frontiers | Frontiers in Horticulture

TYPE Editorial
PUBLISHED 12 January 2026
DOI 10.3389/fhort.2025.1726987

OPEN ACCESS

EDITED AND REVIEWED BY
Sigfredo Fuentes,
The University of Melbourne, Australia

*CORRESPONDENCE
Vasileios Ziogas
ziogas@elgo.gr
Anoop Kumar Srivastava
aksrivas2007@gmail.com

RECEIVED 17 October 2025
REVISED 13 December 2025
ACCEPTED 16 December 2025
PUBLISHED 12 January 2026

CITATION
Ziogas V, Srivastava AK, Chater J and Bora P (2026) Editorial: Citriculture: sustaining quality production.
Front. Hortic. 4:1726987.
doi: 10.3389/fhort.2025.1726987

Editorial: Citriculture: sustaining quality production

Vasileios Ziogas[1]*, Anoop Kumar Srivastava[2]*, John Chater[3] and Popy Bora[4]

[1]Hellenic Agricultural Organization – DIMITRA (ELGO – DIMITRA), Institute of Olive Tree, Subtropical Crops and Viticulture, Chania, Crete, Greece, [2]Indian Council of Agricultural Research–Central Citrus Research Institute, Nagpur, Maharashtra, India, [3]Citrus Research and Education Center, University of Florida, Gainesville, FL, United States, [4]Department of Plant Pathology, Assam Agricultural University, Jorhat, Assam, India

KEYWORDS

citrus, crop regulation, fruit quality, fruit thinning, fruit yield, HLB (Huanglongbing), microbial inoculants, nutrient uptake

Editorial on the Research Topic
Citriculture: sustaining quality production

The world of citriculture operates through the involvement of nearly 153 citrus-growing countries, collectively contributing to the production of 167.82 million tonnes from an area of 10.62 million ha with a current productivity of 15.80 tonnes ha^{-1}. The total grower value of citrus fruits stretches over 1090 billion US dollars, with fruit processing and fresh consumption valued at 986 and 103 million US dollars, respectively. Citrus (family Rutaceae) is considered the world's 210th most traded product, with a total trade of 16.3 billion US dollars (trade of 3.6 billion US dollars through the Asian citrus industry).

Sustaining quality citrus production is one of the most dynamic and globally fast-growing arts of science. Though the crop is one of the most highly researched, after apples and bananas, it still faces multiple challenges amid the growing issues of the climate crisis. These challenges cause either irregular bearing or overbearing (pre-emptive to alternate bearing), requiring thinning at the fruit-set stage and reduced water-use efficiency, warranting irrigation methodologies to be freshly evaluated. The global presence of Huanglongbing (HLB), a plant immunocompromised and vector (citrus psyllid, *Diaphorina citri*)-driven disease caused by bacteria (Candidatus *Liberibacter*), jeopardizes fruit yield and quality across the citrus belt. This Research Topic titled "*Citriculture: Sustaining Quality Production*" emphasizes several critical topics: the response of HLB-tolerant citrus hybrids concerning fruit quality parameters; microbe-mediated soil fertility management under multiple nutrient constraints, particularly in organic matter-depleted soils; subsurface drip irrigation; and the application of deep learning in the automated management of citrus cultivation.

