Cucumber fruit quality at harvest affected by soilless system, crop age and preharvest climatic conditions during two consecutive seasons

M.D. Gómez-López *, J.P. Fernández-Trujillo, A. Baille

Department of Agricultural and Food Engineering, Technical University of Cartagena, Paseo Alfonso XIII ETSIA, 30203 Cartagena (Murcia), Spain

Received 28 October 2005; received in revised form 2 May 2006; accepted 21 June 2006

Abstract

Cucumber fruits (Cucumis sativus L., cv. Trópico F1) grown on perlite substrate and NFT (Nutrient Film Technique) were harvested during two seasons (winter and spring) to monitor the effects of climatic conditions and hydroponic growth systems on fruit quality at harvest. The best fruit quality at harvest, as measured by lightness and hue angle parameters, was obtained during the 3 weeks following the first winter picking. When values of a parameter of preharvest climate value called $G^*$ were lower than 0.4 MJ m$^{-2}$ °C day$^{-1}$ interval$^{-1}$, the cucumber achieved its optimum quality at harvest, as measured by the dark green color of the skin. NFT-grown fruits showed darker and greener skin color (higher hue angle and lower lightness) compared with perlite-grown fruit, irrespective of the season considered. During the winter season, the plant transpiration rate was 30% higher in perlite than in NFT culture, which correlates with higher differences in $G^*$ and 40% additional yield in perlite. However, in spring $G^*$ was not sensitive enough to discriminate between the two hydroponic systems. In general, fruit quality at harvest in spring was lower than during the winter, due to flesh whitening, higher longitudinal and equatorial calibers, and slightly higher pH, as well as worse epidermal color coordinates (ranging from the dark and dull green color typical of winter fruit to a light and vivid green-yellow color). During the spring season, NFT-grown fruit were less acid than perlite-grown fruit with no apparent correlation with the climatic conditions or fruit nutrition.

# 2006 Elsevier B.V. All rights reserved.

Keywords: Cucumis sativus L.; Fruit quality; Hydroponics; Intercepted radiation; Thermal time; Soilless culture systems

1. Introduction

For fresh consumption, cucumber fruits (Cucumis sativus L.) are picked at their full growth stage, before reaching physiological maturity (Kanellis et al., 1986). The fruit is usually classified into quality classes based on shape, uniformity, defects and skin color (Schouten et al., 1997). Growers have to balance cucumber yield and cucumber quality particularly at harvest, the point of the food chain where they get their reward income. It is therefore of importance to observe whether better quality does not mean a substantially lower yield. Skin color is a harvest index also used as the best quality index in cucumber fruit (Gnanasekharan et al., 1992; Schouten et al., 1997, 2002) but other quality traits, particularly for pickling cucumber destined for fresh consumption mainly in Spain and Russia, can be useful for consumers as indicators of early flesh fruit senescence.

Many authors have found that cucumber fruit growth is affected by radiation, growing temperature and fruit load (Schapendonk and Brouwer, 1984; Marcelis, 1993), and these can produce a situation of “source-limited” (low level radiation that it is not sufficient to sustain photosynthesis) or “sink-limited” (low growth rate and high radiation, which generate a poor sink-strength) (Marcelis et al., 1998). Moreover, the quality of horticultural crops is also influenced by the previous...
factors and situations and others such as irrigation, maturity, mineral nutrition and pest management (Wang, 1997). Schouten et al. (1997) found a good correlation between the maximum color in cucumber and plant growing conditions (low plant density or high plant nutrients, as measured by electrical conductivity of the nutrient solution used). However, as far as we know, no reports are available which compare pickling cucumber fruit quality measured immediately after harvest in soilless culture systems in different seasons. Plant nutrition and fruit yield have been studied in different cucumber cultivars subjected to different crop systems (Papadopoulos, 1994; Güll et al., 1999; Gómez et al., 2003a,b). However, systematic studies of differences in cucumber quality during the harvesting season (Jasso-Chaverria et al., 2005; Schouten et al., 2002), or in different stages of fruit development (Kanellis et al., 1986) do not usually take into account different production systems. Soilless systems could be a promising culture alternative, particularly in south-west Spain, because of the serious problems with soil pathogens (Cooper, 1996) and the imbalance between water resources and irrigation demands (Martínez-Fernández et al., 2000). However, information linking fruit quality and soilless systems is lacking in order to provide recommendations for growers.

The objective of this work was to find a reliable predictor of optimum fruit quality at harvest based on preharvest climatic conditions. Two successive seasons (winter and spring) and two hydroponic systems (perlite and NFT) were used to grow pickling cucumbers of different fruit quality traits at harvest and to detect the sensitivity of the prediction.

