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Review

Improving vegetable quality in controlled environments

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ABSTRACT

During the last decades, food security has become a vital global concern driven by projections of population increase and exacerbated by the impending pressure of climate change on agriculture. Vegetable crops represent a fundamental ingredient of human diet due to their high nutritional value and bioactive content and could serve towards improving food security and nutritional quality, especially when managed under highly intensified cropping systems in controlled environments. Greenhouse and indoor growing modules not only allow for significantly higher yields compared to open field cropping systems, but also they can facilitate out of season production and substantial manipulation of the chemical composition and bioactive profile of the final product. The present work provides an updated critical overview of scientific advances regarding genotype and microclimate effects on the quality of greenhouse crops. In this context, innovative crop management practices are discussed, including management of the nutrient solution, biofortification and application of plant biostimulants. The review concludes by proposing future research pathways towards enhancing product quality of greenhouse vegetables.

1. Introduction

A primary challenge for modern horticulture is the need to procure food for the increasing global population, projected to reach 10 billion by 2050. At the same time vegetable growers have to cope with suboptimal crop growth conditions imposed by substantial climate changes (Koevoets et al., 2016). To face these issues, intensive food production systems such as protected cultivation are missioned to increase crop productivity without detrimental effects on quality and sustainability. The advantages of greenhouse and indoor growing modules include: (i) increased offseason vegetable production, (ii) buffering against external weather conditions, and (iii) securing better than outdoor conditions for crop growth and development (Bisbis et al., 2018).

Over the past two decades, demand for quality horticultural products is on the rise, propelled by the growing interest of society in fresh products of high organoleptic, nutritional and functional quality (Bisbis et al., 2018; Kyriacou et al., 2016a). In a recent review, the quality of fresh horticultural commodities was defined as *a dynamic composite of their physicochemical properties and evolving consumer perception, which embraces organoleptic, nutritional and bioactive components* (Kyriacou and Rouphael, 2018). Bioactive compounds present in vegetables, also known as phytochemicals, can modulate beneficially human metabolism and well-being in general (Ferrari and Torres, 2003). Phytochemicals represent an important source of antioxidant molecules (e.g., phenolic acids, flavonoids, anthocyanins, glucosinolates, tocopherols, ascorbate and carotenoids) able to reduce the risk of cardiovascular diseases and specific forms of cancer, while they stimulate cognitive health (Slavin and Lloyd, 2012).

The synthesis and accumulation of bioactive compounds depend upon many preharvest factors, including genetic material, environmental and microclimatic conditions for plant growth, crop management practices and developmental stage at harvest (Weston and Barth, 1997). However, the genotypic effect is undoubtedly the principle determinant of quantitative and qualitative variation in health-promoting metabolites in vegetables, often surpassing the influence of cultural practices and environmental factors (Kyriacou and Rouphael, 2018; Rouphael et al., 2012a, 2016, 2017c). Efforts are made to enhance key phytochemicals by means of conventional breeding and genetic transformation, but the development of new cultivars with enhanced content in specific functional molecules is still at its infancy, with only a limited number of vegetable cultivars yet released at commercial level (Kyriacou and Rouphael, 2018). Furthermore, disproportional increase

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reaching up to 10–35 fold in some target phytochemicals through genetic selection, including carotenoids, glucosinolates and kaempferol-rutoside, has raised safety issues as such concentrations have been proved genotoxic (Brusick, 1993; Poiroux-Gonord et al., 2010; Stopper et al., 2005). The manipulation of secondary metabolites through environmental and agronomic factors could be posited as a meaningful compromise between effectiveness and safety, hence it attracts the interest of food and horticulture scientists and quells consumers' concerns regarding genetically transformed and/or modified products (Kyriacou and Rouphael, 2018).

Environmental factors, particularly air temperature and light, and to a lesser extent vapor pressure deficit and carbon dioxide enrichment impact organoleptic and functional quality of greenhouse vegetables, as discussed in the previous review papers of Gruda (2005) and Wang et al. (2008). Among microclimate controls, advanced light-emitting diode (LED) technology is gaining particular popularity with greenhouse growers since it provides optimal management of light conditions (intensity and spectral quality) which can effectively increase the biosynthesis of secondary metabolites in vegetables, including the new class of specialty crop microgreens (Kyriacou et al., 2016a, 2017a). Additionally, the management of nutrient solution can be instrumental in influencing yield and quality of greenhouse vegetables. In this respect, hydroponic cultivation systems (i.e., substrate culture, nutrient film technique, floating system) facilitate the precise control of plant nutrition, thus modulating the levels of bioactive compounds (Borgognone et al., 2016; Fanasca et al., 2006a, b; Fallovo et al., 2009a, b; Lucini et al., 2016). The application of an *eustress* (positive stress), such as moderate salinity or nutritional stress, by managing the concentration and composition (cationic and anionic proportions or single ions) of the nutrient solution, can be practical and effective in improving the nutritional value of vegetables and in reducing the accumulation of anti-nutrient compounds, such as nitrates (Colla et al., 2018; Kyriacou and Rouphael, 2018; Tomasi et al., 2015). Soilless culture can also be effective in the biofortification of edible plant portions with essential and/or beneficial micronutrients to human health (Tomasi et al., 2015; White and Broadley, 2005).

