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Do soilless culture systems have an influence on product quality of vegetables?

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Summary

In the horticulture industry, the focus has traditionally been on yield. However, consumers' interest worldwide in the quality of horticultural products has increased in the recent past and will become the driving force in the future. Soilless culture systems (SCSs), the most intensive production method in today's horticulture industry, are based on environmentally friendly technology, which can result in higher yields, even in areas with adverse growing conditions. However, using SCSs does not automatically result in the production of high-quality vegetables. Numerous studies confirm that a SCS enables growers to produce vegetables without quality losses compared to soil cultivation. An adaptation of cultural management to the specific cultural system, as well as crop demand, can further result in the improvement of the quality of horticultural products.

Introduction

The significance of the nutritional quality of vegetables is increasingly important for greenhouse growers who want to meet the ever-increasing demand of consumers in the highly competitive fresh vegetable market (FANASCA et al., 2006).

Product quality is a complex issue, and it depends on several factors. A recent comprehensive review of product quality for greenhouse vegetables can be found in GRUDA (2005). It is necessary to differentiate between objective, measurable traits, and subjective quality parameters, for instance, taste. Different countries worldwide establish their set of objective criteria for the quality of fresh fruits and vegetables. These official quality grades and standards for classification and evaluation are based on the Codex Alimentarius of the FAO of the United Nations and the World Health Organization (KADER, 2001; GRUDA 2005).

Process quality, often found in the literature under the term, quality management, is another very important characteristic. While the product quality answers the questions of what has been produced, what extent this product fulfills the quality standards, and how the product corresponds to our quality expectations, the process quality answers the questions of how the product has been produced and which processes have been used during production. However, the dependence on the natural environmental conditions (stochastic influence variables) greatly complicates the control of production. The spatial and temporal heterogeneity for a plant's development condition requires extraordinarily high precision of the processing control (SCHMIDT, unpublished).

The processes of greenhouse production have greatly advanced in the last several decades. This development has usually been accompanied with the development of SCSs, which is the most intensive and effective production method in today's agriculture industry (MORARD, 1995; DORAIS et al., 2001a; GRILLAS et al., 2001). The term „soilless culture" is defined as the cultivation of plants in systems without soil „*in situ*". In recent years, a multitude of innovative cultivation procedures using bags, mats, and containers, in addition to nutrient solutions, have been developed. These cultivation methods include systems without a solid medium, as well as aggregate systems, in which inorganic or organic substrates are used.

SCSs guarantee flexibility and intensification and provide high crop yield and high-quality products, even in areas with adverse growing conditions (MORARD, 1995; GRILLAS et al., 2001). They offer significant advantages: a reduction of soil-borne diseases and complete control over water and nutrient supplies. Therefore, control over the concentration and composition of the nutrient solution, the common issue of SCSs, is more precise and the desiderated ratio of nutrients more exact without the interference of organic matter or cation exchange capacity in soil. However, consumers often criticize such production systems. This negative attitude toward SCS-grown products is the result of greater ecological and health consciousness (KEISER-GLOOR, 1990). Controversy arises because of supposedly unnatural hydroponics production techniques, which is the result of artificial growth and low internal quality, such as taste and nutrient value, as compared to so-called healthier products of plants grown in soil. It concerns SCSs such as nutrient film technique (NFT), plant plane hydroponics (PPH), and rock wool (RW) more than those with organic substrates such as peat, wood fiber (WF), bark, and other organic materials, as well as vegetables more than ornamentals (SCHNITZLER and GRUDA, 2002).

Furthermore, it is important to mention that in this complex combination of „soilless culture" and „product quality", not only the interests of the producers, but also an ideological background could be found. Soil has the highest value in the production chain for the supporters of soil products.

However, one may forget that although the development of a SCS over the last twenty years began primarily for economic reasons (RIVIÈRE and CARON, 2001; BENOIT and CEUSTERMANS, 2004), there was also an important ecological advantage conferred from the use of methylbromide (VANACHTER, 1983). Moreover, the recirculation of drain water changed from a recommended guideline into a widely accepted ecological option by the public (BENOIT and CEUSTERMANS, 2004), so that SCSs today are recognized as environmentally friendly cultivation procedures. Lately, there have been some efforts to bring both positions a little closer, e.g., by use of organic fertilizers in SCSs (LIEDL et al., 2004; PEET et al., 2004; SUCCOP and NEWMAN, 2004; BRENTLINGER, 2007). Microgreens are also being grown hydroponically and organically (BRENTLINGER, 2007). Indeed, vegetables grown in soilless culture can be certified as organic in some countries, for instance, in the U.S.

