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Advances in Vegetable Quality Improvement under Controlled Conditions

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Abstract:

In recent decades, ensuring adequate food supply has become a crucial worldwide issue, particularly due to projected population growth and the additional challenges posed by climate change's impact on farming. Vegetables play a key role in human nutrition through their essential nutrients and beneficial compounds, and could help address both food availability and nutritional needs, particularly when grown in intensive, controlled settings. Growing crops in greenhouses and indoor facilities offers multiple advantages over traditional field farming - not only can it produce higher yields, but it also enables year-round growing and gives farmers significant control over the crops' nutritional and chemical properties. This paper presents a current, in-depth analysis of research developments concerning how plant varieties and environmental conditions affect greenhouse crop quality. It examines cutting-edge farming techniques, including nutrient solution management, biofortification, and the use of plant growth enhancers. The paper concludes with suggestions for future research directions to improve greenhouse vegetable quality.

Introduction:

Modern horticulture faces a dual challenge: feeding a global population expected to hit 10 billion by 2050 while adapting to climate change's effects on crop growth. Protected growing environments like greenhouses offer a potential solution by enabling year-round production, protecting against harsh weather, and providing optimal growing conditions. The last twenty years have seen increasing consumer demand for high-

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quality fresh produce, particularly regarding taste, nutrition, and functional benefits. Product quality is now understood as a complex combination of physical and chemical properties along with consumer preferences. Vegetables contain beneficial compounds called phytochemicals - including various antioxidants like phenolic acids, flavonoids, and carotenoids - that can improve human health by potentially reducing cardiovascular disease and cancer risks while supporting brain function. The presence and quantity of these beneficial compounds depends on several factors, with genetics being the most influential - even more so than growing conditions or farming practices. While traditional breeding and genetic modification aim to enhance these beneficial compounds, progress has been limited, with few commercially available enhanced varieties. There are also safety concerns about dramatically increasing certain compounds through genetic selection, as some high concentrations have shown toxic effects. As a safer alternative that addresses consumer concerns about genetically modified foods, researchers are exploring how environmental conditions and farming practices can be used to optimize these beneficial compounds. Environmental conditions in greenhouses, especially temperature and light, along with humidity levels and CO_2 concentration, significantly affect the taste and nutritional quality of vegetables. LED lighting technology has become increasingly popular among greenhouse growers because it allows precise control of both light intensity and spectrum, which can boost the production of beneficial compounds in vegetables, including in microgreens, a newer specialty crop category. The management of nutrient solutions also plays a crucial role in determining both yield and quality in greenhouse growing. Hydroponic systems (including various methods like substrate culture, nutrient film technique, and floating systems) enable precise control over plant nutrition, which can influence levels of beneficial compounds. Applying controlled amounts of stress - such as moderate salt levels or nutrient limitations - by adjusting nutrient solution composition can effectively enhance vegetables' nutritional value while reducing unwanted compounds like nitrates. Hydroponic systems are also effective for biofortification - enriching plants with micronutrients beneficial to human health. This review paper provides a current analysis of research developments in how plant varieties and environmental management (including temperature, lighting, CO_2 levels, and humidity) affect greenhouse crop quality. It also examines innovative growing techniques, including nutrient solution management, biofortification, and plant biostimulant use, before suggesting future research directions for improving greenhouse vegetable quality.

Genotypic and grafting effects on the quality of greenhouse crops

Over recent decades, plant breeding for both field and greenhouse varieties has primarily focused on improving yields, disease resistance, and shelf life. This focus has often come at the cost of taste and nutritional value - for example, breeding for longer shelf life has sometimes negatively affected taste qualities. When breeders have considered quality, they've typically focused on basic visual characteristics like size, shape, and color that influence immediate purchasing decisions. The choice of plant variety is the most important factor in determining taste and nutritional benefits, particularly in greenhouse growing where environmental conditions are controlled. In fact, when crops are grown in fully controlled greenhouse environments, the impact of genetic selection becomes even more pronounced. The variety's influence on taste and nutrient content can be more significant than either where the produce was grown or short-term storage under proper conditions. When selecting greenhouse crop varieties, important considerations include levels of minerals (especially copper, iron, potassium, magnesium, and phosphorus), various beneficial compounds like carotenoids, carbohydrates, organic acids, and different antioxidants. Grafting - the technique of joining different plant parts - offers another way to combine desired genetic traits while avoiding unwanted ones, as it allows separate selection of root system and above-ground plant characteristics. While initially used as an alternative to chemical soil treatments, grafting is now widely used, especially for cucumber-family and tomato-family crops, to help plants cope with various environmental stresses and increase yields. This increased productivity has made grafting particularly valuable in greenhouse growing, where infrastructure and energy costs need to be offset by high yields. While rootstock effects are most noticeable under stressful growing conditions, their impact on fruit quality must also be considered, as they can influence water and nutrient uptake, fruit ripening patterns, and even genetic expression in the above-ground portion of the plant.