Image-based identification of young citrus fruits during thinning

Citrus plants are highly prone to the alternate bearing effect, the "on-and-off year" cycle, which challenges the sustainability of production incentives. Such physiological facts demand fruit thinning to limit the fruit load in order to optimize the eventual fruit load for desirable fruit quality. At this stage, identifying young green fruits within the dense green tree canopy is highly cumbersome for exercising fruit thinning, either manually or via the foliar spray of a fruit-thinning agent. Leveraging machine learning and artificial intelligence technologies for intelligent fruit thinning is considered highly useful in identifying fruit features, viz., fruit surface defects, spatial localization of young citrus fruits, and desired fruit load detection to improve work efficiency, ensure superior fruit quality, and concurrently reduce production costs, ensuring optimum quality production and sustainability. Feng et al. (2023) proposed a YOLOX-based real-time multi-type surface defect detection algorithm (MSDD-YOLOX) for sweet oranges in order to achieve real-time detection of surface defects on an orange sorter machine. The use of such an algorithm improved the detection of scars at different scales but failed to identify the surface texture-based defects. Ang et al. proposed the improved YOLOV8n (5.4MB size) for the detection of young citrus fruits within the tree canopy. The proposed method involves the following steps: i) construction of a dataset containing images of young citrus fruits grasped from orchards on a real-time basis; ii) reconstructing the detection head and backbone network using pointwise convolution lightweight network for improving detection accuracy; iii) introduction of a fusion attention mechanism for more accurate detection of young fruits in a complex background; iv) introduction of a simplified spatial pyramid pooling fast-large kernel with a separated attention (SimSPPF-LSKA) feature pyramid to further enhance the multi-feature extraction capability; and v) use of the Adam optimization function to strengthen the nonlinear representation and feature extraction ability, having 91.7% precision, 92.7% call, and 97.35% recall. This study provided a non-invasive machine intervention technique to identify small fruitlets and precisely target them for fruit thinning at the early fruit growth stage of citrus.

Enhancing nutrient uptake through soil application of bacterial inoculants

Grapefruit (*C.* x *aurantium* var. *paradisi*), like any other commercial citrus cultivar, is highly nutrient responsive in nature. It has been stated that sustaining quality citrus on soils under long use of inorganic chemical fertilizers is a formidable task. This latter fact is a potential threat of depletion of soil organic matter and, consequently, the onset of multiple nutrient deficiencies, more so in the coarse sandy soils of Florida, USA, renowned for their poor water-holding capacity. Nonetheless, the implementation of precision fertigation that leverages spatial variability in soil fertility, alongside astute leaf analysis interpretation, the use of dwarf canopy-producing rootstocks, meticulous canopy management, optimized planting density, and various crop protection strategies, has enabled Florida's citrus industry to endure despite significant challenges posed by HLB, hurricanes, and freezes. Although citrus productivity has declined by 28% compared to the previous year, the industry persists through extensive multidisciplinary efforts to combat HLB. The multifaceted role of microbial inoculants (plant growth-promoting ability, antagonistic property against plant pathogens, and acaricidal properties) for microbe-mediated citrus production systems is well recognized. The plants' ability to reshape their microbial niches via interacting mechanisms with other rhizosphere microbiomes through a process called rhizosphere hybridization (Srivastava et al., 2025) delivers an additional resilience to soil's ability to sustain fruit yield and quality.

Studies proposed by Cano-Castro et al. under CUPS (Citrus Under Protected Screen) using plastic pots (1.67 L capacity, filled with 50% Canadian peat moss along with pine bark, perlite, and vermiculite) provided some useful insights about the combined use of inorganic fertilizers and bioinoculants for improving the nutrient uptake-associated improvements in growth of Duncan grapefruit seedlings, a concept which could be replicated in mature orchards as well. The combination of *Bacillus velezensis* and inorganic fertilization (0.885gL^{-1} Miracle Gro, 0.402 gL^{-1} Pennington Epsom salt, 0.169 gL^{-1} Sequestrene 138, all diluted as fertilizer solution and applied at 0.129 L pot^{-1} at weekly intervals) significantly improved the leaf nutrient composition (1.97% N, 0.16% P, 2.94% Ca, 0.45% Mg, and 0.54% S) and enhanced the growth of grapefruit seedlings compared to either fertilization alone or inoculation with B. velezensis, including the consortium of *B. subtilis, B. megaterium*, and *Bacillus* spp. as citrus endophytes. These findings offered significant insights into management strategies that can diminish chemical inputs without sacrificing plant productivity.

