, K, Fe and Zn content by 22.9, 7.2, 20.0 and 2.4%, respectively, compared to non-grafted plants. Furthermore, tomato fruits' 'Big Red' grafted onto 'Heman' had higher Ca contents as a result of improved water and nutrient uptake from the rootstock's vigorous root system.[9,114]

Table 2. The main rootstocks used in vegetable crops production and the advantages of their use

Species	Main rootstocks	Advantages
Tomato (*Solanum lycopersicum* L.)	Interspecific hybrid tomato (*Solanum lycopersicum* × *Solanum habrochaites* S. Knapp & D.M. Spooner) Intraspecific hybrid (S. lycopersicum L.)	Better resistance to soil-borne diseases Better tolerant to salinity Greater vigour
Sweet pepper (*Capsicum annuum* L.)	Cultivated and wild pepper (*Capsicum* spp.)	Better resistance to soil-borne diseases Soil fatigue prevention
Eggplant (*Solanum melongena* L.)	Interspecific hybrid tomato (*Solanum lycopersicum* × *Solanum habrochaites* S. Knapp & D.M. Spooner) Devil's fig (*Solanum torvum*)	Better resistance to soil-borne diseases Greater vigour
Watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai]	Interspecific hybrid squash (*Cucurbita maxima* Duch. × *Cucurbita moschata* Duch.) Bottle gourd [*Lagenaria siceraria* (Molina) Standl.] Watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai]	Better resistance to soil-borne diseases Better tolerant to salinity Greater vigour
Melon (*Cucumis melo* L.)	Interspecific hybrid squash (*Cucumis maxima* Duch. × *Cucumis moschata* Duch.) Melon (*Cucumis melo* L.)	Better resistance to soil-borne diseases Better tolerant to salinity Greater vigour Better fruit quality
Cucumber (*Cucumis sativus* L.)	Interspecific hybrid squash (*Cucumis maxima* Duch. × *Cucumis moschata* Duch.) Cucumber (*Cucumis sativus* L.)	Better resistance to soil-borne diseases Better tolerant to salinity Greater vigour

Note: Adapted from a previous study.[105]

Another study found that combining grafting with applying *Ascophyllum nodosum* seaweed extract and *Trichoderma atroviride* significantly improved the mean weight of marketable eggplant fruits, as well as the fruit dry matter, chlorogenic acid, protein, K and Fe concentrations. This approach also resulted in higher-quality fruits with higher ascorbic and chlorogenic acid and lower glycoalkaloid concentrations.[115]

Verzera *et al*.[116] reported increased lutein concentration in melon fruit, whereas some combinations led to eight times more β-carotene in fruit from grafted melon plants than non-grafted plants. In watermelon, grafting onto selected bottle gourd genotypes and triploid watermelon onto zucchini squash and cushaw pumpkin rootstocks led to an 11–27% increase in lycopene content.[117,118] By contrast, grafting did not affect the lycopene content in a study by Walubengo *et al*.[119] The use of specific rootstock varieties also impacted the fruit quality, with tomato 'Profitto' grafted onto the 'Beaufort' rootstock showing higher phenolic acid content than non-grafted plants.[120] Furthermore, the genotype of the rootstock and rootstock-scion combinations significantly impacted the fruit quality, as evidenced by the higher ascorbic acid content in tomato plants grafted onto 'Beaufort' rootstock compared to 'Arnold'.[121] Also, grafting influences aroma compounds. However, there is still limited information on the effects of grafting on aroma volatiles.[9]

LED LIGHTING TECHNOLOGY IN VEGETABLE TRANSPLANT PRODUCTION

Supplemental lighting in producing vegetable transplants in closed and controlled systems is experiencing exponential growth in agriculture.[17] This technology has helped increase productivity and improve the product quality of short-cycle vegetables,[122] as well as medicinal,[123] ornamental,[124] herbs and leafy vegetables.[125,126] It has been considered a positive alternative for obtaining quality young plants and diminishing natural resources,[127,128] considering the climate change era and simultaneously enhancing the nutritional quality of healthy products.

