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Impact of Environmental Factors on Product Quality of Greenhouse Vegetables for Fresh Consumption

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Consumer interest worldwide in the quality of vegetable products has increased in recent years. Product quality is a complex

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issue. As well as visual characteristics, properties such as texture, the content of minerals and vitamins, flavor and other organoleptic characteristics must be considered. In addition, new knowledge shows that vegetables are appreciated for their beneficial health effects in humans and underlines the importance of nutraceutical properties. Many research studies have documented methods for achieving a high-quality vegetable product. Indoor production for fresh vegetables offers advantages compared to outdoor production with regard to quality assurance principally, because the products

are not exposed directly to the rapid changes of climate conditions. On the other hand, vegetable cultivation in a greenhouse under artificially created conditions also affects the internal quality of the product. This is reflected in a different taste and flavor compared with field vegetables. Changes in external as well internal quality attributes of greenhouse vegetables subjected to light intensity, temperature, vapor pressure deficit (VPD), and CO₂ enrichment of the atmosphere concentration are discussed in this paper.

Keywords air humidity, bioactive compounds, CO₂, flavor, internal and external quality, light, nitrate, physiological disorder, preharvest, temperature, VPD

I. GREENHOUSE VEGETABLE PRODUCTION

Protected cultivation plays an important role in the production of fresh vegetables. In 2003, approximately 246.5 million metric tons of fresh vegetables excluding melons were produced worldwide from a harvest area of 16.7 million ha (FAO, 2005). Those include, as Dorais *et al.* (2001) summarized in a review paper, a worldwide greenhouse surface of 306,500 to 450,000 ha, mainly concentrated in China, Japan, Korea, and the Mediterranean basin.

Due to intensive production methods and longer cropping periods, the yield of greenhouse vegetables is much higher than field vegetables. In addition, greenhouse products usually have high visual quality, so that their market value is high in comparison with field-produced vegetables. This justifies the extra costs for investment and operation (Bot, 2003). Unfortunately there are no reliable statistics for greenhouse vegetable area, production, and market value. In the Food and Agriculture Organization (FAO) database they are not separately documented (FAO, 2005).

In recent decades, the increase of protected cultivation in glasshouses has been very small compared with the large spread of low-cost plastic greenhouses around the world (Castilla *et al.*, 2004). First introduced into the horticultural industry in the 1950s, they increased very quickly worldwide and represent 95 percent of total greenhouse area in all the Mediterranean European Union countries and Japan and 99 percent in China (Grafiadellis, 1999; Ito, 1999; Zhibin, 1999; Castilla *et al.*, 2004). In more Northern countries glasshouses remain dominant.

The greenhouses create nearly perfect conditions for plant growth and development and were first used to accommodate rare plants during the cold season. Later they were used more and more to grow high-quality vegetables when climatic conditions were not favorable (Zabelitz, 1986). An interesting recent trend is that protected cultivation has become more common in areas with mild climates and not in the areas with severe climates where it originated (Tognoni *et al.*, 1999). In a paper about greenhouse structures in Mediterranean Regions, Grafiadellis (1999) described the reasons for this development. The main factors that have influenced the huge expansion of greenhouses in this areas are the climate advantages of these regions (mild temperatures during winter months, large number of sunny days with high

intensity of solar radiation), the use of low cost materials for the construction of greenhouses, the high heating cost of greenhouses in northern countries, the improvement of transportation, and the efficient international marketing of horticultural crops. Another important factor, which boosted out-of-season production, is the fact that with the rising standard of living local demand for fresh vegetables increased and people were prepared to pay higher prices (Baudoin, 1999; Wijnands, 2003). Changes in production strategy should also be mentioned. Whereas in the past in areas like the Mediterranean, there was a general tendency to grow the plants in a suboptimal environment, strong competition arising from the globalization of both markets and production highlighted the need for increasing the quality of produce through improved climate control (Castilla, 1994; Castilla *et al.*, 2004). In summary, the profitability of high-quality crops produced in greenhouses is becoming more and more evident, and thus, the quality of the product is very important. But, what is the product quality?

II. PRODUCT QUALITY—DEFINITION

The term *quality* has been defined in several ways. According to Shewfelt (1999) "Quality is a term frequently used but rarely defined." This means that different customer groups such as breeders, producers, market participants, food industry workers, and consumers have different views about quality. This is reflected in the required quality characteristics of a product. For example, several tomato fruit characteristics such as soluble solids, sugar, acidity, and pH are important for both fresh market and processing tomatoes while other characteristics such as taste and shelf life are more important only for the fresh market (Cuartero and Fernández-Munoz, 1999). The influence of different factors on the quality of fresh vegetables only are analyzed in this paper.

However there are also different points of view concerning the quality of fresh vegetables. According to Shewfelt (1999) and Huyskens-Keil and Schreiner (2003) quality has both a product- and a consumer-dependent dimension. From the perspective of product orientation, quality attributes are inherent in a product and can be readily quantified, whereas a consumer orientation, which defines quality in terms of consumer satisfaction, is a much less tangible and less quantifiable concept (Shewfelt, 1999). One must be able to measure quality-related attributes to investigate and control quality (Dris and Jain, 2004). This paper will be focused only on product-oriented quality and objective criteria.

Objective criteria for the quality of fresh fruits and vegetables are established in Europe and North and Central America. 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 (WHO) (Schreiner *et al.*, 2000; Bickelmann, 2001; Kader, 2001; Huyskens-Keil and Schreiner, 2003). In contrast to fruits, where the generative part is used for fresh consumption, many different

parts of plants such as seeds, roots, leaves, stem, rhizome and inflorescence are consumed as vegetables (Huyskens-Keil and Schreiner, 2004). Thus, to determine the product quality of vegetables quality standards for different edible plant organs have to be determined.

These quality standards are objective quality measure for the market value of vegetables. However, they are based more on external qualities, e.g., size and shape, color and form, as well as freshness in normal condition and freedom from physiological disorders and defects (Kays, 1999; Bickelmann, 2001; Schnitzler and Gruda, 2002). Critical concentrations of pesticides and nitrate in plant tissues are included in standards, whereas very important internal qualities such as texture, flavor, and nutraceutical properties are not considered. As a consequence, positive changes in organoleptic characteristics such as sugar, aroma compounds, or organic acid content are not taken into account. These can have promotory effect on the salability of the product (Schnitzler and Gruda, 2002). Recently, consumer demand for these parameters has greatly increased together with requirements for a higher content of minerals, vitamins, and bioactive substances (Schreiner *et al.*, 2000; Schnitzler and Gruda, 2002). Some of these quality characteristics for greenhouse vegetables will be discussed in this paper.

On the other hand, the definition of “product quality” for vegetables is not a fixed time value but changes dynamically. New laws and orders (e.g., residue limits for pesticides) as well as new trends have to be implemented into these new approaches (Huyskens-Keil and Schreiner, 2003). Table 1 presents a comprehensive view of product quality shown by Huyskens-Keil and Schreiner (2003, 2004), modeled after Schuphan (1948, 1961), Huyskens (1996), Shewfelt (1999), Kader (1999, 2001)

and Weichmann (2002). This might serve as a baseline for the quality evaluation of horticultural products (Huyskens-Keil and Schreiner, 2004). Certainly, these criteria will change in the future, based on new knowledge about harmful substances and the content of health promoting substances.

Recent literature shows that vegetables are very appreciated for their secondary plant metabolites presented as bioactive compounds such as glucosinolates (e.g., in brassicas), carotenoids (e.g., in carrots, pepper, spinach, and in tomato mainly as lycopene), polyphenols (e.g., in onion, red cabbage, tomato), saponins (e.g., in bean and pea), terpenes (e.g., in carrots, tomato, celery) as well their dietary fiber (Herrmann, 2001; Scharpf, 2002). These substances are not only involved in plant defense and plant-insect interactions, but could also have a healthy promotion effect in the human body (Schreiner *et al.*, 2000) and prevent diseases of different origins (Steinmetz and Potter, 1996; Fahey and Stephenson, 1999; Charron and Sams, 2004). An extensive body of epidemiological evidence supports the contention that as much as 75 percent to 80 percent of human cancers are related to “nongenetic” factors and that high fruit and vegetable consumption is associated with a reduction in the incidence of cancer at multiple sites (Fahey and Stephenson, 1999).

It is not the objective to present here the scientific results of studies in these topics. However, one must emphasize that no single product attribute can meet all the requirements indicated, being not a fixed value but a process-, product- and time-dependent value (Huyskens-Keil and Schreiner, 2004). The product quality of vegetables for fresh consumption is a complex issue. Many characteristics comprise the full description of product quality of a given vegetable. In the scientific literature they are found under the term intrinsic factors (Jongen, 2000; Shewfelt and

TABLE 1
Quality values and their quality criteria determined by the customer groups of the supply chain¹

Product quality					
Market value	Utilization value	Sensory value	Nutritional and health value	Ecological value	Imaginary value
External quality			Internal quality		
Shape	Shelf life	Taste	Desired ingredients:	Cultivation methods:	Prestige
Color	Transportability	Smell	Vitamins	Integrated	Image
Size	Storability	Flavor	Minerals	Plant	Religion
Freshness	Processing	Textural properties	Carbohydrates	Production,	
Consistency			Dietary fibers	Ecological	
			Bioactive substances etc.	Plant production,	
			Undesired ingredients:	Soilless culture	
			Heavy metals		
			Residues		
			Nitrate		
			Mycotoxins etc.		

¹Taken from Huyskens-Keil, and Schreiner 2003. *J. Appl. Bot.* 77: 147–151. Reproduced with permission.

Modeled after Schuphan (1948; 1961), Huyskens (1996), Shewfelt (1999), Kader (1999, 2001) and Weichmann (2002).