2. Materials and methods

2.1. Greenhouse and plant material

Cucumber fruit (C. sativus L. cv. Trópico F1, Numhem Seeds, The Netherlands) of 140–160 mm length (a pathenocarpic, pickling type with very soft-spined fruits, also used for fresh consumption) were grown for the fresh market in a greenhouse located in the Experimental Research Station ‘Tomás Ferro’ (La Palma, Cartagena), southern Spain. The plants were grown on two different hydroponic systems with a plant density of 2.08 plants m⁻² (Gómez et al., 2003a,b):

- Perlite (type K-13), in polyethylene bags using an average of 8 L of perlite per plant. The nutrient standard solution (in mmol L⁻¹) was: 13.0 NO₃⁻, 1.7 H₂PO₄⁻, 0.5 NH₄⁺, 7.5 K⁺, 3.5 Ca²⁺, 2.0 Mg²⁺ (pH 5.5–6.0, EC = 2.2 mS cm⁻¹). The open-drainage rate was about 30%.
- Pure hydroponics (NFT), with the same nutrient solution, which flowed through a gutter (5 m × 0.35 m × 0.15 m) with a slope of 1%. The water film was about 4 mm thick, and the flow rate about 3 L min⁻¹.

The two successive crops considered in this study were transplanted in January 2001 and in April 2001 (named winter and spring seasons, respectively). Glasshouse orientation was N–S, with a ground area of 200 m². Perlite and NFT crop rows faced N–S. In the NFT system, one single line of plants (with 17 plants) was located in the middle of the greenhouse parallel to the two groups of six lines (with 20 plants each) of the perlite system (six on the east and the other six on the west).

Crops were managed in the usual way for commercial greenhouses. The training system was an inclined cordon (V-cordon) in double rows, 160 cm apart with walking paths, row spacing was 30 cm and the horizontal support wires were at a height of 3.5 m. Plants inclined away from the row of planning, guided by the offset support wires above, and formed a V-shaped canopy in cross-section. The pruning system adopted was a modified umbrella system. At the beginning, the lower foliage (less than 0.5 m) was removed. Above this height, all laterals were removed and only two of every three fruit from each leaf axil were allowed to develop. In spring, when the main stem reached the horizontal wire (3.5 m), the growing point was pinched out and, in the lowest 100 cm, laterals were allowed to grow with two leaves and one fruit per each leaf axil.

To maintain the climate control values (Table 1) the glasshouse was naturally ventilated by means of a roof opening and three sets of equipment, as previously reported (Gómez et al., 2003a): a high pressure mist system (7 L h⁻¹), a heating system (pulsed air and substrate heating by plastic pipes laid along the ground), and a thermal screen with 60% radiation transmission (USL 16F, Ludvig Svenson). During the winter, the nutrient solution of NFT culture was heated with a water heating system.

Plants were harvested twice per week (Monday and Thursday). The fruit development period ranges from 12 to 28 days after anthesis in order to harvest commercial fruit according to Hikosaka and Sugiyama (2004). Our data obtained by non-destructive measurements (fruit length or skin color) were close to 16 ± 2 and 12 ± 2 days after anthesis in the winter and spring seasons, respectively (data not shown). Only fruit harvested on Monday were used for the quality analysis at

| Table 1 | Control climatic values, in winter and spring seasons at day and night time |
|---------|--------------------------|------------------|------------------|------------------|-----------------|------------------|
|         | T air (°C) Day Night     | T perlite (°C) Day Night | T NSNFT (°C) Day Night | RH incidence (%) Day Night | TS (W m⁻²) Day Night |
| Winter  | 23 14 16 16      | 22 15             | 40 –             | 50-60 –          | >650 –          |
| Spring  | 28 18 – –       | – –              | – –             | – –             | –               |

T NSNFT indicate the offset temperature of the NFT-nutrient solution and TS indicate the control values of intercept radiation from which the thermal screen is folded on the culture.

* Outside radiation
harvest of the two soilless systems. The fruit were packed in polyethylene bags to reduce dehydration, transported within 30 min to the laboratory, and stored for 1–2 h at 6 °C until analysis.

2.2. Transpiration measurements

Crop water uptake (W, in L plant\(^{-1}\) day\(^{-1}\)) was assumed equal to the transpiration rate, since the evaporation from the substrate or from the water film was negligible. In the NFT system, the canopy transpiration was determined by measuring the weight loss of the tank containing the running nutrient solution by means of an electronic balance, assuming the nutrient solution density to be equal to 1000 g L\(^{-1}\). In the perlite system, the transpiration was assumed to be equal to the difference between the water supply and the drainage rate. The plant transpiration rate (L plant\(^{-1}\) time interval\(^{-1}\)) was derived by dividing the whole crop transpiration by the number of plants present at that moment in the perlite culture or in the NFT gutter, respectively. The time interval was the days of fruit development (16 and 12 days in winter and spring seasons, respectively).