Aside from some general pieces of information about SCSs (SCHNITZLER and GRUDA, 2002; SAVVAS, 2003), no recent review exists concerning the product quality of horticultural products cultivated in these systems. The objective of this paper is, therefore, to present a brief review, regarding the influence that SCSs may have on the quality of these products.

Quality of product from soil and SCSs

A principle in applied research is to use control treatment which, in this case, prompts the question: what control treatment should be compared with a SCS? Simply, the cultivation in soil. But, in fact, they are two different systems that are not really comparable. From this point-of-view, we can only speak for a system comparison, and this is not very easy. Similar to a comparison between organic and conventional produce, a comparison between a SCS and a conventional cultivation system, could be not explained convincingly due to poor methodology (Giles, 2004) and the high degree of interactions. Indeed, the only reliable way to compare soil with soilless systems is to place both systems in the most optimal growing conditions.

However, for consumers and legislators, the main concerns are safety and product quality with SCSs. Following this statement, it is also clear that an influence of SCSs on the product quality would be expected. One could suppose, in this case, that the results could have several different outcomes: (i) a soilless product is equal, (ii) better or (iii) worse in quality than a product grown in soil.

Among all freshly produced vegetables, the tomato ranks as the highest in consumer preference worldwide. In Europe, Canada, and in the large horticultural industry complexes in the U.S., 95% of greenhouse tomatoes are produced in SCSs (Peet and Welles, 2005). As shown in Tab. 1, all three hypotheses regarding the quality of tomatoes produced in SCSs may be possible. The contradictory results can sometimes be attributed to incomparable data, resulting from differences in growth factors, such as types of fertilizers, climates, plant cultivars, and variations in experimental design (Künsch et al., 1994a; Schnitzler and Gruda, 2002). Furthermore, the physiological state of ripeness is important, e.g., firmness and composition (Schnitzler et al., 1994; Petersen et al., 1998).

Most of the recent literature indicates that there are no objective differences between quality properties of tomato fruits produced in conventional or a SCS (first column of Tab. 1). Künsch et al. (1994a) compared the quality of soilless (RW culture) and conventional

Tab. 1: Quality properties of tomato fruits – A comparison between soil and soilless culture, according to different authors.*