Tijsskens, 2000; Huyskens-Keil and Schreiner, 2004). Product quality parameters are not necessarily consistent with product attributes applied by consumers. Lacking immediate insight into intrinsic product quality parameters (e.g., environmental impact of the cultivation method), consumers' acceptance of vegetable product quality instead is more based on extrinsic product attributes such as price, label or the type of packaging material used (indicating cultivation method, e.g., conventionally or biological method or origin) and other characteristics generally associated with perception of products within the handling system (Jongen, 2000; Shewfelt and Tijsskens, 2000; Schnitzler and Gruda, 2002). This means that consumers form their expectations on intrinsic quality parameters based on cues from extrinsic variables (Schnitzler and Gruda, 2002). The influence of extrinsic factors is excluded in this paper.

III. ADVANTAGES AND DISADVANTAGES OF GREENHOUSE IN COMPARISON TO OPEN FIELD CULTIVATION CONCERNING PRODUCT QUALITY

Greenhouse technology offers many resources to control the conditions of light (quantity and quality), temperature, humidity, CO₂ concentration, and water and nutrient availability (Gary, 2003). Thus, indoor production of vegetable presents some advantages compared to outdoor production with regard to quality assurance (Bot, 2003). The big advantage is that the controlled environments offer a way to optimize environmental parameters and the product is not exposed directly to sudden changes of climate conditions. There is little that growers of field crops can do to increase CO₂ concentration in the vicinity of their crops, but the greenhouse enclosure presents a unique opportunity to modify the aerial environment (Hinklenton, 1988). Besides environmental factors the cultivation factors, such as water supply, can be better regulated under protection. This can be combined with the addition of a precise amount of fertilizer in the irrigation water. Furthermore, by using soilless culture techniques the crop can be grown in isolation from the soil.

The quality of vegetables is greatly influenced by genetics. Cultivar selection is of primary importance in achieving the desired product quality. In general, there are some differences between the cultivars used for indoor and outdoor cultivation. For example, greenhouse tomatoes are indeterminate plants, as opposed to determinate field and processing tomato plants (Dorais *et al.*, 2001), greenhouse grown sweet peppers are harvested at either green or fully red ripe stage, while field peppers are normally commercially harvested at the mature green stage (Tadesse *et al.*, 2002), greenhouse cucumbers are generally tall, with large leaves and the fruits are used for fresh consumption, as opposite to short field plants with relatively small leaves and fruits generally used for pickling industry. On the other hand, several physiological disorders and other abiotic problems can be minimized due to a right choice of cultivar, with resistant characteristics.

Despite advantages in comparison to outdoor production, the greenhouses are never completely free from the influences of stress situations, especially with respect to heat and light energy (Peet, 1999; Tognoni *et al.*, 1999). Indoor grown vegetables are more sensitive to some plant disorders (e.g., tipburn for lettuce) than in outdoor cultivation. Plants grown in controlled environments, such as greenhouses and growth chambers, are affected earlier, more frequently, and to greater extent by tipburn than field grown plants (Saure, 1998). Plants in a greenhouse are given high level of water, heat, and fertility, and forced to grow much faster than they would outdoors (Peet, 1999). This optimized environment results in higher growth rate, that almost always is associated with susceptibility to physiological conditions such as tipburn (Everaarts and Blom-Zandstra, 2001; Frantz *et al.*, 2004).

The use of greenhouses makes possible production outside the normal season. While this usually results in a better price for the producer, the product quality can leave much to be desired. For example there is an increase of nitrate content in lettuce or spinach, produced in the winter period. An important characteristic of glasshouse growing systems is the virtual absence of UV-B (280-320 nm) in the natural solar radiation (Nitz *et al.*, 2004). Stewart *et al.* (2000) reported that field-grown tomatoes in Spain and South Africa contain four- to five-fold more flavonols than those in the United Kingdom, where glasshouses are used for plant cultivation. Flavonoid content in New Asia Salad (*Gynura bicolor*) cultivated in Germany was much higher in field-grown than in glasshouse-grown plants, indicating increased polyphenol synthesis due to UV exposure (Schirmacher *et al.*, 2004). In agreement with well-known results for other vegetable crops, He (1999) shows that the glucosinolate content of different Chinese brassicas is lower if cultivated in the greenhouse than in the field. This is reflected in a different taste and flavor compared to field vegetables. These advantages and disadvantages are discussed in detail based on numerous reference studies. However, a direct comparison between greenhouses with field products is difficult, because quality is principally a result of interactive effects of different factors.

Besides genetic factors, other factors such as climate, cultural practices and postharvest condition control the production of high-quality vegetables. The most important climate factors are light intensity, temperature, vapor pressure deficit (VPD) and CO₂ enrichment of the atmosphere, whereas the cultural practices are defined by growing methods, irrigation regime as well as fertigation of vegetable crops. In addition the time of harvest and the storage condition influence the product quality of vegetables.

Recently many studies have reported the influence of different factors on the quality of vegetables. However, an overall review for greenhouse vegetables is lacking. The quality of greenhouse tomatoes has been described in a detailed review by Dorais *et al.* (2001). Because the tomato is the most widely grown vegetable in the greenhouse, it is included in this review. The influence of different environmental factors on the quality of vegetables will

be shown by referring to results of greenhouse studies carried out over the last 20 years. Occasionally, it will be necessary to refer to examples from older and outdoor studies.

IV. ENVIRONMENTAL FACTORS

A. The Influence of Light Intensity and Duration on Quality Attributes of Greenhouse Vegetables

Greenhouses are a mean of protecting vegetable crops from climatic adversity. Since greenhouses use the sun as a free light energy source (Hanan, 1998; Bot, 2003), the challenge is to control the other factors, e.g., temperature, CO₂ concentration in such a way as to provide the best possible environment for the production of high-quality vegetables given the prevailing light conditions. Too much or too little light can stress greenhouse vegetables that have specific light requirements (Peet, 1999). According to Weston and Barth (1997) light intensity can have profound effects upon quality over the course of time. Lack of radiation will result in a reduction of quality, such as etiolation and vegetative growth at the expense of edible organs, deformed organs such as high-oval tubers in kohlrabi or in radish, abortion of flowers (e.g., tomato), or lack of production of tubers (e.g., radish) (Krug, 1991).

1. The Influence of Low Light Intensity on Vegetable Quality

According to Peet (1999) and Warren *et al.* (1992) the amount of daylight received is reduced by 30 percent or more by the glasshouse structure, while the other environmental factors including nutrients and water are usually at optimal levels. In addition, during winter, the Photosynthetic Photon Flux Density (PPFD) level is far from adequate, and as light is the energy source promoting photosynthesis and growth in plants it follows that under low PPFD the other environmental factors cannot be utilized efficiently (Ottosen *et al.*, 2003). Several researchers have also shown that in northern latitudes, the most limiting climatic factor in greenhouses is low light intensity (Benoit, 1987; Grimstad, 1987; Gaudreau *et al.*, 1994; Drews *et al.*, 1995, 1996, 1997; Cockshull and Ho, 1995; Dorais *et al.*, 2001; Ottosen *et al.*, 2003). This is a problem during summer periods as well because of overcast skies (Blacquire and Spaargaren, 2003) as well as for the Mediterranean areas during the winter period, because of the short and cloudy days (Rylski *et al.*, 1994). Low yields of greenhouse vegetables are often associated with the production of relatively small fruits (e.g., tomatoes), early in the season when daily integrals of solar radiation are suboptimal (Grimstad, 1987; Cockshull and Ho, 1995; Kays, 1999). The literature suggests that the daily light integral for tomato production in greenhouse should not be lower than 12 $\mu\text{mol m}^{-2} \text{day}^{-1}$ (PPF) (Blacquire and Spaargaren, 2003).

Misshapen tomato fruits between the second to the fifth cluster as well as the formation of swollen and hollow fruits have been observed due to low light intensity and inappropriate temperature regimes during the growing season in spring (Dorais *et al.*, 2001). Rylski *et al.* (1994) also reported an increasing of

incidence of puffy fruit and blotchy ripening in tomato growth under low light conditions, whereas Smillie *et al.* (1999) mentioned that green shoulder formation, apparent as intense pigmentation of the proximal pericarp shoulder, was positively related to the degree of shading of the fruit during development. In cucumber, fruits grown under low light conditions will be lighter green at harvest and they will easily turn yellow during shelf life (Vonk Noordegraaf and Welles, 1995). According to Benoit (1987) and Gaudreau *et al.* (1994) low light level resulted in some disproportion in midrib development with the formation of a loose head of lettuce, characterized by comparatively low fresh weight.

Filtering out a portion of the incident solar radiation could be effective in reducing the inside air temperature of a greenhouse (Buffington *et al.*, 2002). Recently, metallized shading materials are recommended to use as a filter in greenhouses during the summer period in warmer areas. They provide uniform shadow, allow air movement and provide diffused light transmission to the crops (Bucklin, 2002a, 2002b; Buffington *et al.*, 2002). However, although some growers use shading to reduce greenhouse temperatures and to improve product appearance, the reduction of light intensity is more likely to be a limiting factor than otherwise (Peet, 1999). For instance, Marcelis (1993b) reported that shading affects cucumber by reducing distribution of photosynthate to the fruits, resulting in a strong decrease in fresh and dry fruit weight. Young fruits usually are relatively more sensitive to a reduction in assimilate supply (irradiance) than older fruits on the same plant (Marcelis, 1993c).

With increasing environmental and health concerns, the transplant vegetable industry is looking for nonchemical or reduced-chemical alternative methods. For instance, far red light absorbing films seem to be effective in reducing stem elongation and producing compact cucumber, bell pepper, and tomato transplants without having to use chemical growth regulators (Evans and McMahon, 2004; Rajapakse and Li, 2004). A plant height control for muskmelon, cucumber, squash, and watermelon transplants has been reported also by UV radiation applications (Farnesi *et al.*, 2004).

Using photoselective films as an end-of-day curtain allows growers to make use of high light during the day and eliminate elongation stimulating far-red light in the evening (Rajapakse and Li, 2004). Kleemann (2004) reported a decrease of the incidence of tipburn and an increase of calcium content by leaf lettuce (*Lactuca sativa* var. *crispa* L.) cultivated under far-red filter. The taste and color of lettuce were also changed. Lettuce tasted less bitter and showed a lighter green color. Cucumber fruit that were covered with a filter-transmitting red light were greener than those with a far-red filter (Lin and Jolliffe, 1996). Vegetable quality has improved by using of infrared reflecting filter, compared with either clear or white painted filter. Tabatabaie *et al.* (2004) reported higher individual fruit fresh weight, reduced incidence of blossom end-rot and higher calcium concentrations at the distal end of fruits of tomatoes, cultivated under infrared reflecting filter. Using this filter reduced temperature without

affecting the radiation level inside the greenhouse, giving ideal conditions for protected crops production in summer.

