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Agronomical Response and Water Use Efficiency of Sweet Pepper Plants Grown in Different Greenhouse Substrates

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***Abstract*. An experiment was carried out to assess the influence of three types of substrate on the growth and yield of sweet pepper (*Capsicum annuum* L.). Plants were grown during three cycles (2005, 2006, and 2007) in coconut coir dust (CC), urea formaldehyde foam (UF), and rice hull (RH) amended with polyacrylamide gel (water absorber). Growth parameters, dry weight (DW) of vegetative and generative parts, intercepted radiation, water uptake, total fruit yield, and quality parameters were analyzed. Plant height, total leaf fresh weight, and stem diameter were higher in CC and lower for the RH substrate, which also showed lower yields and fruit quality. Accumulated dry matter was modeled according to water uptake and substrate using a linear function. Upper and lower limits in water use efficiency, between 2.5 and 5.7 g DW/L, are linked to the irrigation strategies and crop seasons. Light use efficiency (LUE) under different conditions was also determined to predict plant dry matter and a unique value was obtained for the three substrates (LUE = 0.91 g/MJ). Three different irrigation strategies were proposed for each substrate as a function of intercepted radiation and defining an α coefficient (expressed in mm/m^2/MJ) that coupled crop and climate components. These crop characterization and prediction tools could help to optimize plant growth and yield for environmentally friendly substrates.**

Soilless cultures involve plant growth on inert media in place of the natural soil to uncouple the performance of the crop from problems associated with the soil such as soilborne diseases, nonarable soil, and poor physical properties (Savvas, 2003).

However, crop management and recommendations of new substrates for soilless production are different (Papadopoulos, 1994). Furthermore, many of these new substrates often lack proper management. The cost, local variability, and experience of the substrate's performance are usually the factors determining the choice of a particular substrate type (Klougart, 1983). Several physical and chemical factors should also be taken into account when choosing a substrate medium (Cantliffe et al., 2001).

Many types of substrates are currently available for the greenhouse industry, but many of them produce an important quantity of residues at the end of their useful life. A major factor that might help to solve these pollution problems is the possibility of using different substrate materials, many locally available and less costly than imported ones with no pollution limitations but with adequate physical and chemical properties (Tzortzakis and Economakis, 2008). Coconut (*Cocos nucifera* L.) coir, the mesocarp of the fruit, is a waste product of the coconut industry. Worldwide, 12% of the hydroponic industry uses organic media as substrates and/or as composts (Donnan, 1998). Coir dust has a high waterholding capacity and traditionally has been used to improve the physical and chemicals properties of soils (Savithri and Khan, 1993). Rice hulls are available in large volumes as a waste product of the rice milling industry, and it is estimated that 34 million tons of fresh rice hulls are produced annually in the United States alone (Savita and Kamath, 1998). Synthetic gel-forming or superabsorbent polymers also have been used to aid plant establishment where soil properties inhibit water retention and/or aeration and, thereby, retard root development (Terry and Nelson, 1986). A synthetic substrate known as Hydrocell™ (Aqua Resins Technologies bv, The Netherlands) has a spongy form when foamed for application as a soilless substrate (Arbona et al., 2005). Thus, several studies showed different aspect about polyacrylamide application (Entry and Sojka, 2003).

In this 3-year study, we characterized three substrates for sweet pepper plants (*Capsicum annuum* L.). Our aims were 1) to establish the influence of these substrates on vegetative growth, yield, and fruit quality; 2) to characterize the irrigation management according to different irrigation strategies intended to minimize potential contamination; and 3) to model the crop response (biomass) according to environmental variables (such as intercepted radiation or thermal time) to define the best irrigation management practices at any stage of the crop cycle.

Materials and Methods

Plant material and growth conditions. Sweet pepper plants, cv. Cierva, were grown in polyethylene greenhouses; plants were transplanted on 12 May 2005 (Culture 5), on 14 Feb. 2006 (Culture 6), and on 28 Dec. 2006 (Culture 7) from a commercial nursery and grown in a commercial plastic greenhouse located at San Javier (Murcia, Spain). Plants were not pruned during the crop season and were irrigated with the following nutrient solution (which also had the appropriate concentrations of micronutrients; in mM): 12 NO_3^-, 1.5 $H_2PO_4^-$, 3 SO_4^{2-}, 7 K^+, 4.25 Ca^{2+}, and 2 Mg^{2+}. The source of water was obtained from the Tajo-Segura aqueduct. The treatments consisted of three types of soilless substrate: coconut coir dust (CC), rice hull mixed with 10 g polyacrylamide crystals per substrate bag (RH), to improve the water retention of the rice hulls, and urea formaldehyde foam (UF) consisting of aminoplast (plastic made from amino compounds). The urea aldehyde resin is inert and biodegradable; it is claimed that it break downs when exposed to ultraviolet rays from sunlight and it is considered harmless to the environment (Chan and Joyce, 2007). Three identical greenhouse compartments were used for this experiment with the same location and orientation. The compartment for each substrate had 24 rows with 22 bags separated 1.5 m. Each substrate bag had three plants with three self-compensating, $4\text{-L}\cdot\text{h}^{-1}$ drip emitters. Each plastic bag (≈40 L) was filled with the appropriate substrate.