Properties	No differences between soil and soilless culture systems	Soilless culture systems (+)	Soil culture (+)
Uniformity weight		Massantini, 1962; Yuxian et al., 1997; Massantini et al., 1988	
Size	Abak and Celikel, 1994; Alan et al., 1994	Massantini, 1962; Gül and Sevgican, 1992; Alan et al., 1994; Yuxian et al., 1997	Gül and Sevgican, 1994
Consistency, Texture	Gül and Sevgican, 1992; Gül and Sevgican, 1994; Thybo et al., 2005	Massantini, 1962; Benoit and Ceustermans, 1987; Massantini et al., 1988; Osvald and Petrovic, 1997; Gilinger Pankotai et al., 1998	
Dry matter	Granges, 1980; Simitchiev et al., 1983; Bævre, 1985; Abak and Celikel, 1994; Gilinger Pankotai et al., 1998; Thybo et al., 2005	Massantini, 1962; Garan'Ko, 1968; Bævre, 1985; Mauromicale et al., 1996; Özçelik and Akilli, 1999; Yuxian et al., 1997	Granges, 1980; Noguera et al., 1988
Sugar	Simitchiev et al., 1983; Bævre, 1985; Buret and Duprat, 1985; Mars et al., 1985; Schnitzler et al., 1994**; Gilinger Pankotai et al., 1998	Massantini, 1962; Garan'Ko, 1968; Granges, 1980; Bævre, 1985; Lăcătus et al., 1995; Mauromicale et al., 1996	Massantini, 1962
Fiber			
Soluble solids	Buret and Duprat, 1985; Mars et al., 1985; Gül and Sevgican, 1992; Gül and Sevgican, 1994; Alan et al., 1994; çelikel, 1999a; Thybo et al., 2005	Benoit and Ceustermans, 1987; Alan et al., 1994; Mauromicale et al., 1996; Yuxian et al., 1997; Özçelik and Akilli, 1999	
Vitamins	Granges, 1980; Simitchiev et al., 1983; Gül and Sevgican, 1994; Abak and Celikel, 1994; Alan et al., 1994; Gilinger Pankotai et al., 1998; çelikel, 1999a	Benoit and Ceustermans, 1987; Lăcătus et al., 1995; Mauromicale et al., 1996; Özçelik and Akilli, 1999	
Carotenoids		Lăcătus et al., 1995	Granges, 1980
Acidity	Simitchiev et al., 1983; Buret and Duprat, 1985; Mars et al., 1985; Gül and Sevgican, 1994; Alan et al., 1994; Gilinger Pankotai et al., 1998; Gül and Sevgican, 1992; Schnitzler et al. 1994; Abak and Celikel, 1994; çelikel 1999a	Benoit and Ceustermans, 1987; Alan et al., 1994; Özçelik and Akilli, 1999	Granges, 1980; Thybo et al., 2005
Minerals	Simitchiev et al., 1983; Benoit and Ceustermans, 1987; Gilinger Pankotai et al., 1998		
Taste	Künsch et al., 1994b; Osvald and Petrovic, 1997; Auerswald et al., 1996; Granges et al., 2000; Thybo et al., 2005	Osvald and Petrovic, 1997; Massantini et al., 1988, Yuxian et al., 1997	

*Based on Santamaria and Valenzano (2001), modified and supplemented with results from other studies. ** results for sugar/acid ratio.
+ = System advantages for different properties

tomatoes produced in the same variety. Although the sugar/acid ratio was significantly higher in soilless produced tomatoes, no sensory and few qualitative differences were observed between fruit produced by these two methods. Also, ABAK and CELIKEL (1994) found no differences between organic substrates and RW or soil with respect to fruit size, acidity, dry matter, and vitamin C content of tomatoes. Furthermore, no differences were found between the cultivation in different systems in the greenhouse, such as aeroponics, NFT, RW, and soil during two growth periods (GYSI et al., 1997).

Sometimes, the properties in product quality were altered under the influence of different cultivation methods. According to AUERSWALD et al. (1996), the content of reducing sugars, titratable acids, ascorbic acid, and carotenoids in tomatoes alternated under the influence of three cultivation methods, NFT, PPH, and cultivation in the soil, during the course of one year. However, sensory tests revealed no differences in taste or consistency due to the methods of cultivation. Recently, THYBO et al. (2005) reported that for most tomato fruit sensory characteristics, the greatest variation was due to differences in variety, followed by maturity, harvest time, and electric conductivity (EC), while the type of growth medium (soil or RW) had little or no effect.

In addition, no significant differences are found in literature for other products: lettuce (KÜNSCH et al., 1996; SIOMOS et al., 2001), paprika (LĂCĂTUS et al., 1995), melon (GÜLER et al., 1995), or strawberry (PARASKEVOPOULOU-PAROUSSI and PAROUSSIS, 1995; FERNANDEZ et al., 2006) harvested from the SCSs and soil.

Only a few studies have indicated that better tomato fruit quality can be obtained from plants cultivated in soils than in a SCS (Tab. 1). In some instances, the same author showed a similar or better characteristic, e.g., dry matter between treatments (GRANGES, 1980). This result can also be found in literature for other products, e.g., lettuce (SIOMOS et al., 2001).