Accordingly, the present review aims at providing an updated overview of scientific advances addressing genotypic and microclimate management effects (air and root zone temperature, light conditions, CO_2 enrichment and vapor pressure deficit) on the quality of greenhouse crops. Moreover, innovative crop management practices are discussed in the same context, including management of the nutrient solution concentration and composition, biofortification and the application of plant biostimulants. The review concludes by identifying several possibilities for future research to enhance product quality of greenhouse vegetables.

2. Genotypic and grafting effects on the quality of greenhouse crops

In the past decades, breeding for field and greenhouse cultivars has prioritized yield improvement, disease resistance and extended post-harvest life (Bai and Lindhout, 2007; Dorais et al., 2008; Gil, 2015; Klee and Tieman, 2013). Arguably, breeding for these characters has been made at the expense of nutritional value and sensory quality; for instance, breeding for longer shelf-life has resulted in undesirable pleiotropic effects on organoleptic attributes (Causse et al., 2002; Davis et al., 2004). In breeding efforts, quality has featured mainly in reference to key first-level attributes, such as size, shape and color, which can influence momentary purchase decisions.

Genotype selection is the key determinant of organoleptic quality and functional properties of fruits and vegetables, particularly for greenhouse crops where agronomic (e.g., irrigation and fertilization) and environmental factors (e.g., light, temperature and atmospheric CO_2) are largely controlled (Kyriacou et al., 2017a; Rouphael et al., 2012a). Optimal growth conditions provided by fully controlled greenhouse environments highlight further the dominant role of genotype selection for the quality of harvested vegetables. Genotype effect on the sensory quality and phytonutrient composition of greenhouse vegetables may surpass that of the origin of the products as well as the effect of brief postharvest storage under optimal conditions (Nassar et al., 2015). Strong determinants for cultivar selection of greenhouse vegetables include the levels of minerals (particularly Cu, Fe, K, Mg, and P), carotenoids (β-carotene, lycopene, and lutein), carbohydrates, organic acids, phenols, anthocyanins, flavonoids, flavonols and ascorbic acid (Dorais et al., 2008; Nassar et al., 2015).

Collecting desirable genotypic traits while avoiding undesirable ones can be further enhanced by grafting, which facilitates independent selection of rootstock and scion traits. A comprehensive critical review of the effects of grafting on the configuration of fruit quality in vegetable crops, and the biological mechanisms implicated, has been recently produced by Kyriacou et al. (2017b). Initially adopted as an alternative to the use of chloro-fluorocarbon soil fumigants, the grafting of annual fruit crops is no longer restricted to the management of soilborne diseases and has become the mainstream, particularly for *Cucurbitaceae* and *Solanaceae* crops (Kyriacou et al., 2017b). Grafting is increasingly employed for ameliorating abiotic and biotic stresses on vegetable crops, by taping wild genetic resources for root physiological tolerance to stress conditions of salinity, nutrient stress, water stress, organic pollutants and alkalinity (Savvas et al., 2010; Schwarz et al., 2010; Borgognone et al., 2013). The significant yield increase incurred by selecting vigorous commercial rootstocks has encouraged their use under protected cultivation where distribution of infrastructural and energy costs is highly dependent on productivity (Colla et al., 2011). Under soil biotic and abiotic stress conditions, rootstock effects on plant performance clearly outweigh those of the scion; however, rootstock effects on scion fruit quality must also be considered (Kyriacou et al., 2017b). These may be mediated by changes in water and nutrient uptake efficiency, by changes in ripening behavior due to altered source-sink balance, and even by epigenetic factors involving transfer of genetic material from rootstock to scion (Avramidou et al., 2015; Savvas et al., 2010; Soteriou et al., 2014).

Incompatibility and deterioration of fruit quality are much more common problems with melon (*Cucumis melo*) than watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] grafting, particularly with *Cucurbita* hybrid rootstocks (Guan et al., 2014; Kyriacou et al., 2017b; Traka-Mavrona et al., 2000; Soteriou et al., 2016). These problems are exacerbated by widespread rootstock-scion interaction owing to the broad genetic-physiological basis of melon botanical varieties, ranging from the odorous climacteric varieties *cantalupensis* and *reticulatus* (e.g. charentais and muskmelon) to the non-aromatic non-climacteric *inodorus* varieties (e.g. honeydew and canary) (Pech et al., 2008; Allwood et al., 2014). For example, the fruit weight of greenhouse muskmelon and honeydew melon was either increased or not affected by various *C. melo* and interspecific commercial rootstocks, as rootstock-scion interaction underscored these effects (Condurso et al., 2012; Colla et al., 2010; Crinò et al., 2007; Verzera et al., 2014). Variable rootstock-mediated responses of melon types have also been reported for pulp texture. Interspecific and *C. melo* rootstocks had no effect on honeydew dry matter content and pulp firmness (Crinò et al., 2007), but reduced Cantaloupe (Zhao et al., 2011), and also Galia and Ananas melon pulp firmness (Soteriou et al., 2016). Rootstock-scion interaction also affected fruit soluble solids content (SSC) and organoleptic rating of greenhouse melon, but both negative and positive effects were generally limited in scale and impact on overall fruit quality (Crinò et al., 2007; Guan et al., 2014; Soteriou et al., 2016; Traka-Mavrona et al., 2000; Trionfetti-Nisini et al., 2002; Verzera et al., 2014).

Watermelon is the most ubiquitously grafted annual crop, grown however predominantly under open field conditions and marginally under greenhouse conditions for out-of-season or early production (FAO, 2012). Numerous works have examined the implications of grafting for watermelon quality but most refer to open field conditions.