Light plays an essential factor because, for plants to perform photosynthesis properly, they must be provided with the right environmental conditions. Therefore, supplemental lighting and/or total artificial lighting with different lamps [LED, high pressure sodium (HPS), fluorescent] has been investigated with respect to achieving efficient horticultural seedling production. Table 3 shows the main parameters of light quality and quantity [such as photosynthetic photon flux density (PPFD), photoperiod, and daily light integral (DLI)] and their effects on the growth of different vegetable species. The results show that cucumber and tomato are the most evaluated species in the selected articles, with 50% and 25% of the total, respectively. Seedling production in closed and controlled cultivation chambers, also called plant factories, predominates (75%), and the rest carry out production under greenhouse structures (25%). The environmental conditions of the research vary depending on the crop and the productive structure. The relative humidity was 70% on average, with a CO_2 concentration of 400 μmol·mol^{-1}. The temperature ranged from 24 to 28 °C during the day from 16 to 22 °C at night. Twenty-four different PPFD values were found, with 195 to 200 μmol m^{-2} s^{-1} being the most repeated value, representing 19% of the total, and 17% of the investigations were carried out with a PPFD between 145 and 150 μmol m^{-2} s^{-1}. Concerning photoperiod, photoperiods of 12, 16 and 18 h were used, accounting for 30%, 22% and 11%, respectively. The DLI values depended on the amount of illumination and photoperiods provided, obtaining a significant variability, ranging from 1.5 to 28.8 mol m^{-2} s^{-1}. This dispersion is a result of the combinations of photoperiods and illumination because they are closely related. A high-light photoperiod with a high PPFD value results in a high DLI. Some studies consider that a DLI between 10 and 12 mol m^{-2} s^{-1} is recommended for young plants because a higher DLI may cause burns in the plant canopy[141] and thus will not produce seedlings that can be used for transplanting.

Regarding the specific spectrum used, more than 60% of the researchers have used a combined spectrum of blue and red LED lamps, which is in absorption peaks between 450–495 and 620–750 nm, respectively. Incorporating and specifying spectra in research has concluded that LED lamps positively increase plant dry weight[142,143] and improve plant photosynthetic activity. These factors are essential for young plants because they can utilise water and nutrients more efficiently to convert them into plant material.[144] In addition, other studies[138] have also determined that blue/red ratio (2:1) LED lamps produce more compact plants, indicating resistant and high-quality plants in nurseries, ensuring future productivity and product quality. Furthermore, a combination of red and blue is also suggested as the suitable light spectrum to promote plant growth and photosynthetic performance in grafted tomato seedlings.[145]

BIOSTIMULANTS AND MICROORGANISMS AS SEEDLINGS AND TRANSPLANT BOOSTERS AND STRENGTHENING AGENTS FOR SUSTAINABLE CROP PRODUCTION

The interest in biostimulants and growth-promoting microorganisms for vegetable cultivation and their application in vegetable nurseries increased over time. Environment-friendly farming practices and quality plants are a prerequisite for successful planting and, subsequently, for uniform plant growth and development.[43]

The plant biostimulants fall into different categories, such as 'Plant beneficial microbes' (PBMs), 'Plant growth-promoting rhizobacteria' (PGPR),[13,14] natural substances (humic and fulvic acids, macro and microalgal extracts, silicon),[146] arbuscular mycorrhizal fungi (AMF), compost and compost teas, agro-industrial by-products[43] and some more, as reported in other studies.[9,147]

Below, we report the most significant results of the application in vegetable nurseries.

Microbial and non-microbial plant biostimulants

Regulation (EC) 2019/1009 lays down the rules on the marketing of fertilising products in the EU. The microbial biostimulants comprise both AMF and PGPR. The application of plant biostimulants and microorganisms in nurseries unveiled several advantages: it has a relatively low cost, is effective at low dose rates and only a single treatment is required.[148] In addition, the PBMs may enhance the growth of plants and improve their resistance towards biotic and abiotic stress.[149,150]

PBMs can be inoculated at the seed stage using a minimal amount of inoculum placed at the interface between the seed and soil or growing media. During early growth, this direct contact between roots and PBMs can benefit plant growth, health and vegetable nutrient quality.[151,152] Some recent researchers have focused on applying AMF in vegetables to improve seedling characteristics, such as dry matter content and root system in

Table 3. Impacts of lighting conditions for seedling growth and their effect on seedling production