2.3. Climatic data

Measurements of global solar radiation \(G\) (W m\(^{-2}\)) and dry and wet bulb temperatures were recorded continuously throughout both seasons by data logger (Campbell CRX, Utah, USA). Measurements of interception by the canopy \((G_{int})\) were carried out at regular intervals by means of two linear radiation sensors (Delta-T Inc. Devices, Cambridge, UK) placed at the top and at the bottom of the canopy, when the leaf area index, LAI, was greater than 1.0 m\(^2\) leaf m\(^{-2}\) greenhouse soil. The glasshouse air temperature was recorded by means of a ventilated psychrometer located at a height of 2 m, in the middle of the greenhouse. The thermal time, \(ST\) (°C day\(^{-1}\)) was calculated as is usual, summing the daily mean air temperature and subtracting a base temperature, \(T_b\) (Perry et al., 1986) assumed to be 10 °C (Gómez et al., 2003a,b). The cumulated intercepted radiation \((MJ m^{-2} \text{ time interval}^{-1})\) and thermal time \((°C \text{ day time interval}^{-1})\) were calculated for the same periods as for transpiration in each crop. The \(G^*\) parameter was defined as follows: \(G^* = \Delta G_{int} \Delta ST^{-1}\) (MJ m\(^{-2}\) °C day\(^{-1}\)). The relation between \(G^*\) and cumulated \(ST_h\) (as defined by using the first harvest as the reference or baseline, with \(ST \approx 500 °C \text{ day} \) and then \(G^* = 0\)) was calculated by linear regression analysis.

Maximum, minimum and average night and day temperatures were also tabulated from data obtained every 30 min.

2.4. Fruit quality attributes

The fruit quality standards laid down for cucumbers in EU include, for example, minimum requirements of sound, intact fruit, in fresh appearance and firmness, and a classification of the fruit into three classes depending on fruit shape, defects in coloration, etc. (Commission Regulation 1677/88). In our case, fruit quality was evaluated weekly in fruit obtained from six different replicates of five to six non-contiguous, labelled plants of the plot. Fruit were harvested in their commercial maturity stage with lengths of 140–160 mm and free from spoilage (mainly Botrytis sp.). Replicates consisted of five fruit each in either perlite or NFT culture. During the winter season, the replicates were six in the perlite system per each orientation of the greenhouse (east and west), and six in the NFT system. During the spring only three replicates were harvested per culture. Cucumber weight was measured with a digital balance (±0.1 g accuracy). Fruit equatorial caliber (maximum cross-section) and length (longitudinal caliber, between distal proximal apex, or from calyx to apex) were measured with a digital calliper of 0.01 mm precision that covered 0–300 mm. Cucumber color characteristics, namely the darkest side of the skin (proximal position), equatorial area of the skin, pale side of the skin (distal position), and flesh after peeling the fruit, were measured with a Minolta CR-300 colorimeter (three readings that were averaged) calibrated with a white reference plate, C illuminant and 2° observer. Standard C.I.E. \(L' C' H\) color space coordinates (lightness, chroma or saturation, hue angle) were measured at three points per fruit (two equatorial, one each at the distal and proximal apexes) and one point in the flesh immediately after peeling about 2 mm from the fruit equator and in the juice. Flesh firmness was measured at the same point of the fruit equator where flesh color was evaluated after removing cucumber skin, by means of an Effegi FT-327 fruit pressure tester equipped with a 7.9 mm cylindrical probe with a flat surface. The juice extracted from five peeled fruit was used to determine pH and total soluble solids (SS, using a hand refractometer). Titratable acidity (TA) was measured in juice that was frozen at −20 °C, immediately after squeezing, to be used for further analysis. Five millilitres of juice were diluted up to 40 mL with distilled water, then manually titrated with 0.1N NaOH up to pH 8.1. The results were calculated in mmol H\(^+\) L\(^{-1}\).

2.5. Shelf-life of perlite-grown fruit

Two experiments using perlite-grown fruit were conducted and fruit quality traits, shriveling and weight loss on a fresh weight basis were examined after 4, 8 or 11 days in six to nine replicates of five fruit. These were sealed in 20 ± 2 μm thick, non-oriented macro-perforated (32 holes of 1.2 mm diameter per dm\(^2\)) cast polypropylene film (Plásticos del Segura, Murcia, Spain) and stored at 20 ± 1 °C and 95% RH. Representative data of one of the experiments is shown as supplementary information.