Shading had a significant effect on glucose and sucrose concentrations. In general, the sucrose and glucose concentration was inversely proportional to the level of shading (Watson *et al.*, 2002). Previous data from tomatoes (Winsor and Adams, 1976) showed also a high correlation between juice sugar content and solar radiation across a season.

Investigating, the influence of growing season on some quality parameters of melon (*Cucumis melo* L.) plants cultivated in nutrient film techniques in greenhouse Mediterranean climate, Pardossi *et al.* (2000) presume that lower solar radiation was responsible for a reduced leaf carbon assimilation. This shortage of photo-assimilate supplies and inadequate sucrose synthesis may have led to the production of fewer fruits of larger size and poorer quality due to reduced sucrose content in summer compared with spring. Sucrose concentration represented 76 percent and 54 percent of total soluble sugar in spring and summer, respectively. In previous work (Pardossi *et al.*, 1994) also reported that summer plants produced less sweet and less firm melon fruits. Other conditions such as overall temperature has certainly also influenced those processes. Due to temperature and light dependency of photosynthesis increasing irradiation combined with enhanced temperature promote photosynthesis, which causes an accumulation of monosaccharides (Huyskens-Keil and Schreiner, 2004). The content of glucose was only moderately affected in radish roots, whereas the content of fructose was distinctively influenced by seasonal climatic factors (Schreiner *et al.*, 2002). According to Hess (1999) and Huyskens-Keil and Schreiner (2004) this could be explained by the fact that in the Calvin cycle the fructose 1.6 phosphate, as a primary product, is formed by triose phosphates which in further steps will be converted to different monosaccharides or polymer carbohydrates.

Seasonal influences have been shown on strawberry "*Fragaria vesca* L." cv. "Regina delle Valli," cultivated under plastic double-tunnels in NFT-systems in Italy. Caruso *et al.* (2004) reported higher sucrose, acids (citric, malic, succinic, and ascorbic), vitamin C as well as calcium and chlorine in fruit harvested in spring, whereas carotenoids, magnesium, copper, nitrates, phosphorus and sulphur accumulated to a greater extent in autumn.

The flower capacity to accumulate sugars and starch during the day is an important factor in determining flower retention and fruit set of pepper (Aloni *et al.*, 1996). Low light intensity decreased sugar accumulation in the flower and subsequently caused pepper flower abscission. Furthermore, tomatoes and strawberries produced in fully sunlight contained more sugar and dry matter than those grown in shade (Winsor, 1979; Weston and Barth, 1997; Caruso *et al.*, 2004). Shinohara and Suzuki (1981) reported that with increasing levels of shading, the fresh weight and number of leaves of lettuce decreased, the shape of leaves became narrower and sugar content and ascorbic acid (AA) decreased markedly.

It is well known, that from sugars supplied through photosynthesis in plants ascorbic acid (AA) is synthesized (Lee and Kader, 2000). Shinohara (1987) showed that the translocation of photosynthates into tomato fruit was necessary for the ascorbic acid synthesis to take place. Although light is not essential for the synthesis of AA, the amount and intensity of light during the growing season have a definite influence on the amount of AA formed. In addition the exposure of fruits to light appeared to accelerate the ascorbic acid synthesis. The AA content of tomato fruits was low in lower clusters and remarkably high in the uppermost fourth cluster of tomato plants (Shinohara *et al.*, 1982). However, the content of AA during seasonal changes was more a cultivar function. The fruits of Japanese cultivars which matured in the early summer showed the highest content of ascorbic acid, while those which matured in winter the lowest value, the fruits of European cultivars maintain about the same level as in a summer crop (Shinohara *et al.*, 1982; Shinohara, 1987). Leaf Ca and Mg and AA composition of spinach (*Spinacea oleracea* L.) and lettuce (*Lactuca sativa* L.) increases with minor reduction in temperature and high light intensities due to climatic or weather changes. Ascorbic acid concentration also generally increases with increased exposure to light, particularly in leafy greens (Oyama *et al.*, 1999; Weerakkody, 2003).

Close relationship between the light conditions and the ascorbic acid content for different vegetables such as tomato, lettuce, sweet pepper and strawberry was revealed (Shinohara, 1987). In general, the lower the light intensity, the lower the content of ascorbic acid in plant tissues (Weston and Barth, 1997; Lee and Kader, 2000). Vitamin C, including ascorbic acid and dehydroascorbic acid, is one of the most important nutritional quality factors in many vegetable crops and has many activities in the human body (Lee and Kader, 2000).

Caruso *et al.* (2004) reported that shading caused a reduction in the dry matter and the content of the main taste-determining compounds, sugar and acids, as well as mineral elements, except for nitrates in strawberry fruits. This could be the explanation for a poor taste sometimes associated with autumn-grown vegetables.

In addition volatiles and many other compounds individually that elicit sensory responses that give the vegetable its distinctive flavor have been influenced (Mattheis and Fellman, 1999; White, 2002). Evidence exists for the effects of low light intensity and shading on the flavor quality of some crops (Winsor and Adams, 1976; Watson *et al.*, 2002; White, 2002). Watson *et al.* (2002) tested the hypothesis, that a reduction of the carbohydrate source through shading would adversely affect strawberry fruit quality. They found that a brief period of shading for 2 weeks, commencing 1 week prior to first fruit ripening significantly reduced the amounts of volatile flavor compounds in strawberry fruit.

Different enzymes are important in the synthesis of volatile compounds (Gardner, 1995; Baldwin *et al.*, 2000; Watson *et al.*, 2002). According to Watson *et al.* (2002) whatever the pathways involved, the starting point for volatiles begins with indirect or direct changes. An indirect changes means changes

in photosynthesis through shading while a direct pathway is a direct result of shading.

The color of vegetables plays a major role for consumers making purchasing decisions on fresh vegetables (Gironi and Testoni, 1990; Kays, 1999; Schreiner *et al.*, 2002). For example green lettuce and spinach as well as red tomatoes or radish always signify high products qualities. Schreiner *et al.* (2002) investigated the color development of radish throughout the whole year, partly cultivated in the greenhouse and partly in the field and found positive correlations between light intensity and color of radish. Dorais *et al.* (2001), reported that low light intensity reduced pigment synthesis by tomatoes, resulting in uneven fruit coloring. According to Kleinhenz *et al.* (2003a), shading affected anthocyanin levels of lettuce. Regardless of temperature regimen, shading generally reduced the anthocyanin content in three lettuce cultivars and only for one cultivar, shading tended to increase the anthocyanin levels of lettuce leaves (Kleinhenz *et al.*, 2003a, 2003b).

Raymundo *et al.* (1976), Gross (1991), and Huyskens-Keil and Schreiner (2004) showed that carotenoid biosynthesis is light independent. However, Dorais *et al.* (2001) report that light intensity received by the plant affects the lycopene in tomato fruits. Not only the content of reducing sugars, titratable acids, ascorbic acid, but also carotenoids of tomato fruits varied in the course of one year in experiments with three cultivation methods (Auerswald *et al.*, 1996). Higher concentrations were found at the end of the harvest period than at the first harvest in May. Greater light intensity at the higher tomato trusses and less shaded leaves and fruits may have been responsible. However it was not possible to separate the influence of plant age from light intensity (Auerswald *et al.*, 1996).

Oyama *et al.* (1999) reported that on a fresh weight basis, β -carotene concentration increased in spinach and lettuce exposed to high light intensity. Nevertheless, seasonal differences only influences the content of β -carotene for leaves up to 2 g of fresh weight with higher concentrations in March to April than September to October, but no differences were shown for leaves over 2 g (Oyama *et al.*, 2000). Similar results were found by Helyes *et al.* (2003). Different harvesting time also affects lycopene content of tomato. They found significant differences measured for photosynthetic active radiation during development and conclude that radiation intensity was an essential determinant of lycopene content. Raymundo *et al.* (1976) do not exclude the possibility that lycopene content may be stimulated by light, but light is not required for its induction (Gross, 1991).

Light intensity can also have effects on the shelf life of greenhouse grown vegetables. Generally, postharvest shelf life of long English cucumber (*Cucumis sativus* L.) was generally related to fruit greenness upon harvest and the lower the light intensity incident on a cucumber, the shorter its shelf life (Lin and Jolliffe, 1996). Using filters to cover individual fruit, authors found that the average shelf life was 8, 5, or 1 days for cucumbers receiving 100, 66, or 31 percent of natural daylight, respectively.

Light is the main factor influencing nitrate concentrations in vegetables. The accumulation of nitrate in the plant tissues is most frequently under poor light conditions, e.g., in greenhouse in winter and in green leafy vegetables, such as lettuce and spinach (Blom-Zandra and Lampe 1985, Steingröver *et al.* 1986; Drews *et al.*, 1995, 1996, 1997). Spinach plants grown at a photon flux density of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$ under a 10/14 h (light/dark) photoperiod showed decreased growth, a decreased leaf area per plant and the leaves contained more oxalate and nitrate after five weeks in comparison with plants grown at $800 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Proietti *et al.*, 2004). Sritharan and Lenz (1992) reported also an increase of nitrate concentration in the tuber of kohlrabi (*Brassica oleracea* var. *gongyloides* L.) within three weeks under low light intensity ($100 \mu\text{mol m}^{-2} \text{s}^{-1}$) as compared to those under high intensity ($600 \mu\text{mol m}^{-2} \text{s}^{-1}$), respectively. In addition to nitrate content, other adverse effects, such as fewer leaves, less leaf area, smaller tubers, and lower dry matter were observed for kohlrabi cultivated under low light condition, confirming previous studies in growth chambers with spinach (Cantliffe, 1972a, 1972b).