The indispensable requirement that a SCS does not negatively affect the product quality assumes the proper use of SCS procedures and an adapted culture technology. For example, it is well known that SCSs represent a finite buffer capacity regarding water and fertilizer supply, as well as pH-value of the nutritive solution, due to relatively small and restrictive root areas. Consequently, insufficient water supply and nutrient imbalance could induce blossom end-rot (BER) of greenhouse tomatoes. Failure to provide plants with irrigation during noon hours in the summer could result in quality losses and potentially plant death in SCSs. Plants that are cultivated in the soil have a better chance of recovering without visible quality deficiencies. Despite indications that the quality of SCS crops may be worse than those grown in soil, one should keep in mind that plant abnormalities are not necessarily „soilless culture-specific“, but caused by deficiency of water supply at high temperatures. According to ADAMS (2002), the most common cause of BER is a combination of both high temperature and water stress, regardless of production system. For properties, such as uniform weight, size, and consistency, SCS tomatoes present a better fruit quality than tomatoes grown in soil. According to GRANGES (1980), tomatoes grown in greenhouse soil have higher acidity and less reduced sugars than those grown in NFT systems. BENOIT and CEUSTERMANS (1987) found that tomatoes produced in a NFT-system were firmer and richer in vitamin C than the soil-grown plants. Tomato fruit also contains more sugar, acid, and sodium, which result in a more distinctive taste. Moreover, the nitrate content of NFT-grown fruits was considerably lower, while the phosphorus, potassium, calcium, and magnesium concentrations were practically identical to those in the soil grown plants.

ROUPHAEL et al. (2004) reported that no differences were observed in dry matter or total protein content, while carbohydrate concentration (glucose, fructose, sucrose, and starch) was higher in SCSs zucchini (*Cucurbita pepo* L.) *cv.* 'Afrodite' over soil culture.

For several good reasons, there are far fewer reports comparing the product quality of ornamentals and nursery shrubs in SCSs and soil. Generally, (i) SCSs have proven to be very suitable for the production of flowers, (ii) substrate cultures for pot or container plants have become the normal technique, and (iii) these systems are regarded by consumers as more environmentally friendly for ornamentals and nursery plants than for vegetable production (SCHNITZLER and GRUDA, 2002). However, using SCSs does not automatically always result in high-quality products, although it has been shown that it is possible to produce soilless crops without quality losses. Additionally, there are a lot of references (e.g. for tomatoes, second column of Tab. 1) that indicate that by using SCSs, the product quality could be improved.

Comparing different systems requires primarily optimizing them. Only under these circumstances, will it be possible to make a direct and accurate comparison. Since many SCSs use a solid growing medium, the comparison between the substrates could be also applicable.

Product quality for different growing media

As soon as substrates began to be environmentally hazardous in the 1980s, a strong emphasis was placed on research for modern horticultural techniques to comply with ecological mandates (BENOIT and CEUSTERMANS, 2004). Consequently, a lot of new organic growing media, based on renewable raw materials, were and continue to be investigated. Nowadays, the utilization, nature of materials used for SCSs, and growing media are diverse (GRUDA et al., 2005).

As in the above example, the large spectrum of substrates offered in horticulture along with the importance of the cultural guidelines should be emphasized. Only adapted cultural guidelines will confer the advantages of substrates and culture procedures for successful cultivation. Physical, chemical, and biological characteristics of the substrates must correlate with water and fertilizer supply, climate conditions, and plant needs (GRUDA and SCHNITZLER, 2000a, 2000b, 2004a, 2004b, 2006).

These differences between growing media have to be considered. For example, in a comparison between peat and its substitutes, such as bark, wood fiber substrate, paper and straw substrates, the activity of microorganisms must be evaluated. In order to build up their own body protein components, these microorganisms need mineral nitrogen (N), which they gain from the available N content in the substrate. Consequently, N would not be readily available for the plants. This effect is one of the most important factors leading to potential quality losses (GRUDA et al., 2000). It is possible that given equal N tomato transplants grown in a (wood fiber substrate), WFS will not grow as well (e.g., more slowly and with N-deficiency symptoms) as one produced in a peat substrate. Thus, transplant producers may determine that using WFS has a negative effect on the quality of their product (= transplants). However, it was also shown that this growth-retarding effect, due to N immobilization in WF, can be eliminated by N-impregnation of the substrates and additional N fertilization during cultivation. Thus tomato transplants, which were grown on impregnated WFS substrate, showed the same quality as plants that were cultivated in peat (GRUDA et al., 2000).