Surface versus subsurface drip irrigation

Sustaining high productivity of citrus is a highly challenging proposition amid the absence of a crop phenology-based drip irrigation scheduling, despite the significant cultivar-wide success of drip irrigation in optimizing fruit yield and quality coupled with the saving of irrigation water and nutrients compared to the basin method of irrigation widely adopted in citrus orchards. Therefore, optimizing irrigation water for improved water productivity by aligning water requirements with critical growth stages is an essential component of profitable citrus cultivation. Combining water productivity with nutrient-use-efficiency gave rise to the concept of fertigation, which developed over the years in its popularity amongst different citrus cultivars, significantly reducing nutrient leaching losses while enhancing nutrient-uptake efficiency to as high as 90% compared with 40%–60% with traditional basin irrigation (Sravani et al., 2020). Nagpur mandarin (*C.* x *aurantium* var. *deliciosa ined.*), a globally famous loose-peel mandarin cultivar grown extensively in central India, is no exception. It still faces an inevitable issue of suboptimum productivity. Surface drip irrigation-mediated water management has frequently been questioned in regulating the irrigation on smectite-rich black clay soils with shrink-swell properties, paving the way to better alternatives. Previous research by Meshram et al.

(2025) showed sensor-based fertigation schemes that saved 60%–70% of water and increased fruit yield by 40%–50% compared with conventional fertigation. Subsequently, Meshram et al., while comparing the agronomic efficacy of surface versus subsurface drip irrigation in Nagpur mandarin raised on Typic Haplustert soil, showed subsurface drip irrigation outperformed surface drip irrigation treatments with regard to water productivity, water requirement, fruit yield, and fruit juice content by 6.43 kg m^{-3}, 9410 L $plant^{-1}$ $year^{-1}$, 25.91%, and 6.65%, respectively, coupled with correspondingly 17.5% and 15.7% higher leaf N and Zn contents. The study further revealed that subsurface drip irrigation design involving inline laterals placed 100 cm from the tree trunk at 30 cm soil depth with 50 cm dripper spacing and 26 drippers $tree^{-1}$ area provided the best agronomic response over surface drip irrigation, carrying double inline laterals placed 100 cm from the tree trunk with 6 drippers per tree with 1 area as a control.

Fruit quality in Huanglongbing-tolerant citrus hybrids

The emergence of HLB in commercial citrus areas has initiated a new phase of citrus research. This disease impacts citrus from both genomic and agronomic perspectives, encompassing the availability, absorption, and translocation of nutrients within HLB-infected citrus trees. Researchers are still divided on whether or not plant nutrition is consequential in the fight of citrus against HLB. Although limited research explicitly delineates the impact of enhanced nutrition programs in combating HLB to induce acquired systemic resistance in HLB-infected citrus plants, thereby preserving fruit yield and quality, certain rootstocks, particularly citrus hybrids with *Poncirus trifoliata* L. Raf. introgression, have garnered attention for their tolerance to HLB. In the work of Jeffries et al., data from commercial orange cultivars viz., Valencia and Hamlin; the HLB-tolerant *Poncirus* hybrid US Sun Dragon; and the mandarin hybrids, viz., Sugar Belle, FF-5-51-2, and US Superna, showed positive citrus flavor quality. The flavonoid linarin was more abundant in Poncirus hybrids with off-flavors than in the Poncirus hybrid US Sun Dragon, which had a high orange flavor. Two mandarin hybrids, FF-5-6-36 and FTP-6-32-67, were not bitter at harvest, but the juice exhibited delayed bitterness after storage at −20°C, which was associated with significant increases in limonin, nomilin, naringenin, and prunin. These studies provided new insights into the flavor and chemistry of the fruit juice of HLB-tolerant citrus hybrids.