High amounts of nitrate in vegetables are considered a potential threat to human health due to its implications through nitrite in the occurrence of methaemoglobinaemia in the blood of infants and in gastric cancer (Walker, 1990). This has led to calls for restriction on nitrate in food products and acceptable nitrate concentrations in vegetables are set by legislation, e.g., by the European Union (Commission Regulation, 2001). Recent literature recognizes that methaemo-globinaemia has been linked to endogenous nitrite production and reports that nitrate may be useful for human diet accompanied by ingredients such as ascorbic acid, as is the case with vegetables (Dykhuizen *et al.*, 1996, 1998; McKnight *et al.*, 1999; Diehl, 2000; Leifert and Golden, 2000). However, Leifert and Golden (2000) recommended a reasonable limit on nitrate levels for environment reasons. Different strategies are developed to maintain the limit set by the authority in lettuce and spinach products. Demšar *et al.* (2004) suggested a dynamic light-dependant application of nitrate in accordance with changeable light conditions. Under unfavorable light conditions nitrate was supplied at limited rates to the plants resulting in efficient reduction of accumulation in lettuce leaves and without concomitant yield loss.

2. The Influence of Additional Light on Vegetable Quality

Many studies reported an increase of photosynthesis rates, plant growth and development, and as consequence, of yield, of various vegetable crops by supplementing the natural light in high altitude regions, such as North America and Northern Europe. Furthermore, supplemental lighting influences the external and internal quality of vegetable crops (Gaudreau *et al.*, 1994; Hao and Papadopoulos, 1999; Dorais and Gosselin, 2002; Schnitzler and Gruda, 2002; Fukuda *et al.*, 2004).

A report from Canada showed that supplemental lighting effect profoundly cucumber growth, fruit yield, and total dry matter production as well as early marketable yield in three types

of greenhouses (Hao and Papadopoulos, 1999). It also increased fruit quality. Larger fruit, higher percentage of grade 1 fruit, and about 31 percent higher skin chlorophyll content was obtained (Hao and Papadopoulos, 1999). Earlier work done with tomatoes showed that increasing supplemental lighting from 100 to 150 $\mu\text{mol m}^{-2} \text{s}^{-1}$ did not have a significant effect on fruit quality expressed by the percentage of fruit with BER, small fruit and misshapen fruit. However, the percentage of class one fruit increased from 77 percent to 81 percent (Dorais *et al.*, 1991). On the other hand, sugar content as well as ascorbic acid concentration of tomato fruit increased with applications of additional light (Dorais and Gosselin, 2002). Adams *et al.* (2001b) reported that increasing the light available in controlled environment experiments with tomato plants increased mean fruit size and the number of fruits picked. However, a decrease of mean fruit size was found in subsequent weeks, presumably due to the increased competition for assimilates caused by the heavy fruit load (De Koning, 1989; Adams *et al.*, 2001b). In greenhouse-grown lettuce, the use of supplementary light increased the biomass by more than 270 percent and head firmness as well as shortening production cycle by 30 percent compared with natural light conditions (Gaudreau *et al.*, 1994).

Additional light increases the content of essential oils and other compounds in herbs and medicinal plants (Dorais and Gosselin, 2002; Schnitzler and Gruda, 2002). Michalsky *et al.* (1997) demonstrated that by applying additional light, the amount of essential oil in watercress (*Nasturtium officinale* R. Br.) grown in greenhouse conditions in Germany increases, thereby causing an intensified spicy flavor, whereas the nitrate content was reduced. Supplemental lighting increased the essential oil content of thyme by 73 percent as well as the percentage content of thymol in relation to the total essential oil composition compared with natural light in Canada (Letchamo and Gosselin, 1995). Palaniswamy *et al.* (1997) also found differences in the content of ingredients in watercress. Leaves of plants grown under 8 h photoperiod (PP) subjected to 435 $\mu\text{mol m}^{-2} \text{s}^{-1}$ one week before harvest, produced approx. 60 percent higher concentration of phenethyl isothiocyanate, a promising cancer inhibitor, than those that were grown continuously at 265 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

In general, supplemental lighting has been used not only to add the artificial light to solar radiation, but also to extend the photoperiod (PP) for an increase of photosynthesis (Fukuda *et al.*, 2004). The temperature is also an important factor. For instance, the highest phenethyl isothiocyanate concentration in leaves and stem of watercress were produced from plant grown at 12 h PP and 25°C in comparison to plants grown at 15°C and 12 h PP, or plants grown at 8 h PP and either temperature (Palaniswamy *et al.*, 1997).

Growth promotion of some leafy vegetables was shown also in a mid-latitude area, by supplemental lighting during the period from middle of the night to morning, 23:00 to 7:00 (Fukuda *et al.*, 2004). Supplemental lighting increased top fresh weight and number of leaves in lettuce (*Lactuca sativa* L.) and tsukena

(*Brassica campestris* L.), cultivated in NFT systems in the greenhouse. Shoot fresh weights of lettuce and tsukena under supplemental lighting with high light intensity (Photosynthetic Photon Flux Density of 76 $\mu\text{mol m}^{-2} \text{s}^{-1}$) were 53 percent and 37 percent higher compared with the control (without supplemental lighting). Furthermore, the leaf thickness was increased 31 to 43 percent and 32 to 38 percent more than control, respectively, for lettuce and tsukena. Palisade tissue also became thicker than the control for both vegetables. Consequently, a dark green leaf color of products resulted (Fukuda *et al.*, 2004).

Unfavorable economics has limited the use of additional light in greenhouse vegetable production (Hao and Papadopoulos, 1999), or allowed it sometime only for the production of seedlings and transplants.

The use of additional light during the winter period is a common practice in the northern latitudes for the production of vegetable transplants used to establish either field or greenhouse crops. Supplementary light (100 $\mu\text{mol m}^{-2} \text{s}^{-1}$) increased shoot dry weight 44% in peppers and 32% in tomatoes seedlings (Fierro *et al.*, 1994). Plant height, leaf number, leaf area, and dry weight of aerial tomato plant parts were significantly increased with increasing levels of supplementary light (McCall, 1992). Greater early yield and market value was found with increasing levels of supplementary light prior to planting, due to an increased number of harvested fruit in the early cropping period (McCall, 1992). These results are in agreement with earlier results of Boivin *et al.* (1987). They found that the use of supplemental lighting for greenhouse tomato seedlings from 50 to 100 and 150 $\mu\text{mol m}^{-2} \text{s}^{-1}$ increased by 19, 30, and 42 percent, respectively, the marketable yield of the first three harvests of tomato compared with natural light conditions in Canada. Dorais and Gosselin (2002) recommended supplemental lighting as follows for different seedlings: 50–75 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for lettuce, 75–100 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for sweet pepper and 75–175 $\mu\text{mol m}^{-2} \text{s}^{-1}$ mainly in the period from mid-November to mid-February.

In addition to supplemental light, there are also other measures of practical importance such as cleaning of the glass surfaces, direction of the plants rows, plant spacing as well as pruning and deleafing. Usually in the greenhouse, producers try to raise the reflection of the ground surface by laying out white plastic foil between plant rows. Greenhouse construction plays an important role as well. Higher photosynthesis rates, generally, increase product quality for vegetable crops cultivated in favorable light condition.

The use of cover greenhouse materials such as glass, acrylic, polycarbonate, polyvinyl chloride, fiber reinforced plastic, polyethylene, and polyester causes loss of light. Clear materials such as glass are ideal but expensive (Hanan, 1998). Hao and Papadopoulos (1999) compared a glasshouse, a double-inflated polyethylene and a twin-wall acrylic greenhouse for effects on quality of cucumber (*Cucumis sativus* L.). Higher fruit dry matter content was found in glasshouses as compared with either

acrylic or double-inflated polyethylene houses. This might have been the effect of a higher solar irradiance on the upper parts of the canopy, and slightly lower temperature (Hao and Papadopoulos, 1999).

In order to improve light transmission in greenhouses the optimization of other parameters, such as the moisture condensation, the dust accumulation, and the size and form of the roof slopes as well as of greenhouse are also important. Due to a lower radiation in a conventional flat roofed greenhouse, significantly lower values of dry matter in the cucumber fruits were recorded in comparison to new type of plastic greenhouse (a north-south oriented multispan of symmetrical 17° roof slope and an east-west oriented single span of asymmetrical roof angles, 18° and 8°) in Almeria, Spain (Castilla and Lopes-Galvez, 1994).

3. *The Influence of High Light Intensity and Light Spectrum on Vegetable Quality*

Extreme light intensity or strong direct radiation can cause loss of product quality. Geissler (1985) reported that high light intensity on the fruits could promote the occurrence of green shoulder of tomatoes. Excess light results in sunscald that is a significant problem for a wide range of crops, such as tomatoes, bell peppers, eggplants, and pepinos (Geissler, 1985; Kays, 1999). Excess solar energy initially results in degradation of the pigmentation in the affected area and if the duration of exposure or intensity is sufficiently high, cellular death and collapse of the tissue follows; the skin turns papery thin (Kays, 1999; Prohens *et al.*, 2004). Infrared thermography of salad and dessert pepino fruits (*Solanum muricatum*) showed that maximum surface temperature of more than 44.5 °C was registered. The mesocarp in the exposed part of the fruit was 2.2 K warmer than in the shaded part (Prohens *et al.*, 2004). With sun exposure the average electrolyte leakage increased, while the ascorbic acid content decreased. Changes in AA content reflected damage ($r = -0.71$) more accurately than changes in electrolyte leakage ($r = 0.49$). Sunscald and cracking in tomato and pepper fruits, and uneven ripening and blossom-end rot (a calcium-related disorder) of tomato are caused by high light intensity (Peet, 1999).