2.6. Statistical analysis of quality parameters

Quality analysis data from each season was subjected to analysis of variance (ANOVA), with the soilless culture system (perlite substrate – east and west orientation only during the winter season – or NFT system), and harvest time, as factors. Non-destructive analysis (skin or flesh color) used single fruit as replicates. Destructive analysis was performed in batches of
five fruits (\(n = 3\) for NFT and \(n = 6\) for perlite-grown fruit during the winter season; \(n = 4\) for both treatments during the spring season). Color analysis at the end of the spring season was not recorded because the colorimeter was unavailable. The ANOVA of flesh firmness and chroma of the darkest cucumber side (from the winter season) were performed on data transformed to natural logarithms after normal probability plot analysis (Box and Cox, 1964). Mean comparisons between soilless culture systems were performed using LSDs and harvest time effects by polynomial trends. Regression analysis of each variable against crop age (harvest date) within each season was applied when a clear polynomial trend was statistically confirmed.

### 3. Results

#### 3.1. Plant transpiration, climatic variables and crop data

##### 3.1.1. Plant transpiration

Both culture systems (perlite and NFT) showed a similar rate of water consumption in spring (\(\approx 116 \text{ L plant}^{-1}\)) until day 75, whereas, the transpiration of the perlite culture measured during the winter season (\(62 \text{ L plant}^{-1}\)) was 30% higher than in the NFT culture (Table 2). The transpiration rates were closer in the two cultures (Table 2), during the spring fruit growing period (12 days), than in the winter fruit growing period (16 days).

##### 3.1.2. Intercepted radiation (\(G_{\text{int}}\))

The cumulated intercepted radiation at the end of the winter season (Table 3) was 20% higher in the perlite culture than in NFT. In the spring season, the intercepted radiation showed the highest value in NFT culture (456 MJ m\(^{-2}\)) (Table 3). \(G_{\text{int}}\) cumulated during fruit development generally increased during the two seasons and in the two culture systems due to plant growth. The intercepted radiation in spring, measured at 12-day intervals, fell during the last two harvests (Table 3) in both cultures, as a result of plant senescence or the shade produced by the laterals. The reduced \(G_{\text{int}}\) at the end of spring resulted in a constant transpiration rate in the perlite culture and a slight decrease in NFT culture, compared with previous rates during the season in question (Table 2).

##### 3.1.3. Temperature

As expected for a typical spring season, the highest mean, maximum and minimum temperatures for both day and night were obtained in June, at the end of the season (Table 4). For the same season, the lowest values were obtained in May. Winter day time temperatures showed a similar trend to that observed (until day 54 in spring) (Table 2). The transpiration rates were closer in the two cultures (Table 2), during the spring fruit growing period (12 days), than in the winter fruit growing period (16 days).

---

**Table 2**

Values of \(\sum \Delta T_R\) at the end of the season, and \(\Delta T_R\) cumulated in the time interval (16 or 12 days in winter or spring crop, respectively), for every harvest date, expressed in days after transplant (dat), during winter and spring season under two soilless culture systems (perlite and NFT).

<table>
<thead>
<tr>
<th>Culture</th>
<th>(\sum T_R) (L plant(^{-1}))</th>
<th>(\Delta T_R) (L plant(^{-1}) time interval(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>46</td>
<td>52</td>
</tr>
<tr>
<td>Perlite</td>
<td>62</td>
<td>14.2</td>
</tr>
<tr>
<td>NFT</td>
<td>43</td>
<td>8.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Culture</th>
<th>(\sum T_R) (L plant(^{-1}))</th>
<th>(\Delta T_R) (L plant(^{-1}) time interval(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td>Perlite</td>
<td>118</td>
<td>13.2</td>
</tr>
<tr>
<td>NFT</td>
<td>114</td>
<td>17.6</td>
</tr>
</tbody>
</table>

46, 52, 59, 66, and 74 denotes winter harvest date (dat), and 38, 40, 47, 54, 61, 68 and 75 denotes spring harvest date (dat).

**Table 3**

Values of \(\sum G_{\text{int}}\) (MJ m\(^{-2}\)) at the end of the season, and \(\Delta G_{\text{int}}\) (MJ m\(^{-2}\) time interval\(^{-1}\)) cumulated in the time interval (16 or 12 days in winter or spring crop, respectively), at each harvest date, expressed in days after transplant, during winter and spring season under both soilless culture systems (perlite and NFT).

<table>
<thead>
<tr>
<th>Culture</th>
<th>(\sum G_{\text{int}}) (MJ m(^{-2}))</th>
<th>(\Delta G_{\text{int}}) (MJ m(^{-2}) time interval(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>46</td>
<td>52</td>
</tr>
<tr>
<td>Perlite</td>
<td>212</td>
<td>48.5</td>
</tr>
<tr>
<td>NFT</td>
<td>176</td>
<td>43.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Culture</th>
<th>(\sum G_{\text{int}}) (MJ m(^{-2}))</th>
<th>(\Delta G_{\text{int}}) (MJ m(^{-2}) time interval(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td>Perlite</td>
<td>425</td>
<td>61.7</td>
</tr>
<tr>
<td>NFT</td>
<td>456</td>
<td>70.1</td>
</tr>
</tbody>
</table>

46, 52, 59, 66 and 74 denotes winter harvest date (dat), and 38, 40, 47, 54, 61, 68 and 75 denotes spring harvest date (dat).
in the spring season (high values at the end of the season, in March, and the lowest values in February). In the winter, the highest night time values were obtained in January as a result of the climate control system.