In conclusion, each substrate requires its own optimum growing technology. The quality of the product reflects the adherence of different guidelines to each substrate. If we focus on peat, a high-quality product could be expected (and not only quality). A similar case is if we focus on peat-free substrates. Usually in optimal culture guidance for each substrate and there is no impact of substrate *per se* on product quality (ABAK and CELIKEL, 1994; ÖZEKER et al., 1999; ÖZÇELIK et al., 1999; SCHNITZLER and GRUDA, 2002; ANGELIS et al., 2001; LOPEZ et al., 2004; PARKS et al., 2004). Recently, RODRIGUEZ et al. (2006) investigated different combinations of media (coarse perlite, medium perlite, and pine bark) and containers (polyethylene bags and plastic pots) for hydroponic production of 'Galia' musk-melons (*Cucumis melo* L.) and found that fruit yield and fruit quality were not affected by any combination of media and containers. The average content of soluble solids was generally greater than 10 degrees Brix.

Possible ways to improve the product quality due to SCSs

Climate conditions could have enormous influences on the product quality of greenhouse fresh vegetables. They do not only affect the physiological processes and lead to differences in appearance of vegetable products, but they also influence the internal quality of vegetables. Sensory ingredients such as sugars, acids, and flavor substances as well as vitamins and secondary plant compounds can be affected by changing the climate condition in the greenhouse (GRUDA, 2005). However, according to HO (2004) the key to the future of glasshouse production will be the further development of SCSs. The use of a SCS not only makes it possible to have better control over water and nutrient supplies, but such a system is ideal for holistic control of crop development, crop yield, and product quality (HO, 2004). Moreover, the improvement of yield will not be the sole driving force for the horticultural industry in the future. More importantly, qualities such as taste and health value for vegetables will become the criteria for the consumer's choice (HO, 2004).

Several properties of the nutrient solution can effectively modify produced quality, for instance, EC or nutrient concentration, chemical forms of the elements, nutrient management, temperature of the nutrient solution, pH, etc. The following examples will illustrate the possibility of an improvement of vegetables product quality due to a precise amount of nutrients in SCSs:

a) Proper management of the salt concentration of the nutrient solution can provide an effective tool to improve the vegetable quality. Many investigations have shown that using solutions with moderate electrical conductivity, achieved by adding NaCl or nutrients, can improve the tomato fruit quality in terms of organic acidity and soluble solid (MIZRAHI and PASTERNAK, 1985; SONNEVELD and WELLES, 1988; ADAMS, 1989, 1991; CORNISH, 1992; PETERSEN et al., 1998; ADAMS and HO, 1989; ELIA et al., 2001; DE PASCALE et al., 2001). Moreover, an increase in the dry matter of tomato fruits occurred due to an active osmotic adjustment of plants to guarantee further water uptake under high saline conditions (HASEGAWA et al., 2000; PLAUT et al., 2004). A detailed review of these effects is presented in DORAIS et al. (2001b). Furthermore, SATO et al. (2006) found an increase not only in sugar content, but also in the organic and some amino acids that may contribute to a better taste (NELSON, 2002) of tomato fruits, due to a NaCl application in the nutrient solution.

Recently, consumers' awareness increased concerning health-promoting compounds and properties such as antioxidant capacity and nutritional value in vegetables (D'AMICO et al., 2003; DUMAS et al., 2003). KRAUSS et al. (2006) investigated the influence of three different salt levels (EC = 3, 6.5, and 10 dS m^{-1}) in SCSs grown tomatoes. Rising EC-values of the nutrient solution increased vitamin C, lycopene and ß-carotene (the precursor to vitamin A) in fresh fruits up to 35%. The phenol concentration was tendentiously enhanced, and the antioxidative capacity of phenols and carotenoids increased on a fresh weight basis. Additionally, the higher EC values caused an increase of total soluble solids and organic acids, parameters determining the taste of tomatoes. An enhancement of some of these health-promoting substances was also found in earlier investigations by PETERSEN et al. (1998) affirming the hypothesis that saline water may increase desirable compounds in tomatoes.