Gaudreau *et al.* (1994) showed an even greater development of tipburn of lettuce compared to control plants in a study under conventional greenhouse production condition at a northern location in Canada. This calcium related disorder is caused by a localized calcium deficiency in leaf margins triggered by a high light intensity. These results are similar with the ones found by Collier and Tibbitts (1982). The faster the growth rate, the more calcium is needed and the rate and extent of tipburn increases (Cox *et al.*, 1976; Frantz *et al.*, 2004). Generally the conditions that stimulate growth also tend to increase the probability of incidence of tipburn. Gaudreau *et al.* (1994) found good correlations between the light intensity and tipburn of greenhouse lettuce. Wissemeyer and Zühlke (2002) showed a highly significant positive linear regression coefficient between tipburn severity and the irradiation in open field lettuce, particularly 3 to 4 weeks prior to harvest. Eliminating tipburn by blowing air

directly onto the meristem, allowed Frantz *et al.* (2004) to operate with light levels of 1000 $\mu\text{mol m}^{-2} \text{s}^{-1}$ that are two to three times higher than normally used for lettuce.

Spectral quality of light is important and could have effects on some quality parameters of greenhouse grown vegetables. Leaves of lettuce grown in continuous light quality showed characteristic differences in leaf area, shape, dry weight, and bitter taste intensity. However, red light supplied for the first 7 d of growth conditioned weak bitterness intensity whether or not plants were switched to white light for 18 or 26 d (Eskins *et al.*, 1996). Hanyu and Shoji (2002) reported a general increase of dry matter, plant height, and specific leaf area of spinach by supplementary lighting and exposure to either blue light at the end of the dark period or red light. Further, UV-B induces accumulation of a range of secondary metabolites, which consequently influences numerous plant physiological functions as well as internal quality of vegetables (Jansen *et al.*, 1998; Nitz and Schnitzler, 2004). Thus the accumulation of plant flavonoids is enhanced in response to increased light exposure, especially UV-B rays (Stewart *et al.*, 2000; Aherne and O'Brien, 2002). This is in agreement with results of Nitz *et al.* (2004) and Heuberger *et al.* (2004) for chive and spinach, respectively.

B. *The Influence of Temperatures on Vegetable Product Quality*

Temperature affects chemical reactions and physical properties of plants and this influence occurs at both cellular level and plant level. Numerous studies have revealed the temperature requirements for various plant species. Temperatures are highly affected by the light intensity and to a lesser extent, by the CO₂-concentration. Specific requirements of the vegetable species in addition to the growth seasons and plant stage are to be considered.

Increasing air temperature generally increased the growth rate of the individual vegetable fruits (Marcelis 1993a; Dorais *et al.*, 2001). Marcelis (1993a) showed that with the same number of fruit per plant, the biomass allocation of the fruits increased with increasing temperature from 18 °C to 25 °C, at the expense of the vegetative plant parts. Similar results were found with tomato by De Koning (1989, 1996), due to an influence of temperature on the assimilate partitioning (De Koning, 1989). According to Dorais *et al.* (2004) temperature is the most important climatic factor influencing sink strength and consequently photo-assimilate partitioning between plant organs. On the other hand, the number of fruits on a plant decreased at increasing temperature (Marcelis, 1993a). Flower abortion and delay of growth of newly set fruits acted as a feedback control mechanism to prevent too generative growth due to a high sink-source ratio, influenced by high air temperature (De Koning, 1989). Conversely, low sink-source ratio may adversely affect fruit quality. Therefore, De Koning (1996) recommended that both high, as well as low sink-source ratios should be avoided.

However, air temperature is not the only decisive parameter. Plant temperature serves as an indicator on the growth processes

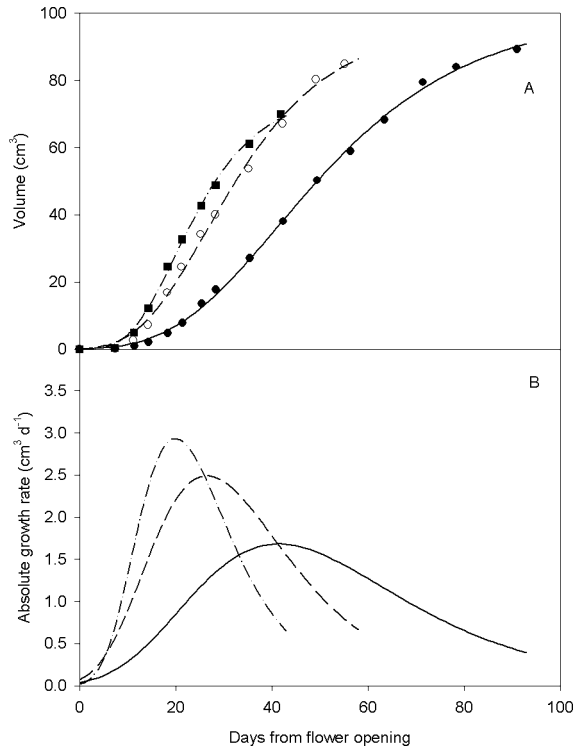


FIG. 1. The effect of cooling or heating individual trusses on growth (A) and absolute growth rates (B) of tomato fruit grown at 15°C (●, —), 20°C (○, ---) and 25°C (■, -■-■-), according to Adams *et al.* (2001b). Points represent the mean volume of ten fruits calculated assuming fruits are spherical. Lines represent a Gompertz function fitted to each data set using Genstat 5.

of the vegetable crop. Adams *et al.* (2001a) investigated the effect of cooling or heating individual tomato trusses and found a dependence of fruit volume growth on truss temperatures. Lowering the temperature resulted in lower absolute growth rate of tomato fruit and a delay in the time at which the absolute growth rate maximizes (Figure 1).

1. The Influence of Low Temperatures on Vegetable Quality

Plastic greenhouses are widely used for vegetable production in warm regions. Production is very successful under high irradiation and mild temperature ranges. In contrast, during the cold season, suboptimal temperatures and low irradiation can affect yield, and reduce product quality of vegetable crops grown under protected cultivation. Reports from Israel (Rylski *et al.*, 1994; Pressman *et al.*, 1998; Aloni *et al.*, 1999) showed that low temperature caused fruit malformation and fruit misshape, seedless, pericarp cracking, and pigmentation in pepper, and misshaped tomato fruits. Pressman *et al.* (1998) reported about the effects of night temperatures on the function and fertility of flower parts. Low night temperatures (14°C or less) reduced the number of pollen grain per flower and impaired their germination ability, and affected fruit set and fruit shape in sweet pepper. In addition, pollen release is inhibited, especially if low temperature is combined with high humidity (Picken, 1984; Rylski *et al.*,

1994). These results are in agreement with results from experiments carried out in Turkey with greenhouse tomatoes. Baytorun *et al.* (1999) reported a twice-higher pollen germination rate in 13°C greenhouse than in 5°C greenhouse in February. Also the fruit sizes obtained from two cultivation conditions showed large differences in favor of the heated greenhouses during the cold season (Baytorun *et al.*, 1999). Moreover, low temperature combined with low irradiance, caused puffiness and blotchy ripening in tomato, as well as a deterioration of taste, due to a decline in sugar content, while citric acid content was unchanged (Rylski *et al.*, 1994). Generally tomato cultivated in cold greenhouses will result in less juicy and aromatic fruit, with low acidity content, and thinner skin with worse keeping quality (Anonymous, 1999). Ottosen *et al.* (2003) reported that temperatures below 17°C resulted in reduced fruit quality of bell peppers in terms of size and quality and increased risk of grey mold and also caused a delay in harvest.

The shape and regularity of fruit vegetables are known to be determined at a very early development stage (Wada *et al.*, 2001; Aloni *et al.*, 1999). Wada *et al.* (2001) reported an increase of number of irregularly shaped fruits on single-truss tomatoes when seedlings were exposed to 5 and 10°C in comparison to seedlings exposed to 15 and 20°C and further cultivated at 20°C.

Flower and fruit malformations, induced by low temperature have been studied in tomato and bell peppers (Aloni *et al.*, 1999; Adams *et al.*, 2001a). Aloni *et al.* (1999) and Jovicich *et al.* (2004) reported small, flattened fruits of bell pepper (*Capsicum annuum* L.), which are commonly parthenocarpic. These fruits develop under low temperatures (below 16°C) from flowers with enlarged ovaries. In such flowers self-pollination is not efficient because of the large distance between the stigma and stamens (Aloni *et al.*, 1999). Also Adams *et al.* (2001a) reported a tendency of small parthenocarpic tomato fruits at low temperatures (14°C).

Some other effects of low temperatures on vegetable production include a reduction of quality characteristics, such as appearance. Low greenhouse temperatures in connection with water deficiency lead mostly to grittiness in cauliflower. In addition, if air temperatures are lower than soil temperatures, it leads to water core in the lettuce (Geissler, 1985).

The effect of temperature on color of vegetable fruits is well known (Dorais *et al.*, 2001; Geissler, 1985; Zipelevish *et al.*, 2000). The red color of ripe tomato fruits is attributed to lycopene, a carotenoid synthesized and stored in the chromoplasts (Dorais *et al.*, 2001; Kleinhenz *et al.*, 2003b), and most probably the key for carotenoid biosynthesis is the temperature (Helyes *et al.*, 2003). According to Robertson *et al.* (1995), temperatures between 18 and 26°C favor the biosynthesis of these compounds, while Gross (1991) has shown that optimal temperatures for lycopene formation in the tomato are 16°C to 21°C, Helyes *et al.* (2003) reported three times higher lycopene contents in cherry greenhouse grown tomatoes at 16°C than in 25°C, and Dorais *et al.* (2001) recommended to keep temperatures inside the

greenhouse between 12°C and 21°C for best tomato fruit color. However, in agreement with all authors very low air temperature (<10°C) may fully inhibit lycopene production (Geissler, 1985; Robertson *et al.*, 1995; Paiva *et al.*, 1998b; Dorais *et al.*, 2001). Air temperatures may also influence fruit color for other fruit vegetables. In Israel, eggplant (*Solanum melongena* L.) grown under winter condition in unheated polyethylene-covered greenhouse display a weaker intensity of fruit skin color than in the normal hot growing period (Zipelevish *et al.*, 2000).