### 3.1.4. Thermal time

The date of the first harvest in cucumber can be predicted by thermal time (Marcelis, 1993). In cucumber plants grown during the winter and spring seasons, the first harvest was at 500°C day/C01 under both culture systems (perlite and NFT) (Gómez et al., 2003a). At the end of the spring season the ST value was 30% higher than in the winter crop (Table 5). The DST in the fruit-growing period of the winter season (16 days) showed values of between 175 and 220°C day/C01, while at the end of the spring season (fruit growing period of 12 days) DST was close to 230°C day/C01.

### 3.1.5. G* parameter

The G* parameter was calculated during the fruit development time in all the fruit harvest (Fig. 1), 16 days and 12 days in winter and spring crop, respectively. G* increased throughout the season (Fig. 1) as was to be expected in a temperature controlled greenhouse with increasing intercepted radiation, with the exception of the last two harvests of the spring, where G* presented a trend to decrease concomitant with a plateau in the plant growth rate (Gómez et al., 2003a). The values of G* in the winter crop were lower than 0.4 MJ m⁻²°C day⁻¹ 16 day⁻¹, except at the last harvest in the perlite culture (Fig. 1). However, during spring G* values were usually above 0.4 MJ m⁻²°C day⁻¹ 12 day⁻¹ (Fig. 1).

The G* pattern as a function of STh₁ in the winter season was:

\[ G^* = 0.00042 \text{STh}_1 + 0.28 \quad r^2 = 0.91 \quad \text{(perlite culture)} \]  

and in the spring season, until the established plant growth rate (June 4th):

\[ G^* = 0.00042 \text{STh}_1 + 0.30 \quad r^2 = 0.99 \quad \text{(perlite culture)} \]  

\[ G^* = 0.00042 \text{STh}_1 + 0.35 \quad r^2 = 0.99 \quad \text{(NFT culture)} \]  

STh₁ was used instead of dat in order to use the same scale for the purpose of comparing the two seasons. The G* versus STh₁ slopes showed similar values in both the spring and winter perlite cultures. However, in NFT-winter culture, the slope value was half that of the slope obtained in spring. The intercept value of the linear regression was lower in winter than in spring in both culture systems.

### 3.1.6. Crop growth and yield

Some differences between culture systems were found in the leaf area index (LAI). Average LAI at the end of the winter cycle was 2.4 m² leaf m⁻² greenhouse soil and 1.6 m² leaf m⁻² greenhouse soil* for perlite and NFT systems, respectively. In spring average...
LAI was around 3.5 m\(^2\) leaf m\(^{-2}\) greenhouse soil for perlite and 4.0 m\(^2\) leaf m\(^{-2}\) greenhouse soil for NFT systems.

The average yield per plant in the winter season was 3.3 or 2.0 kg pl\(^{-1}\) in perlite and NFT systems, respectively, whereas, in the spring season the yields were 8.3 kg pl\(^{-1}\) in perlite and 7.3 kg pl\(^{-1}\) in NFT systems.

3.2. Quality attributes measured non-destructively

The orientation of perlite-grown fruit did not affect fruit quality during the winter season (data not shown), and so the results were combined.

3.2.1. Fruit size

The fruit weight gradually increased during the winter but exhibited a progressive decrease after the third harvest during the spring (Fig. 2). The fruit equatorial diameter followed a similar pattern to the weight (Fig. 3). The length of NFT and perlite-grown fruit were significantly different only at certain harvest dates in the winter season (Fig. 3). However, perlite-grown fruit were wider and longer during the spring compared with the winter season fruit (Fig. 3). Fruit were always straight.

3.2.2. Skin color

During the winter season, the pale or distal side of the skin of fruit from NFT was darker (1.2 U higher lightness) and, during both seasons, greener (0.8–1.2\(^{\circ}\) higher hue angle; \(P < 0.05\)), and more vivid (1.5 U of chroma more) than perlite-grown fruit (Fig. 4; data not shown). The cultivar was relatively resistant to skin yellowing, because senescence was absent throughout the experiment at harvest (Picture 1, supplementary information).

The color of the darkest side of the skin (Fig. 4) also revealed higher chroma values in perlite than in NFT (1 and 2.6 U more in the winter and spring seasons, respectively; \(P < 0.001\)) particularly at the first two harvest dates during the winter season (interaction crop \(\times\) harvest time, significant at \(P < 0.001\)).