Conclusions and futuristic outlook

Maintaining citrus production in light of current challenges requires a significantly more visionary approach that necessitates immediate attention. The climate change affecting citrus performance must be resolved by altering the spatial distribution of global citriculture, analyzing production trends in relation to the climate crisis, assessing fruit quality and plant nutritional variations, distinguishing between nutritional and physiological disorders, adjusting citrus phenology, recalibrating input utilization, establishing quality standards, employing climate modelling for citrus, and implementing climate-smart agricultural techniques. Climate-related changes bring up drought-salinity redressal on an emergent basis. Citrus tolerance to salinity, the citrus-drought relationship, various markers associated with abiotic stress tolerance, microbial interventions for tolerance associated with salinity/drought, and insights into rhizosphere health in relation to salinity/drought are some of the yet unanswered riddles of sustainable citriculture. The global prevalence of HLB has cast uncertainty on the sustainability of the entire citrus industry. The challenges of plant nutrition in contemporary citrus cultivation encompass the examination of significant issues in plant nutrition, advancements in diagnosing nutrient limitations, forecasting fertilizer requirements based on the citrus-fertilizer response relationship, reevaluating the 4R nutrient stewardship principles (pertaining to nutrients, irrigation, and microbes as bio-fertigation analogous to conventional fertigation), integrating agroecology for soil health preservation, bioprospecting for soil-plant health, and fostering disease-suppressive soils, as well as the development of specialty fertilizers (fertilizer composites and green composites) and customizing fertilizer application according to spatial variability in soil fertility.

Changing attributes of rootstocks is another important issue that must not be overlooked. The identification of disease-tolerant citrus hybrids with desired fruit flavor quality at juicing as well as after storage, where delayed bitterness may develop, has great significance for future breeding efforts for fresh fruit or for use in stand-alone juice/juice blends. Facilitating the development of novel rootstocks with a focus on enhancing the fruit quality of citrus in the context of HLB prevalence is important. Other avenues which should be explored include investigating HLB-tolerant gene(s) within current citrus germplasm diversity; advancing rootstock breeding focused on HLB, specifically focusing on the significance of interstocks concerning novel scion traits; studying high-density orcharding and HLB-vector fertility; utilizing CUPS (citrus under protected system) for managing HLB and ensuring quality yield; and exploring microbially engineered rootstock for HLB tolerance. In addition to these issues, the Phytophthora-HLB nexus presents a dual challenge, encompassing pathogenesis and the pursuit of disease control through the reconfiguration of microbial niches, the identification of molecular signals involved in pathogen-host interactions, and the role of secondary metabolites as a secondary line of plant defense. Additionally, the advancement of synthetic microbes (SymComs) represents another focal point for researchers seeking solutions.

Author contributions

VZ: Writing – original draft, Writing – review & editing. AS: Writing – original draft, Writing – review & editing. JC: Writing – review & editing. PB: Writing – review & editing.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Feng, J., Wang, Z., Wang, S., Tian, S., and Xu, H. (2023). MSDD-YOLOX: An enhanced YOLOX for real- time surface defect detection of oranges by type. *Eur. J. Agron.* 149, 126918. doi: 10.1016/j.eja.2023.126918

Meshram, D., Srivastava, A. K., Utkhede, A., Pangul, C., and Ziogas, V. (2025). Response to sensor- based fertigation of Nagpur mandarin (Citrus *reticulata* Blanco) in Vertisol of central India. *Horticulturae* 11, 508. doi: 10.3390/horticulturae11050508

Sravani, G. C., Singh, L., and Bakshi, M. (2020). Performance evaluation of drip irrigation (Fertigation) in citrus cultivation: a review. *J. Pharmac. Phytoch.* 9, 2557–2560. doi: 10.22271/phyto.2020.v9.i5aj.12726

Srivastava, A. K., Majid, S. M., Bora, P., Hota, D., Malhotra, S. K., Pandey, V., et al. (2025). Rhizosphere to rhizosphere hybridization: new initiatives in fruit crops. *Front. Hortic.* 4. doi: 10.3389/fhort.2025.1584807