Low temperatures could also directly influence the organoleptic properties of vegetable products. For instance, low temperatures will produce less juicy tomato fruit with a mealy taste (Anonymous, 1999; Brückner *et al.*, 2004). Moreover, Kano and Goto (2003) reported a higher occurrence of bitter fruits in cucumber (*Cucumis sativus* L. cv. Kagafutokyuri) plants grown in lower temperatures than in plants grown in higher temperatures, which may be due to high active protein synthesis, which caused a high activity of HMG-CoA reductase that further provokes a brisk synthesis of cucurbitacin C.

Sub optimal low temperatures, when used appropriately, can sometimes improve vegetable quality. Ventura and Mendlinger (1999) investigated 23 cultivars of melon, *Cucumis melo* L. in two temperature regimes in (1) a heated greenhouse with temperatures similar to those used in commercial cultivation in the winter in Israel; and (2) an unheated greenhouse with lower night temperatures. Melon fruits from the unheated greenhouse were smaller and lighter than those from the heated greenhouse. However, they also had higher amounts of total soluble sugars (TSS), sucrose and fructose (Ventura and Mendlinger, 1999). There is also an improvement in fruit carbohydrate accumulation (fructose and glucose) in tomato harvested in cool seasons than in warm season crops (Islam and Khan, 2001).

Sometimes there are stress situations that enhance the content of some bioactive compounds such as glucosinolates in cabbages. Charron and Sams (2004) found that the concentration of total glucosinolates in leaves of rapid-cycling base populations of *B. oleracea* L. was 44 percent higher at 12°C than at 22°C under constant light of 300 mol m⁻² s⁻¹. The myrosinase activity on a fresh weight basis was 30 percent higher in leaves and stems at 12°C than at moderate temperatures. Despite the increase of total glucosinolate in leaves, the authors observed that the total glucosinolate were 50 percent lower in roots at 12°C than at 22°C.

2. Differences of Day/Night Temperature and Their Influence on Vegetable Quality

Temperature pattern has an influence on the quality of the product for most vegetable species. Krug (1977) determined the fluctuations of the natural daily temperature and showed that under constant climate conditions there is a strong cauliflower leaf necrosis and a decay of anthotaxy.

Grimstad and Frimanslund (1993) reported that differences between day and night temperatures during propagation had no

effect on earliness nor the yield, but they improved fruit quality of cucumbers. Marcelis and Baan Hofman-Eijer (1993) investigated the fluctuations of temperature effect in promoting fruit production compared to growth at constant temperature and concluded, that stronger variations in temperature between day and night need to be avoided, because they can lead to a reinforced pushing off of the cucumber fruits. Furthermore, high temperature differences (particularly cold shock) linked with an impairment of other growth factors (deficiency of nutrient, water or poor light conditions) also young fruit cause incision and yellowing of cucumber (Geissler, 1985).

High day/night temperature differences or wide fluctuations in temperature can also induce cracking of tomato fruits (Peet, 1992). According to Dorais *et al.* (2004) tomato cracking is positively and linearly correlated with the averages of the day, night, and daily (24-hr) temperatures, as well as the average of the day/night temperature differential.

3. High Temperatures and Their Influence on Vegetable Quality

Greenhouse temperatures in summer rise due to solar radiation and the greenhouse effect, in spite of counter-measures like ventilation, shade, and cooling. Castilla and Lopez-Galvez (1994) indicated that the microclimate inside plastic greenhouses is not optimum for vegetable production because of insufficient ventilation, which leads to extreme air temperature. Sometimes, a circular leaf burning around the petiole on leaves in the upper layers of the cucumber crops after starting of rapid ventilation is observed. According to Bakker (1984a), leaf burning occurs when stomata are open in the area of high temperature and the leaves in full sunlight are stressed before starting the ventilation. The increase of transpiration causes a further increase of water deficiency after which an irreversible situation arises. However, according to Erickson and Markhart (2001) deleterious effects of high temperature on pepper fruit set does not appear to be temperature induced water stress, but is more likely a direct temperature response.

Excessive temperatures lead to quality losses, e.g., alterations in form, color and texture of tomato, pepper, cucumber and eggplant fruits (Geissler, 1985; Zipelevish *et al.*, 2000). For instance when greenhouse temperatures are above 35°C, burn spots appear on the top of bell pepper fruits (Geissler, 1985). Direct effects of high temperature stress include damage to cellular membranes, proteins, and nucleic acids (Kays, 1999). Indirect effects to appearance include inhibited pigment synthesis and thermal degradation of existing pigments giving a wide range of sun scald or sun burn symptoms (Kays, 1999), as were presented above. In fact in this case fruit temperature is more important than air temperature. Consequently, according to Ho (2004) it is fruit rather than ambient temperature that must be recorded and greenhouse controls need to be linked with fruit temperature requirement. Fruit temperature is affected by the amount of solar radiation to which fruits are exposed (Adams *et al.*, 2001a) and sunburn spots known in literature as sunscald are a result of

the combination of high temperatures and high solar radiation (Wien, 1997).

Fruit vegetables will not remain generative enough in the greenhouse during hot summer months. Plant growth becomes more and more vegetative due to higher environment outdoor temperatures and there is an abortion of flowers and young fruits (Geissler, 1985; Atherton and Harris, 1986; De Koning, 1996; Anonymous, 2000).

Sato *et al.* (2002) reported that continuous growing of tomato plants at 32/26°C (day/night) led to the disruption of development in the pollen, endothecium, epidermis and stomium of anthers. Pressman *et al.* (2002) observed a prevention of the transient increase in starch concentration and decrease in the concentrations of soluble sugars in the anther walls and the pollen grains in tomato grown at the same high temperatures under growth chamber conditions, which possibly contribute to the decreased pollen viability. Karni and Aloni (2002) found that in pepper (*Capsicum annuum* L.) initial sugar metabolism includes sucrose hydrolysis by invertase and subsequent phosphorylation of glucose and fructose by hexokinases. High-temperature treatment (day/night, 32/26°C) of pepper plants reduced the percentage of pollen that germinated compared with that under normal temperatures (26/22°C), and in parallel reduced the activity of fructokinase in mature pollen. High temperature also reduced fructokinase and hexokinase activity in the anther. The results suggest that pollen and anther fructokinase may play a role in the regulation of pollen germination, possibly by providing fructose-6-phosphate for glycolysis, or through conversion to UDP-glucose to support the biosynthesis of cell wall material for pollen tube growth (Karni and Aloni, 2002). Peet and Bartholemew (1996) emphasized the role of night temperatures on pollen characteristics and reported that total and percentage normal pollen grains were higher in tomato grown at normal night temperature than at high night temperatures. Further, Peet *et al.* (2003) found under controlled environment that the percentage pollen germination of tomatoes was most sensitive to high humidity at high temperature.

Pollen grain release and germination are the most important factors determining the ability of plants to set fruit (Sato *et al.*, 2000). Adams *et al.* (2001a) reported that high temperatures led to small parthenocarpic tomato fruits, and poor fruit set under controlled conditions. A reduction of tomato fruit set and yield, with a high rate of incidences of abnormalities like cracked fruits, blossom end rot, watery tissue, small and immature fruits, was also observed in investigations of Abdul-Baki (1991). Finally, the reaction of tomato plants to high temperatures is very genotype dependent (Abdul-Baki and Stommel, 1995; Sato *et al.*, 2000).

Light intensity must also be considered when adjusting temperatures. Geissler (1985) indicates that high temperatures during cultivation in poor light periods can lead to a delay or loose head of lettuce. Environmental factors, such as increased daily radiation and temperature have been also reported to increase the incidence of BER by promoting the rate of fruit growth

(Sonneveld and Voogt, 1990; Ho *et al.*, 1993; Wui and Takano, 1995a, 1995b; Saure, 2001). According to Ho *et al.* (1993) temperature may be the major environmental factor, which induces BER. Leaf vegetable crops, such as Chinese cabbage and lettuce grown at high temperature are more susceptible to tipburn than others, especially near maturation (Saure, 1998).

The synthesis of certain pigments such as carotenoids has been shown to be temperature sensitive (Gross, 1991). Very high air temperature (>30°C) inhibits normal fruit ripening and the development of lycopene in the tomato (Gross, 1991). However, tomato fruit are not exposed all the time to high temperatures, so that for formation of lycopene night temperatures lower than 30°C are very important. Also Oyama *et al.* (1999) reported that on a fresh weight basis, β -carotene concentration increased in spinach and lettuce exposed to low air temperature 15/10°C (day/night) in comparison to temperatures of 20/15°C (day/night).

Temperature has an effect on the nitrate content of vegetables. For instance, cultivation at higher temperatures resulted in higher nitrate contents in lettuce (Van der Boon *et al.*, 1990) and radish (Nieuwhof, 1994). Roots of radish plants grown continuously at higher temperature or transferred for 11 days before harvest to higher temperatures had higher nitrate content than plants under lower temperatures (18°C > 14°C > 10°C) (Nieuwhof, 1994).

Air temperatures could influence the internal quality characteristics as well as the organoleptic characteristics of vegetables. Not only low but also high temperature can influence the glucosinolate content emphasizing the role of plant reaction against the environmental stress situations. For instance, Charron and Sams (2004) reported a 114 percent higher concentration of total glucosinolates in leaves of rapid-cycling populations of *B. oleracea* L. at 32°C than at 22°C, whereas the concentration of glucoraphanin, the precursor of sulforaphane, a compound with chemoprotective properties, was 5-fold higher at 32°C than at 22°C. The myrosinase activity on a fresh weight basis was also higher in *Brassica* leaves and stems at higher in comparison to moderate temperatures, while the total glucosinolates were 50% lower in roots at 32 than at 22°C. The authors concluded that consideration of climatic factors that influence the glucosinolate-myrosinase system may be necessary to optimize the planting and cultivation *Brassica* crops to maximize health benefits.