As regards equatorial color, cucumber fruit from the spring season followed a typical pattern of increasing \(L^*\) and \(C^*\) and decreasing hue angle (\(P < 0.001\)). This means a change from dark and dull green color to light and a vivid green-yellow.
Fig. 2. Cucumber fruit weight, flesh firmness, and juice pH values at harvest (cv. Trópico) during two consecutive seasons (winter and spring) in different crops (perlite [■]; NFT [△]) as a function of days after transplant. Bars are ±S.D.

Fig. 3. Cucumber fruit length and equatorial diameter (cv. Trópico) in winter and spring seasons under two soilless culture systems (perlite [■]; NFT [△]) as a function of days after transplant. Bars are ±S.D.
NFT-grown fruit showed delayed changes compared with perlite-grown fruit (Fig. 1; \( P < 0.001 \)). Note that the flesh color followed the same trend as regards \( L^* \) and \( H^* \) (Fig. 1) but an opposite trend for \( C^* \) during ripening (Fig. 4).

### 3.2.3. Flesh color

Flesh lightness remained around 68 ± 4 U during the winter and increased less than 4 U during the spring (\( P < 0.001 \)). During the winter, flesh chroma progressively increased from 25 to 32 U irrespective of the crop, but during the spring, chroma remained below 30 U (see supplementary information). The flesh hue angle trend was erratic during the winter and linearly decreased during the spring (0.53° or 0.68° per week in perlite and NFT-grown fruit, respectively; \( r^2 = 0.9 \)) (see supplementary information).

### 3.3. Destructively measured quality attributes

In general, soluble solids were mainly affected by harvest date (\( P < 0.001 \)), with slight differences between crops with time only in the spring (\( P < 0.003 \)), with values ranging from 3.5 to 5° Brix. No general pattern of increased soluble solids was found. Titratable acidity during the winter season was 14 mmol H+ L−1 overall, but during the spring season remained higher in perlite-grown fruit than in NFT (Fig. 5). Although, from a statistical point of view, fruit pH of the winter season was affected by crop, harvest date and crop × harvest date (pH was higher during the second and third harvest), differences were lower than 0.3 U (0.12 U more in NFT systems than in perlite system). Overall, the pH was higher during the winter season (5.8, 0.3 U higher than during the spring season, see supplementary information).

Flesh firmness decreased with time during the winter and increased during the spring (\( P < 0.001 \), Fig. 2), with slight

![Fig. 4](image-url) Color parameters at harvest measured on the proximal (pale), equatorial, or distal (dark) side of the skin of cucumber fruit cv. Trópico during two consecutive seasons under two soilless culture systems (perlite (■); NFT (△)) as a function of days after transplant. Bars are ±S.D.

![Fig. 5](image-url) Titratable acidity of cucumber fruit cv. Trópico during the spring season under two soilless culture systems (perlite (■); NFT (△)) as a function of days after transplant. Bars are ±S.D.
differences between crops. The interaction harvest date × crop (winter season) indicated a linear decrease in perlite-grown fruit and significant differences between perlite and NFT crops after the second harvest (Fig. 2).

3.4. Shelf-life quality attributes of perlite-grown fruit

Flesh color changes indicated loss of vivid light green (common in the flesh of this type of pickling cucumbers) and flesh whitening during the shelf-life of perlite-grown fruit. A sudden decrease in pH (concomitant with an increase in titratable acidity), and a linear decrease in soluble solids were also indices of shelf-life during post-harvest storage at 20 °C (see supplementary information). Flesh firmness or hardness or skin color did not show significant changes during 1 week of storage (data not shown). Senescence symptoms were slight shriveling and an abnormal increase in flesh firmness, as a result of dehydration after the first week of storage at 20 °C. Then the shelf-life of this cultivar is 6–7 days at 20 °C, and weight loss after this time was 1.7% plus an additional 0.24% loss per day after this time.

4. Discussion

4.1. Fruit quality

The pickling cucumbers grown under protection at the beginning of the winter (Fig. 2) did not always comply with the minimum requirements of fruit weight (250 g), as laid down by EEC, for cucumbers (Commission Regulation 1677/88). The progressive decrease in fruit weight during spring (Fig. 2) can be explained by a decrease in the dry matter content of the fruit that occurs during the spring season (Gómez et al., 2003a). This is a typical “sink limited” situation (Marcelis et al., 1998) because of the higher increase in the G parameter than in ST during the spring season (Fig. 1). The analysis of cucumber epidermal color measured by lightness and hue angle in different zones of the fruit (Figs. 1 and 3) revealed highly significant differences among harvest dates and, to a lesser extent, between crops. These color differences pointed to better fruit quality from the NFT system (Schouten et al., 2002). Fruit with flesh firmness above 50 N or with more than 65 mm equatorial diameter or 165 mm length are not usually considered to be of commercial quality for this cucumber cultivar (Figs. 2 and 3). An undesirable increase of cucumber fruit flesh firmness at the end of the spring season was also reported in this cultivar by Fernández-Trujillo et al. (2003) and in our shelf-life experiments (data not shown), and also during the fall season but not during the spring season in a perlite-grown culture (Jasso-Chaverria et al., 2005). Following the cucumber quality legal regulations in Spain (Regulation 1677/88), the fruit can be classified into the first category, although fruit of top extra quality can be harvested particularly in the middle of the season. Lightness and hue angle measured on the fruit epidermis were good quality indices for this cultivar, in agreement with results from long-type cultivars obtained by Gnanasekharan et al. (1992) and Schouten et al. (2002), because in cucumbers they can separate senescent from physiologically mature fruit. In fact, a dark-green and dull skin is the main quality factor for the market of this type of cucumber (Nunhem Seeds, personal communication).