Similar results were also obtained for sweet pepper and cucumber (SONNEVELD and VAN DER BURG, 1991; TRAJKOVA et al., 2006), eggplant (SAVVAS and LENZ, 1994), celery (PARDOSSI et al., 1999), as well as watermelon (COLLA et al., 2006). ROUPHAEL et al. (2006) reported that increasing salinity from 2.0 to 4.1 dS m^{-1} improved fruit quality of zucchini squash with regard to a higher content of dry matter, reduced sugars, starch, total carbohydrates, and vitamin C.

However, at some point increases in salinity limit marketable yield, increase the incidence of BER, and reduce the fruit size. Manipulating the indoor climate, such as humidity, temperature, and ambient CO_2 level, may offset the negative effect of high salinity on yield and fruit quality (DORAIS et al., 2001b). An unequal EC achieved with a split root system was suggested for growing tomato plants in hydroponics, in order to avoid or mitigate these high salinity issues, and as a consequence, to improve both yield and fruit quality (TABATABAIE et al., 2004).

b) FANASCA et al. (2006) investigated the effect of cationic proportions (K/Ca/Mg) in the nutrient solution on fruit quality (quality attributes and antioxidant content) of tomatoes grown in soilless culture and demonstrated that a high proportion of K in the nutrient solution increased the attributes and antioxidants' content (especially lycopene) of tomato fruit, whereas a high proportion of Mg in the solution improved the total antioxidant activity of tomato, *cv.* 'Lunarossa'. Antioxidants are believed to be important in the prevention of diseases such as cancer and cardiovascular disease. Lycopene is one of the main antioxidants found in fresh tomatoes and processed tomato products. The lycopene content also accounts for the redness of the fruit, which is one of its main qualities that interests the industry and consumers (DUMAS et al., 2003).

c) Different strategies are developed to maintain the nitrate limit set by the authority, although recent literature shows that methaemoglobinaemia has been linked to endogenous nitrite production (LEIFERT and GOLDEN, 2000; TREWAVAS, 2004; GRUDA, 2005). Closed SCSs or the use of only small volumes of substrate is regarded as a possibility to control nitrate contents during critical periods (SHINOHARA and SUZUKI, 1988; KÜNSCH et al., 1996; MATTHÄUS, 1996; SCHNITZLER and GRUDA, 2002). GONNELLA et al. (2004) reported that the replacement of the nutrient solution with rain water three days before harvesting resulted in one third of the nitrate reduction in leaves. These results are in agreement with the findings of MARTIGNON et al., 1994 for endive and celery. By eliminating 90% of N in the nutrient solution one week prior to harvest, the nitrate content of endive (*Chicorium endivia* L. var. *crispum* Hegi) leaves was halved and decreased by 56% and 32%, in leaf blades and in the ribs of celery, respectively (MARTIGNON et al., 1994).

Environment concerns

Effective greenhouse production means dealing with environmental conditions. Location properties relate to components such as: climate (irradiation, temperature, the length of the day, water balance, etc.), edaphic (structure, chemical and biological soil properties, water and air content at different water tensions), and management (cultivation measures) factors. A recent trend shows that protected cultivation has become more common in areas with mild climates, but not in areas with severe climates where it originated (TOGNONI et al., 1999; GRUDA, 2005). However, sometimes, although the climate conditions for plant cultivation are adequate, the lack of soil properties, such as salinization, erosion, poor soils structure, infertility, contamination, etc., makes a profitable greenhouse production in those areas impossible. An approach seems to be the development of SCSs. In particular, these systems are widely used in countries, such as Israel or those in the Mediterranean region, where favorable climate conditions and problematic soil properties exist.

Since this paper referred only to the quality of vegetables, some important general aspects regarding the application of a SCS have yet to be considered. Through the application of SCSs, an increase in the efficiency of fertilizers and water use should be emphasized. Moreover, due to the maintenance of hygienic conditions and an integrated pest management, a reduction of pesticides rather than in conventional greenhouse production could be realized.

Conclusion

In conclusion, horticultural production through SCSs is environmentally friendly and enables application of specific quality management. However, using SCSs does not automatically result in the production of high-quality vegetables. The adaptation of cultural management to the specific conditions of the system or substrate as well as crop demands can improve their product quality. High yields do not automatically imply high quality, therefore, a compromise between both needs to be established.

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