Vegetable species	Growing conditions	Light treatment: PPFD (μmol m^{-2} s^{-1})	Light treatment: Photoperiod (h^{-1} d^{-1})	Light treatment: DLI (mol m^{-2} d^{-1})	Spectrum	Effects on crop performance	References
Cherry tomato (*Solanum lycopersicum* Mill qianxi.)	Chamber	50; 150; 200; 300; 450; 550	12	2.2; 6.5; 8.6; 13; 19.4; 23.8	LED blue/red	300 μmol m^{-2} s^{-1} was fit for the culture of young tomato plants and induced the highest energy efficiency and activity of Pn	129
Tomato (*Solanum lycopersicum* 'Komeett') and Cucumber (*Cucumis sativus* 'Cumlaude')	Greenhouse	55	18	3.6	LED blue/red	Plant growth of the young seedlings were largely improved by supplemental LED lighting in both species, and dry mass was increased by 39 and 47% (tomato and cucumber)	130
Tomato (*Solanum lycopersicum* 'Komeett') and Cucumber (*Cucumis sativus* 'Cumlaude')	Greenhouse	55	18	3.6	LED red; HPS light	The growth of tomato seedlings under 100% red LED was better than HPS, but the growth of cucumber seedlings was the contrary	130
Rootstock 'Maxifort' (*Solanum lycopersicum* × *Solanum habrochaites*) and production cultivars Komeett, Success, Felicity, Sheva Sheva, and Liberty	Greenhouse	88	16	5.1	LED red/blue; HPS lamp	For all tomato cultivars evaluated, a combination of red and blue wavebands in SL has the potential to increase seedling growth	131
Strawberry (*Fragaria* × *ananassa* var. Elan and Yotsuboshi)	Chamber	115; 175; 230; 310	24; 16; 12; 8	10	led red/blue	The production of strawberry plugs under artificial lighting with an optimised photoperiod could provide high-quality transplants	132
Pepper (*Capsicum annuum* L. cv. CAU-24)	Chamber	250	12	10.8	LED blue/red	Under the white LED with R:B of 1.5, the biomass and photosynthetic characteristics of pepper seedlings were the best	133
Cucumber (*Cucumis sativus* L. cv. Yuexiu no. 3)	Greenhouse	35; 50; 75	12	1.5; 2.2; 3.2	LED red/blue	Increasing light intensity was more effective than increasing blue light proportion in enhancing the seedling index	134
Rudbeckia fulgida (var. sullivantii 'Goldsturm')	Glasscovered greenhouse	150; 200; 230; 273	12, 15, 18, 21	12	Cool-white LED	Supplemental lighting can increase the growth of *R. fulgida* seedlings, especially when supplied over longer photoperiods at a lower PPFD	135
Cucumber (*Cucumis sativus* L. 'Joeunbaekdadagi')	Plan factory	200	12	8.6	LED red/blue; UV-A; far-red	The combined R and B treatments and UV-A treatments produced compact plants and increased seedling quality	136
Cucumber (*Cucumis sativus* L. cv. Jintong, cv. Yunv and cv. Xiazhiguang)	Plant factory	100; 200; 250	12, 16	4.3; 5.8; 8.6; 10.1; 11.5; 13; 14.4; 17.3	Fluorescent lamp	Suggested a DLI of 14.4 mol m^{-2} d^{-1} for Jintong and Xiazhiguang, and a DLI of 17.3 mol m^{-2} d^{-1} as the light environment conditions for Yunv	137
Cucumber (*Cucumis sativus* L. var. 'Joeunbaegdadagi') with grafted vine-leaved pumpkin rootstock (*Cucurbita ficifolia* Bouché var. Heukjong)	Chamber	50; 100; 150; 200; 250	12; 16; 20	2.16; 2.88; 3.6; 4.32; 5.76; 6.48; 7.2; 8.64; 10.8; 11.52; 14.4; 18	LED white	Increasing the light intensity and the photoperiod increased the growth of seedlings and compactness	138
Cucumber (*Cucumis sativus* L. cv. Tianjiao No. 5)	Chamber	457; 320; 246; 200; 168; 145	7, 10, 13, 16, 19, 22	11.5	LED blue; green; red	Photoperiod to 16 to 19 h and PPFD 168 to 145 were beneficial for improving the quality and mechanical strength of seedlings	139