Grafting tomatoes in greenhouse production is becoming standard practice, though its effects on fruit quality are generally less dramatic than in grafted cucumber-family crops. Vigorous hybrid rootstocks can increase fruit size, while less vigorous ones may reduce it. Certain rootstocks (like 'Brigeor', 'Maxifort', and LA1777) can improve overall yield and visual quality by reducing blossom-end rot, though this benefit depends on the specific rootstock, scion, and growing conditions affecting nutrient and water uptake. The main quality impact of grafting on tomatoes appears to be a moderate decrease in firmness, despite increased calcium uptake. Effects on taste factors like sweetness and acidity are minimal compared to the influence of the fruit-bearing portion of the plant, and grafting doesn't significantly affect overall flavor. While grafting onto hybrid rootstocks may alter fruit aromatics, more research is needed in this area. For eggplant, Solanum torvum is the most common rootstock, though many other species and hybrids are used. The effects of rootstocks on eggplant quality are inconsistent due to varying interactions between rootstock and scion, different growing conditions, and inconsistent harvest timing. While grafting generally doesn't affect fruit size, some rootstocks can reduce firmness. Taste characteristics typically remain unchanged regardless of the rootstock used. Pepper grafting is still relatively uncommon, with limited research on its quality impacts. Most rootstocks are selected pepper varieties. Decreased fruit size usually indicates incompatibility between rootstock and scion, while compatible combinations typically show modest increases in fruit size or no change. Grafting can increase antioxidant capacity and beta-carotene content in peppers, but doesn't affect lycopene or phenolic compounds. Its impact on vitamin C content is minimal compared to the influence of the fruit-bearing variety.

Microclimate factors affecting greenhouse vegetable quality

Greenhouse vegetable production plays a vital role in agriculture because it enables control over growing conditions and allows for profitable off-season growing. Today's greenhouses are equipped with advanced technology, including sensors and automated systems that can adjust multiple environmental factors - including air and root temperature, light (both intensity and spectrum), humidity, and CO2 levels - based on plant needs and growth stage. Beyond enabling improved year-round production, this environmental control capability provides growers with powerful tools to enhance both the taste and nutritional qualities of vegetables during the growing period.

Air and root-zone temperature

Research extensively documents how temperature control affects vegetable quality. Studies show that combining higher air temperatures with low light levels can increase beneficial compounds (glucosinolates, vitamin C, and lutein) in greenhouse-grown broccoli. While higher temperatures generally benefit plant growth and yield, when they exceed certain species-specific limits, they can harm plant development and product quality by disrupting nutrient and hormone balance, protein structure, and antioxidant activity. Research on greenhouse tomatoes in tropical conditions found that cooling systems improved fruit quality in different ways: fan and pad cooling in plastic-covered greenhouses reduced blossom end rot and small fruit while increasing calcium content, whereas ventilation in net-covered greenhouses reduced fruit cracking. Some tomato quality characteristics - including firmness, juice electrical conductivity, sugar content, and phenolic compounds - strongly correlate with cumulative temperature (the total temperature above a certain threshold during growing). However, other characteristics like dry matter, vitamin C, acidity, and pH don't show this correlation. Temperature also critically affects tomato color development through lycopene production: temperatures below 12°C or above 32°C inhibit lycopene formation, and the difference between day and night temperatures influences carotenoid production, especially lycopene. More specifically, temperatures between 21-26°C reduce total carotenoids but don't affect lycopene, while higher temperatures (27-32°C) decrease both lycopene and its precursor compounds.

Light conditions

Cover materials have a big impact on the light conditions in a greenhouse, and new developments in material design enable manufacturers to choose cover material parameters that will provide the desired light conditions. In addition to providing protection from biotic and environmental elements, greenhouse cover materials can be used to modify light conditions by using shade nets to reduce light intensity or photo-selective film covers to filter solar radiation. In any event, there is a considerable correlation between vegetable quality and cover materials.