Pardossi *et al.* (2000) showed that melons grown in Mediterranean summer not only exhibited a faster growth, development, and produced fewer fruits of larger size, but also of poorer quality due to reduced sucrose content, compared with spring produced melons. The dry-matter production and partitioning to the fruits was also significantly lower in summer than in spring (Pardossi *et al.*, 2000). Furthermore, sugar accumulation in watermelon (*Citrullus lanatus*) is suppressed by high air temperatures around the fruits (Kano, 2004). Islam and Khan (2001) investigated seven successive sowings of two large-fruited and one cherry-fruited tomato cultivars made at 45-day intervals under greenhouses conditions in Japan. They found that fruit picked in cool seasons (early winter to spring season) had higher sugar

concentration than those of warm seasons. The authors concluded that this warm-season quality reduction was due to lower enzyme activities, and probably unusually high temperatures in the greenhouses.

Kang *et al.* (2002) reported that preharvest temperature of cucumber fruits influences their tolerance to postharvest chilling. Fruit grown at high temperatures, average day temperature of 32°C had a storage life of 16 days at 10°C and did not exhibit chilling injury, while fruit grown at 27°C (control) developed symptoms of chilling injury after 12 days at 10°C. In addition during storage: firmness, vitamin C content, activity of superoxide dismutase, and catalase were higher in high temperature grown fruit than in control fruit (Kang *et al.*, 2002). Further, Linke and Kläring (2004) reported that low air temperature (17°C) during fruit growth negatively affected postharvest keeping quality of greenhouse tomatoes.

An important quality characteristic for vegetable seedlings is to be short and sturdy. Different strategies such as light quality manipulations, shaking or shot brushing, inside greenhouse temperature regulation, as well as differences between day and night temperatures are recommended to control the plant height. Recently, Chen *et al.* (1999) reported that the irrigation with cold water (tomatoes 5 to 15°C, cabbage 5°C) of plug-grown seedlings, is an effective method for improving quality.

4. Root Temperatures and Their Influence on Vegetable Quality

Not only air temperature, but also the root environment has an effect on product quality (Thompson *et al.*, 1998; Adams, 1999; Dorais *et al.*, 2001; Schnitzler and Gruda, 2002). It is easier to impact roots in hydroponic or substrate culture than in soil-based plants. Optimum root temperatures will stimulate a constant new growth of root and improve uptake of nutrients and water, which is most important at times of rapid development of tomato, bell pepper, or cucumber fruits (Schnitzler and Gruda, 2002). Kafkafi (2001) shows that at the same water potential gradients, and at constant light radiation and air humidity as well as temperature of canopy, the rate of water flow through the stem in tomato was increased by 250 percent when the root temperature changed from 12 to 20°C.

Studies with lettuce grown in a floating hydroponic system have shown that the head size, leaf color and thickness, as well as root structure, developed best at 24°C water temperature, regardless of air temperature. Keeping water temperature at 24°C maintained the market quality of lettuce heads even at 31°C air temperature (Thompson *et al.*, 1998). Benoit and Ceustermans (2001) and Li *et al.* (2002) reported a much lower rate of BER of soilless sweet pepper plants grown on cooled slabs than on non-cooled slabs, maybe due to a higher root activity from better oxygen content in the root environment. According to Adams (1999), high root temperatures (>20°C) cause poor quality in early tomato fruit, but are usually beneficial for fast growing crops such as cucumbers.

To avoid too high temperatures in the root zone it is important to protect the substrate and nutrient solution from direct

sunlight. Some general recommendations to keep temperatures in the greenhouse at optimum levels during warm weather are given by Schnitzler and Gruda (2002).

C. The Influence of Air Humidity on Quality of Vegetables

Humidity is one of the most important environmental factors that influence the water status of greenhouse vegetable plants and consequently affects all processes that are associated with the transpiration such as water balance, transpirational cooling and ion translocation (Bakker, 1984c). According to Grange and Hand (1987) vapor pressure deficit (VPD, 0.2 to 1.0 kPa) has almost no effect on the growth and development of horticultural crops. This is in agreement with results of Bakker (1989, 1990b) working with greenhouse eggplants and sweet pepper. Nevertheless, the relative humidity (RH) in greenhouses affects vegetable quality (Dorais *et al.*, 2001). On the other hand VPDs smaller than 0.2 kPa can be produced for extended periods in modern glasshouses (Holder and Cockshull, 1990). There are some factors that influence the humidity in greenhouses e.g. evaporation as well as air exchange with the atmosphere, water condensation at the roof level, as well as the plants.

Humidity has proven to be economically the most difficult environmental factor to control especially when heating costs are high. The most efficient method of control used in cool weather is to open the vents slightly; much of the water vapour is lost with the escaping heat. Other methods have been tested but have not provided a practical solution (Adams, 2002). Due to an introduction of energy-saving measures in greenhouses reduced ventilation and increased insulation of greenhouses have led to restricted air exchange and concomitant increase in humidity (Bakker, 1989). Bakker (1984c) showed three potentially harmful effects of extreme humidity to plants: (1) heat damage is likely to occur because of the reduction of transpirational cooling, (2) increased injury by air pollutants due to changes in stomatal resistance, and (3) finally the reduced transpiration rate under high humidity reduces the translocation of some ions from roots to the shoots. The growth, development and quality of vegetable fruits are strongly affected by high air humidity, and fruit production seems to be more influenced than vegetative growth (Bakker, 1984b). Several authors reported that low VPD in the greenhouse leads to a reduction in the average weight of marketable fruits of tomato plants (Bakker, 1990a; Holder and Cockshull, 1990). In contrast Mulholland *et al.* (2001) found that larger and fewer tomato fruits under low VPD may be due an increase rate of flower abortion and a reduction of pollen viability. An increase of fruit weight was also reported for sweet pepper (*Capsicum frutescens* var. *grossum*) by air humidity enrichment (RH 60% = VPD 0.94 kPa at 20°C) (Li *et al.*, 2002), whereas Baër and Smeets (1978) reported no differences between 55 and 80 percent RH. At very low VPD (95% RH) flower drop of sweet pepper started much earlier than at 55 and 80 percent RH and the number of fruits per plants was considerably smaller,

but the fruits were heavier. However, Mulholland *et al.* (2001) reported a reduction of tomato fruit quality and an increasing of the proportion of waste fruit due to high incidence of physiological ripening disorders. In addition high humidity (0.1 kPa VPD) severely reduced the K concentration in young leaves and fruit, whereas Ca concentrations were unaffected in young expanding leaf tissue but were increased in the fruit (Mulholland *et al.*, 2001).

Controlling VPD could influence the excess or deficiency of Ca content in the fruits or in some fruit parts and consequently the occurrence of at least related two physiological disorders. For instance, in some circumstances and depending on the variety, low VPD can cause tiny yellowish spots around the calyx and on the shoulder of tomato fruit. This physiological disorder known as "gold specks," is consequence of an increased movement of Ca into the fruit and an accumulation of an excess of Ca, deposited as calcium oxalate, in cells below the epidermis (De Kreij *et al.*, 1992; Adams, 2002). According to Dorais *et al.* (2001) at low VPD, tomato fruits are generally smaller, softer and misshapen and showed a high incidence of gold specks.

De Kreij (1996) and Paiva *et al.* (1998a) showed that under conditions of low VPD, a reduction in the incidence of BER in tomato is achieved. The incidence of BER in soilless sweet pepper (*Capsicum frutescens* var. *grossum*) was also significantly reduced by air humidity enrichment (RH 60%) (Li *et al.*, 2002). Plants grow best at high air humidity levels, as long as the transpiration flow will sufficiently support the uptake and distribution of essential nutrients (e.g., calcium, magnesium, boron) and phytohormones (e.g., cytokinin) in the plant (Krug, 1991). According to Ho and White (2005) the induction of BER in young fruit of tomatoes is influenced by a number of environmental factors. These are most likely to exert their effects by affecting the transport of Ca to the fruit and/or the rate of cell expansion. Whereas light intensity and ambient temperature influence the rate of fruit growth, air humidity influences Ca uptake (Ho and White, 2005). According to Ho (1989), Adams and Holder (1992), Adams (1999), and Ho and White (2005) high canopy transpiration rates reduce Ca fluxes to the developing fruit by diverting the xylem stream preferentially to leaves and promote BER in tomato fruits. According to Bradfield and Guttridge (1984), calcium uptake of the fruit was greater when nights were humid rather than dry. High air humidity, especially during the night when the stomata are normally closed, appears to prevent Ca deficiency in lettuce (Collier and Tibbitts, 1982). Stanghellini *et al.* (1998) reported an incidence of only 2 percent BER in tomato fruits, produced by high concentration of nutrient solution ($EC = 10 \text{ dS m}^{-1}$) and low transpiration (RH = 65% of potential evaporation). Meanwhile, at high transpiration, 20 percent of fruits show BER. Recently, Cariglia and Stanghellini (2001), and Li *et al.* (2001) suggested an improvement of taste and flavor of tomato fruits by increasing the salinity, and applying the right management of the shoot environment. With respect to marketable production, 1 dS m^{-1} increase at high potential transpiration was equivalent to a 1.4 dS m^{-1} increase at

low potential transpiration (Li *et al.*, 2001). A humid shoot environment (aiming a reduced potential transpiration) can modify the effect of the root zone salinity, both by reducing the proportion of nonmarketable fruits, e.g., by the incidence of blossom end rot and reducing the decline in fresh weight (Cariglia and Stanghellini, 2001, Li *et al.*, 2001).

Bertin *et al.* (2000) also reported that controlling the VPD reduced BER for tomato fruits, but generally made cracking worse in the case of low fruit load because of rapid fruit growth. This is in agreement with the results of Leonardi *et al.* (2000) with tomatoes and Aloni *et al.* (1998), Moreschet *et al.* (1999), and Yao *et al.* (2000) with bell pepper. Factors that encourage the development of high turgor pressure at night (low night VPD) increase the rate of cracking due to a limitation of night transpiration. Recently, also Dorais *et al.* (2004) reported that the occurrence of cracking was negatively correlated with VPD during the night and positively correlated with VPD during the day.