Table 3. Continued

Vegetable species	Growing conditions	Light treatment: PPFD (μmol m^{-2} s^{-1})	Light treatment: Photoperiod (h^{-1} d^{-1})	Light treatment: DLI (mol m^{-2} d^{-1})	Light treatment: Spectrum	Effects on crop performance	References
Cucumber (*Cucumis sativus* L. cv. Tianjiao No. 5)	Plan factory	200; 400	12, 16, 20	8.64; 11.52; 14.40; 17.28; 23.04; 28.80	LED blue; green; red	DLI at 14.40–23.04 mol m^{-2} d^{-1} is suggested for cucumber seedling production	53
Cucumber (*Cucumis sativus* L. cv. Yuexiu No.3)	Chamber	Exp. 1: 125; 126; 146; 148; 151; 195; 199 and Exp. 2: 111; 125; 146; 176	Exp. 1: 12; 14; 16 and Exp. 2: 10; 12; 14; 16	Exp. 1: 5.41; 6.35; 7.47; 7.64; 8.52; 8.43; 10.05; 11.26 and Exp. 2: 6.31; 6.36; 6.40	LED red; blue	Optimal conditions for time optimisation were PPDF to 110–125 μmol m^{-2} s^{-1}, photoperiod 14–16 h and DLI 6.35 mol m^{-2} d^{-1}	45
Watermelon (*Citrullus lanatus* cv. Fascination and Carnivor)	Chamber	100; 150; 200	18	6.5; 9.7; 13	LED blue/red	Light intensity to 200 μmol m^{-2} s^{-1} and 1589 ± 10 μmol mol^{-1} CO_2 supplementation increased dry mass, leaf area, and photosynthetic rate	140

Abbreviations: PPFD, photosynthetic photon flux density; LED, light-emitting diode.

watermelon,[153] onion[154] and tomato.[155] Also, rhizobacteria have shown some positive effects in increasing the resistance to salt stress on tomato,[154] aubergine,[155] lettuce[156] and zucchini seedlings.[157] Moreover, there is a significant improvement on growth and some morphometric parameters, such as root length, fresh and dry weight, in tomatoes, lettuce, cucumber and some brassica.[158,159]

Microbial biostimulants may also help face abiotic stresses, such as salt stress, particularly when poor-quality (brackish) water is used. Micelli *et al.*[160] found that inoculating the substrate with microbial biostimulants may represent a sustainable way to improve lettuce and tomato seedlings in vegetable nurseries by limiting the negative effect of brackish water on seedling growth.

Fungi are used to some extent to improve the quality of seedlings because of their biostimulants activity. For example, using *Trichoderma saturnisporum* on melon seedlings improved crop productivity, by increasing the average fruit weights and by increasing the average fruit weights without negatively affecting fruit quality.[161] Additionally, Pascual *et al.*[162] used *Trichoderma harzianum*-enriched compost as a growing medium for melon seedling production in the greenhouse nursery and found a positive effect on plant fresh weight and lower pathogen incidence.

Concerning non-microbial plant biostimulants, such as humic acid and macro and microalgal extracts, several studies have reported not only that the application of algae produced several advantages in lettuce,[163] tomato[164] and broccoli seedlings,[165] but also humic substances yielded positive results.[166] Furthermore, some studies[167,168] reported the feasibility of replacing synthetic auxins to produce seedlings for transplantation in the organic nursery. This is an essential facet of producing seedlings for organic agriculture, an actively growing sector in which synthetic growth-promoting substances are not allowed.

Compost and compost tea

Compost is the most used in the nursery sectors because of its positive effects on the quality and growth of plants, its biostimulant and suppressive effects on pathogenic microorganisms, and the improvement of physical and chemical properties when blended, for example, with peat.[169,170] Furthermore, composts may decrease the incidence of disease in the telluric zone due to their suppression activity, caused by pathogens such as *Verticillium dahlie*, *Fusarium oxysporum*, and *Fusarium oxysporum* f. *sp. melonis*.[43] Compost may also be used to realise (utilising extraction process) of 'compost tea' (CT), an organic liquid for which several advantages have been reported (such as improved plant nutrition and productivity), even if the results in nurseries are limited so far.[43] Nevertheless, Villecco *et al.*[171] used several types of CT that were sprayed on tomato, pepper, and melon seedlings during the nursery growing stage and their results showed that CT increased plant growth and quality parameters.