According to weight and size as well as color, the length of the harvest season should be less than 3 weeks if best fruit quality is the goal, irrespective of the growing method used. The best quality (firm fruit with dark green skin color and acidity around 14 mmol H+ L−1) was obtained during the first 2 weeks of harvesting. From an economic point of view, it is difficult to ensure that higher cucumber quality in the winter crop growing in NFT systems can guarantee the grower’s income (the yield per plant was 40% lower in NFT systems and the average fruit weight was lower at the beginning of the winter season). However, if we compared the efficiency obtained in terms of yield for leaf area index in the two winter systems (perlite and NFT), we obtained similar values of efficiency. Nevertheless based on our finding and in the similar yield obtained during the spring season in both culture systems, the NFT system is preferable to perlite for obtaining the fruit quality, as measured by flesh firmness, and the dark-green and dull skin color of this cucumber type demanded by the market, particularly in fertirrigation control systems. Additionally, diseases or other problems were not found during cucumber growth in NFT systems and the slightly retarded growth indicated by G (Fig. 1) was not relevant, due to the similar levels of efficiency of both culture systems. The better color quality obtained in the NFT system may be associated with the increased average percentage of nitrogen (on a dry matter basis) in the NFT fruit (3%) compared with 2% in the perlite substrate (Gómez et al., 2003b), as well as with mineral uptake differences (particularly nitrogen, potassium, magnesium and calcium) between the two techniques used (Altunlu et al., 1999; Gómez et al., 2003b; Jasso-Chaverria et al., 2005). These results must be interpreted carefully because other cucumber types are longer and heavier than pickling cucumber grown for fresh consumption (Papadopoulos, 1994), and also the total cucumber production in Murcia greenhouses is around 80% lower than in Almería, the main area for cucumber production in Spain.

In our experiment, TA levels during the spring were lower in NFT-grown fruit than in the perlite crop (Fig. 5), and differences in TSS were negligible (data not shown). However, using perlite with or without recirculation of the nutritive solution, Fernández-Trujillo et al. (2003) found better pickling cucumber fruit quality during the winter than in the spring, and also a linear increase in TSS during the winter from 3.8° to 4.2° Brix (in 6 weeks), while the opposite trend was observed in spring (from 4.1° to 3.4° Brix in 5 weeks). These results indicate that the effect of nutrients on fruit quality may vary depending on the season and also on the soilless cultivation technique used. The higher pH values in winter indicated better fruit quality because pH rapidly decreases as a result of senescence according to shelf-life experiments in perlite-grown fruit (see supplementary information). Additionally, excessively high pH values (above 6.2) in the second harvest of the winter season may be a sign of extremely immature fruit
(Fig. 2) as a consequence of a transitory excess of nitrogen uptake (Altunlu et al., 1999) or too early a harvest date.

4.2. Climate conditions versus fruit quality

The strong effect of the season on cucumber fruit quality, irrespective of the hydroponic culture used was also found by Fernández-Trujillo et al. (2003). It is well known that radiation and temperature influence fruit growth and quality (Gruda, 2005), because of the well-known relationship with photosynthesis, transpiration and growth rate (Marcelis and Gijzen, 1998). In most plants, temperatures above 15 °C, as in this experiment during both seasons (Table 4), result in the growth of new organs. In this experiment, relative humidity was controlled within the greenhouse and temperatures did not fall below 14 °C, thus avoiding the risk of chilling injury (Zhou et al., 2004) (Table 4). So, in a non-stressed greenhouse culture without CO2 enrichment and with adequate RH controlled by ventilation, temperature and intercepted radiation are the only climatic variables that interact with the cucumber plant system (Gruda, 2005).