Leonardi *et al.* (2000) demonstrated that higher VPD brought out an increase in color intensity of tomato fruits (Leonardi *et al.*, 2000). Dorais *et al.* (2001) also reported a more intense coloration of tomato fruits when plants were grown under high VPD, consistent with earlier results of Lipton (1970). Fricke and Krug (1997) showed also for cucumber a reduction of fruit quality in humidified treatments, in agreement with earlier experiments (Bakker, 1984b, 1984c; Bakker *et al.*, 1987). Light-colored or malformed cucumber fruits were found under such conditions (Bakker, 1984b, 1984c). Bakker *et al.* (1987) investigated the effect of different day humidity levels in combinations with either a high or low humidity during the night on fall- and spring-grown cucumber and reported that fruit quality expressed as fruit color, was reduced by a high 24-hour average humidity at harvest after 14 days' storage. Therefore, the authors recommended a combination of high daytime humidity and relative low night-time humidity for optimum cucumber fruit production and quality (Bakker *et al.* 1987). No significant relationships were found between keeping quality and humidity by day, night or 24-hour mean for sweet pepper (Bakker, 1989). This is consistent with results of Janse (1989), who showed that other factors such as temperature regime and EC level influenced firmness and shelf life of sweet peppers.

In contrast with light and temperature, data concerning the influence of air humidity on greenhouse vegetable quality are generally scarce except for tomato fruits. For instance, the dry matter and sugar concentrations of fruit exposed during their growth to high VPD was higher than those of fruit exposed to low VPD (Bertin *et al.*, 2000, Leonardi *et al.*, 2000), apparently due to a decrease in the water accumulation by the fruit (Guichard *et al.*, 2001). Guichard *et al.* (1999) showed that increased VPD (from 1.0 to 2.5 kPa during the daytime) leads to a reduction in the net accumulation of water by the fruit of -30 percent and the phloem flux into the fruit less than 9 percent of daily phloem flux. According to Bertin *et al.* (2001) reducing VPD diluted both the dry matter and sugar content of tomato fruit picked in July, whereas for fruits harvested later in summer,

these negative effects were attenuated because fruit growth was also carbon limited. In contrast, no effects of VPD on the sugar content and firmness were found for sweet pepper (*Capsicum frutescens* var. *grossum*) (Li *et al.*, 2002).

High humidity levels may also indirectly influence the quality of vegetable plants by increasing the spread of pathogens, such as Botrytis and other diseases (Bakker, 1990b; Vonk Noordegraaf and Welles, 1995; Cockshull, 1998).

D. The Influence of CO₂ Enrichment on Quality of Vegetables

The interest in CO₂ enrichment has risen and declined several times throughout the history of horticulture (Mortensen, 1987). The traditional straw bale cultural technique for cucumbers used for many years is one of the oldest and simplest methods of CO₂ enrichment in greenhouse. The importance of CO₂ enrichment has increased with the trend towards produced crops in nutrient film, peat bags, peat modules, and rockwool, where natural evolution of CO₂ is small compared with CO₂ coming from the soil. Indeed, in greenhouses, the soil is frequently covered with plastic sheets when alternative soilless media are used (Hicklenton, 1988; Slack, 1986). On the other hand, the CO₂ enrichment methods have continued to develop and sources of nonpolluting CO₂ have been introduced (Mortensen, 1987), so that the negative effects of air pollution associated with burning of hydrocarbons have been reduced.

Greenhouse vegetable plants show very positive effects from CO₂ enrichment by increasing dry weight, plant height, number of leaves, and lateral branching (Mortensen, 1987). Plant quality expressed by growth habit and number of flowers is often enhanced by CO₂ enrichment. CO₂ enrichment decreases the oxygen inhibition of photosynthesis and increases the net photosynthesis in plants. This is the basis for increased growth rates caused by CO₂ (Mortensen, 1987). The extra assimilate can be used directly for increased leaf development in leaf vegetables such as lettuce (Andreas, 1984; Hicklenton, 1988; Mortenson, 1994; Both *et al.*, 1998), or can be accumulated as reserve to be withdrawn to sites of high sink strength in fruit vegetables, e.g., developing trusses by tomatoes (Slack, 1986). Peet and Willits (1987) reported that prolonging the period of CO₂ enrichment significantly increased the yield of cucumber, but did not effected fruit quality in terms of cull number or cull percentage. Mortensen (1994) showed that increasing the CO₂ concentration in plastic "field chambers" from ambient to 800–900 $\mu\text{mol mol}^{-1}$ increased the dry weight, of lettuce, carrot, and parsley by 18, 19, and 17 percent, respectively.

Since photosynthesis occurs primarily in the leaves, the initial accumulation of dry matter is also in the leaf tissue (Hicklenton, 1988). This means that crops, which are grown exclusively for their leaves such as lettuce, tend to be the most efficient using additional CO₂ sources (Hicklenton, 1988). Andreas (1984) showed an increase of 16 to 36 percent of weight of heads for butterhead lettuce and of 11 to 15.6 percent of weight of heads

for different iceberg lettuce by supplementing greenhouse CO₂. Earliness has been reported for Kohlrabi (Andreas, 1984) and for winter grown lettuce with increasing of CO₂ concentration in greenhouses (Hicklenton, 1988).

CO₂ enrichment seems to be beneficial, and it can diminish the negative effect of other environmental factors such as low light conditions (Fierro *et al.*, 1994) or cultural practices such as high salinity levels in irrigation water available in Mediterranean coastal (Romero-Aranda *et al.*, 2002) or high EC levels of nutrient solutions (Li *et al.*, 1999). For instance, during the reproductive phase, enrichment induces earlier flowering and fruit set in fruit vegetables in poor light conditions (Slack, 1986). An increase of CO₂ concentration (1200 $\mu\text{mol mol}^{-1}$) can avoid the negative effect of high salinity in yield and slightly improve the tomato quality in terms of TSS, glucose and acidity (Li *et al.*, 1999). Further, elevated CO₂ concentrations also increase the optimal levels of other environmental factors such as temperature (Mortensen, 1987) or light.

Enrichment with CO₂ (900 $\mu\text{mol mol}^{-1}$, 8 h day⁻¹) and supplementary lighting for approximately 3 weeks before transplanting, increased accumulation of dry matter in shoots by 50 percent for tomato and pepper seedlings, as compared with the control, improving the early yields after transplanting to the field (Fierro *et al.*, 1994). Calvert and Slack (1975; 1976) determined a nearly linear reduction of flower abortion on the first truss of tomato, normally caused by low light conditions in winter, with increasing CO₂ concentration in greenhouse from ambient to 1000 $\mu\text{mol mol}^{-1}$.

Both *et al.* (1998) showed that a 190 g lettuce (*Lactuca sativa* L. cv. 'Vivaldi') head can be grown in 35 days from seed using different combinations of daily integrated PAR levels, and CO₂ concentrations suggesting that a coordinated management strategy regarding climate parameters for the most economic lettuce production. The integration of CO₂ supplementation may make the economics of supplemental lighting more attractive.

Supplementing CO₂ in the greenhouse increases the weight of bell pepper fruits by 10 percent (Andreas, 1984). A CO₂ concentration of 1000 $\mu\text{mol mol}^{-1}$ from January to April resulted in increases in total weight of cucumber fruits, fruit numbers, and mean weight per fruit (Slack and Hand, 1984). Speed of plant production and quality of tomato transplants can be both improved during the critical winter period (Hicklenton, 1988).

It was established that a CO₂ enrichment of up to 900 $\mu\text{mol mol}^{-1}$, lowered the nitrate content of kohlrabi (Bentrup and Lenz, 1987). Hucklesby and Blanke (1990) reported that when raising CO₂ concentration of 1000 $\mu\text{mol mol}^{-1}$ the nitrate content of spinach leaves increased for photoperiod sensitive cv. 'Vital GS' and decreased for insensitive cv. 'Mazurka.' Thus, the NO₃ content is affected by the difference between the relative rate of stimulation of nitrate reduction and nitrate uptake by higher CO₂ concentrations (Hucklesby and Blanke, 1990).

There is less information on the effect of CO₂ concentration on the internal quality of vegetables. Most of the publications report no effect on product quality. For instance, Özçelik and Akilli

(1999) reported that CO₂ enrichment did not affect tomato fruit quality characteristics such as vitamin C, flesh firmness, titratable acidity, pH, total soluble solids, and dry matter content. Slack (1986) reported that the effect of CO₂ on tomato crops increased the weight of individual fruit, however no clear effects on fruit quality were attributed. These are in agreement with the results of Davies and Winsor (1966), Blanc (1986), and Ho and Grimby (1990) who found no differences with CO₂ enrichment on the dry matter and total soluble solid concentration of tomato fruit. Indeed, the increase in the quantity of sugar imported by the fruit following CO₂ enrichment is accompanied by an equivalent increase in the quantity of water entering the fruit (Dorais *et al.*, 2001; Guichard *et al.*, 2001). Solely, Behboudian and Tod (1995) reported an improvement of fruit quality of tomato at 1000 $\mu\text{mol mol}^{-1}$ CO₂, compared to ambient CO₂ fruits, in terms of increased concentration of soluble sugars and total soluble solids. High CO₂ fruit also ripened more slowly and was characterized by lower respiration and ethylene production rates than ambient CO₂ fruits (Behboudian and Tod, 1995).

Further research with the CO₂ factor should mainly be concentrated on how CO₂ enrichment affects the optimal levels of light, temperature and air humidity for a better product quality.

V. CONCLUSIONS

Climatic factors have an enormous influence on product quality of most greenhouse fresh vegetables. They not only affect the physiological processes, and lead to differences in appearance of vegetable products, but they also have direct and indirect influence on the internal quality of vegetables. Sensory ingredients such as sugars, acids and flavor substances, which affect taste, as well as vitamins and secondary plant compounds, important for human nutrition can be affected by changing the climate condition in the greenhouse. With increasing emphasis on the beneficial health effects of fresh vegetables, it is more necessary than ever that the impact of environmental factors on the internal quality of fresh vegetables will be considered in the production process.

Documenting the response of vegetable quality to changes in climate conditions of protected production give us the knowledge to control the quality by managing these growth factors in order to produce high quality products.

The influence of other factors on product quality of fresh greenhouse vegetables will be reported in another paper.

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