CO2 enrichment

In order to boost yield and earlyness, greenhouse farming frequently uses enrichment to raise the concentration of carbon dioxide (CO_2) to levels as high as 1000–1200 μmol mol−1 (Chalabi et al., 2002). Its use, however, is heavily reliant on environmental factors, such as temperatures that permit ventilators to be closed for extended periods of time, greenhouse design, cultivation intensity, and the final product's market value, all of which can offset increased production costs. The majority of research on CO_2 enrichment in greenhouse environments to date has been on fruit, vegetables, and lettuce; in addition to production increases of up to 30%, a notable impact on chemical composition has also been shown. In two red lettuce cultivars, CO_2 enrichment up to 1000 μmol mol−1 increased the content of flavonoids and derivatives of caffeine, while the rise in sugars, which are precursors in the production of flavonoids, may have contributed to the greater flavonoid content. According to Sgherri et al. (2017), red lettuce cultivars exhibit a higher amount of secondary metabolites and antioxidant activity, suggesting that they are more sensitive to increased CO2. Elevated ambient CO2 had a detrimental effect on lettuce plants infected with arbuscular mycorrhizal fungus because more photosynthates were antagonistically utilized for mycorrhizal colonization and shoot growth rather than supporting leaf biosynthesis.

Fruits and vegetables like tomatoes are significantly impacted by elevated CO2. There was a negative impact on the amounts of vitamin C, protein, organic acids, fat, and ash, and a positive impact mostly on the amount of sugars (total, reducing, and non-reducing), and less so on the amount of fiber. While the similar pattern was shown in the composition of fatty acids, the mineral composition was also impacted, and a varied response based on genotype and particular elements was recorded. On the other hand, Jin et al. (2009) found that CO2 enrichment through the composting of crop waste and animal manure in a greenhouse setting significantly increased the amount of sugars and ascorbic acid and decreased the amount of nitrate in leafy vegetables like Chinese cabbage (Brassica chinensis L.), celery (Apium graveolens L.), leaf lettuce (Lactuca virosa L.), stem lettuce (Lactuca sativa L.), oily sowthistle (Sonchus oleraceus L.), and celery (Apium graveolens L.).

Vapor pressure deficit

Relative humidity (% RH) or vapor pressure deficit (kPa VPD) are two ways to express air humidity. Reduced evapotranspiration rates, which are plants' primary cooling mechanism, caused by high relative humidity or low VPD cause heat damage. At the same time, decreased sap flow through the phloem decreases ion translocation within plant tissues, leading to symptoms of nutrient deficiencies and poorer visual quality. According to Bakker et al. (1987) and Leonardi et al. (2000), high relative humidity also causes high turgor pressure, which can lead to more tomato fruit shattering, particularly at night, as well as light coloration and deformity in cucumber fruits. In comparison to open fields, screenhouses without fogging systems, and screenhouses with a fogging system and plastic covering, it has been reported that using a fogging system to increase RH in screenhouses increases the amount of lycopene and organic acid as well as the antioxidant activity of tomato fruit. Leonardi et al. (2000) and Rosales et al. (2011) have reported similar findings about the impact of reduced VPD on the lycopene content of cherry and salad tomato fruit. High

VPD typically occurs in conjunction with high temperatures and solar radiation, which together cause oxidative stress and have detrimental effects on marketable yield, mineral and carotenoid contents, while increasing sugar content, phytonutrients, and antioxidant activity.

Conclusion

It is extremely difficult for scientists and extension specialists to suggest sustainable and efficient preharvest techniques for enhancing product quality without sacrificing yield because of the ongoing pressure on growers and the agro-food sector to produce premium quality greenhouse vegetables with useful qualities. By managing the environmental factors during plant growth, grafting combinations, and proper genotype selection, these goals can be achieved. It will be difficult to determine the best combinations of these elements to optimize product quality. The nutritional value of greenhouse vegetables can be significantly impacted by a variety of environmental conditions as well as cutting-edge cultural approaches including grafting and the use of plant biostimulants, as this review has shown. Hydroponic vegetable production appears to be a useful method for boosting phytochemicals and important and/or advantageous micronutrients in vegetables (such as biofortification) and for managing anti-nutrient buildup, such nitrates.

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