If the intercepted radiation is expressed as a function of the thermal time, the radiation can be weighed against the temperature effect, and this could be a good tool for predicting fruit quality. Therefore, we checked the usefulness of the G* parameter for quality assessment purposes. The gradual increase in G* (Fig. 1) was similar in the two consecutive seasons studied until the fifth harvest date in the spring crop (June 4th), when G* showed a tendency to slow down, owing to the established rate of plant growth (and so in LAI and indeed in Gint parameters) (Gómez et al., 2003a) and to the increase in the external temperature. The G* parameter exhibited a similar trend to lightness and an opposite pattern to hue angle (Fig. 1), the two main variables in fruit quality assessment. In fact, if fruit is free from dehydration and shrivelling, the dark green skin color is the main attribute to judge quality during the consumer’s purchase, particularly when fruit are marketed in plastic bags to avoid fruit dehydration. G* can, therefore, be used to discriminate optimum cucumber fruit quality when G* (in the fruit development stage) shows values near to 0.3 MJ m⁻² °C day⁻¹ interval⁻¹, while values above 0.4 MJ m⁻² °C day⁻¹ interval⁻¹ indicate medium to poor quality.

The differences in the slope obtained by fitting G* versus STh1 are explained by a 30% lower leaf area index (and consequently lower Gint) in NFT-winter culture compared with perlite culture (data not shown). However, although LAI was higher in NFT culture than in perlite in spring, the G* pattern and the G* versus STh1 functions obtained were similar. The explanation of this contradictory result is again the “sink limited” situation reported by Marcelis et al. (1998).

By substituting threshold G* by 0.4 in the linear regressions of G* versus STh1 (Eqs. (1)–(4)), we can obtain a STh1 prediction of the best fruit quality according to the season. The best fruit quality in the winter season could be obtained with STh1 = 300 and 700 °C day⁻¹ in perlite and NFT cultures, respectively; in the spring season these values could be 250 °C day⁻¹ in perlite and 125 °C day⁻¹ in NFT. The NFT winter crop could be extended far beyond the time used in this experiment, since the time predicted for optimum cucumber fruit quality during the winter (STh1 = 700 °C day⁻¹) exceeded the time when the NFT crop was uprooted (at STh1 = 400 °C day⁻¹), obviously this is an unrealistic situation. The reason for establishing these limits is the need to maintain equilibrium between the growth rate and photosynthesis in order to support optimum cucumber fruit quality. The intercept values of the linear regression equations G* versus STh1 indicated the differences in initial G* between seasons (lower during the winter crop), which may be directly proportional to fruit load. In fact, the winter yield was only 27–40% of the spring yield in perlite or NFT systems, respectively. In cucumber crops with G* values above 0.4 m⁻² °C day⁻¹ interval⁻¹, the fruit load rate clearly predominated over photosynthesis.

The differences of skin coloration between seasons can be explained in terms of the optimum temperature for chlorophyll degradation (around 28 °C) and the optimum temperature for carotenoid biosynthesis (around 18 °C) (Jiménez-Cuesta et al., 1983). During the spring, with higher temperatures and radiation than during the winter (Table 4), enhanced carotenoid biosynthesis and higher rates of chlorophyll degradation, probably, adversely affected epidermal color. During the winter, biochemical processes may have been more compensated. The differences in epidermal color between both seasons can also be observed from the flesh whitening during the spring season, a symptom of fruit senescence that must be avoided at least in this cultivar (Picture 1, supplementary information) and particularly in fruit destined for fresh-cut processing. Other reasons that may influence color development, such as low soil temperatures (below 12 °C) or night time temperatures falling below 12.8 °C (Grierson et al., 1986), were not observed inside the greenhouse (Tables 1 and 4).

5. Conclusions

Optimum quality of this cucumber type at least in terms of visual quality was achieved at around 3 weeks in both seasons. However, cucumber fruits grown during the winter had a darker and dull green skin color, and showed better quality than during the spring. The main differences between the winter and spring crops were the climate conditions, irrespective of the soilless culture used. A parameter that relates the intercept radiation and the thermal time in the time between anthesis and harvest, G*, has been defined and is proposed as a predictor of optimum fruit quality. In order to obtain the best cucumber quality under non-stressful conditions during fruit growth, the G* parameter must be below 0.4 MJ m⁻² °C day⁻¹ interval⁻¹, irrespective of the season considered. In the winter season, the G* parameter was sensitive enough to detect quality differences between both hydroponics systems, but not during the spring season. Although differences of cucumber fruit quality were mainly due to climate conditions, in the NFT system fruit quality was also improved with darker and dull green skin color (lower lightness and chroma). During the spring season, NFT culture offered fruit with lower acidity than perlite-grown fruit. This
result is explained in part by the about 1% higher nitrogen fruit uptake that occurs in NFT (Gómez et al., 2003b).

Acknowledgments

Financial support was partly provided by the National Spanish Project MCYT AGL2000-0450. Thanks are due to C. Sánchez, J. Obando and J.M. Mercader for technical assistance.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2006.06.021.

References