BIOFORTIFICATION AS A NUTRITIONAL QUALITY PLANT ENHANCER

Biofortification is a promising approach to enhance the nutritional quality of vegetables, which involves increasing the density of specific essential micronutrients in their edible parts. Various agronomic approaches have been explored to achieve biofortification.[172] Even though such a practice is more common in staple crops such as rice,[173,174] it is also becoming commonplace in vegetables and has been shown to be effective. For example, Funes-Collado *et al.*[175] found that selenium enrichment of peat during the seedling stage improved the selenium content of crops such as cabbage, lettuce, chard and parsley without adverse effects on biomass production. Similarly, Businelli *et al*.[176] reported that seedlings of cucumber, tomato and lettuce biofortified with selenium had significantly higher selenium concentrations in their edible parts than untreated controls. Puccinelli *et al*.[177] reported that supplementing the growing substrate with sodium selenate immediately after sowing could effectively increase the levels of selenium and iodine in lettuce and sweet basil, resulting in improved nutritional value. Likewise, self-grafting combined with iodine biofortification at a concentration of 600 mg L^{-1} improved total anthocyanin concentration in eggplants by 8.5% compared to the combination of no grafting and no iodine biofortification.[113] These findings suggest that biofortification can be a viable strategy to address micronutrient deficiencies in populations with limited access to diverse and nutritious diets.

Customised vegetables can now be produced to meet the specific needs of individuals with metabolic disorders. This method, called 'tailor-made' or 'personalised vegetables', involves enhancing the nutritional content and reducing anti-nutritional substances such as phytates, oxalates, nitrates, histamine and some heavy metals. In addition, the early application in seedling production of grafting, biostimulants, biofortification and PGPMs can promote the sustainable enhancement of vegetable nutritional quality by accumulating secondary metabolites, vitamins, antioxidants and minerals.

CONCLUSIONS

The recent and growing need to boost global vegetable production worldwide has spurred the development of more efficient and effective agricultural techniques, with a particular emphasis on the critical seedling stage.

The seedling stage emerges as a crucial juncture in modern agriculture, significantly influencing the quality of adult plants, overall crop success and the quality of the final product. Ongoing developments in research underscore the growing importance of sustainable practices and the integration of new technologies. Critical practical issues and research directions are identified, encompassing aspects such as seed tray design, environmentally sustainable growing media, grafting techniques, and the integration of LED lighting and biostimulants to augment the nutritional quality of vegetables. The combination of sustainable and efficient vegetable transplant production systems positions itself as a valuable resource for future research efforts in horticulture. As advancements continue to bolster the quality and resilience of vegetable seedlings and transplants, the pursuit of increased nutritional quality in vegetable produce stands as a focal point for ongoing and future agricultural investigations.

In conclusion, this comprehensive analysis of global research on vegetable seedlings and transplants could provide valuable statistical, technical and scientific insights to shape the trajectory of future investigations. Although extant studies suggest the potential of seedlings to enhance nutritional quality, the presence of conflicting results underscores the imperative for further exploration into the intricate relationship between seedlings and transplants on one side and the nutritional quality of vegetables on the other.

Further research is essential to explore operational mechanisms, devise novel strategies for early-stage vegetable production, and optimise transplant processes. The analysis revealed the need to develop research that applied innovative techniques to optimise transplant production, selection and mass screening for high-quality vegetables. Thus, a comprehensive understanding of the major pathways involved in quality and the identification of early markers would shed light into the cultural requirements to improve product quality. There is a need to focus on breeding techniques to develop cultivars with improved nutritional profiles, focusing on essential vitamins, minerals and antioxidants. In addition, investigating the role of beneficial microorganisms, such as bacterial, mycorrhizal fungi or algae, in promoting seedling health, improving nutrient absorption, and their impact on nutritional content in mature plants is a potential avenue for future research.

ACKNOWLEDGEMENTS

VMG-C and CN were funded by a grant for re-qualifying the Spanish University System, Margarita Salas modality, by the University of Almería (Grant UP2021-004 funded by Ministerio de Universidades and by the 'European Union NextGenera-tionEU/PRTR'). AS and NSG were also supported by a grant for the re-qualification of the Spanish University System, Maria Zambrano modality (Grants funded by Ministerio de Universidades and by the 'European Union NextGenerationEU/PRTR').

AUTHOR CONTRIBUTIONS

VMG-C, NSG and JAF defined the structure and topics of the review. VMG-C led the writing and reviewing process with CN, AS, JO, JG, CE-G, NSG and JAF. VMG-C, NSG and JAF provided editorial integration, critical review and the overall focus of the entire manuscript. VMG-C, CN and JG, produced the diagrams. VMG-C, CN, AS, JO, JG, CE-G, NSG and JAF contributed sections in their areas of expertise, critically reviewed and commented on the overall manuscript, and approved the submitted work.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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