Climatic measurements, water uptake, and water use efficiency. The greenhouse temperature was recorded by a ventilated psychrometer located at a height of 1.5 m in the middle of each greenhouse compartment. The dry and wet bulb temperatures were recorded continuously throughout the crop

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cycle. Air temperatures and solar radiation in each greenhouse were measured using thermocouples and a pyranometer (Campbell Scientific Inc., Logan, UT). The climate station was located in the middle of the greenhouse at a height of 1.5 m. Data were collected with a data logger (CR10X; Campbell Scientific, Inc.). The evolution and the values of these variables were similar in the 3 years of culture (T_{max}: 33.5 ± 1.5 °C; T_{min}: 14.7 ± 0.3; RH_{max}: 85.4 ± 1.7; RH_{min}: 19.3 ± 9.6; average inside solar radiation: 9.37 ± 1.4 MJ $m^{-2}\cdot d^{-1}$). The intercepted radiation was simulated in each plant harvested date by the relationship described in Monsi and Saeki (1953), which is based on Beer's law. So, the intercepted radiation was calculated as:

$$G_{\text{int}} = G_o\left[1 - e^{-k\,LAI}\right] \qquad (1)$$

where G_{int} = intercepted canopy radiation ($W\cdot m^{-2}$), G_o = incident canopy radiation ($W\cdot m^{-2}$), k = attenuation radiation coefficient (0.78; Heißner, 1997), and LAI = leaf area index, m^2_{leaf}/m^2_{floor}.

Water uptake, Q_w (m^3/pl), was calculated from the difference between water supply and drainage assuming that evaporation from the substrate surface was negligible. The water use efficiency (WUE, $g\cdot L^{-1}$) was calculated from the ratio of dry matter production to water uptake and an energetic WUE (mm/m^2/MJ) was also calculated as the ratio of water uptake to intercepted radiation.

The main strategy in substrate systems is to supply nutrient solutions through drip irrigation with a surplus of 30% to 40% of the water uptake of the plants to avoid nutrient imbalance and/or excessive salinity in the rhizosphere (del Amor et al., 2001). Irrigation applications were scheduled by means of the accumulated radiation within two irrigation frequencies (low = 3800 kJ/m^2 and high = 650 kJ/m^2); additionally, the daily control of the irrigation was also checked in selected drippers (for both irrigation uniformity and irrigation balance). To control drainage, two bags of substrate (six plants) were placed in trays to collect and measure the drained solution everyday. Three controls (inputs–outputs) for plant water uptake were placed for each substrate. To obtain and to characterize the response of these substrates, irrigation management varied each year with a maximal drainage limited to 40% (Table 1). The CC was selected as a control substrate for irrigation application (this substrate is used widely for pepper in this region and will provide a useful reference for farmers' advisors to elaborate the best environmental management guidelines). Thus, during the 2005 crop season, the same irrigation was applied: 2 $mm\cdot d^{-1}$ [0 to 75 d after transplanting (DAT)] to 4.22 $mm\cdot d^{-1}$ (75 to 117 DAT) for all substrates. In 2006, considering the different drainages obtained in the previous year, the irrigation application was increased for UF by 20% to 25% and for RH by 35%, compared with CC, especially at later crop stages (bigger plants): 7.1 $mm\cdot d^{-1}$ and 7.6 $mm\cdot d^{-1}$, respectively. Finally, in 2007, we reduced the irrigation. Briefly, in the first year, we compared substrates under the same irrigation strategy; in the second, we aimed to evaluate RH and UF at increased irrigation; and in the last year, we aimed to optimize the procedure through a reduction of the irrigation (Table 1).

Growth analysis. During the crop season, four plants per substrate were harvested (destructive analysis): at 75 and 117 DAT in the 2005 season; at 0, 30, 55, 84, 114, and 167 DAT in the 2006 season; and at 0, 119, 165, and 215 DAT in the 2007 season. At each harvest, the fresh (FW) and dry (DW) weights of the leaves and stems (including petioles) were measured. Dry weight was determined after at least 72 h at 80 °C. Total plant leaf area was measured with an LI-3100 (Li-COR Inc., Lincoln, NE).

Fruit yield and quality. Total fruit yield was determined, on a DW basis, from the three central rows of each compartment. Four blocks of six bags each were examined for total yield and quality (72 plants per substrate). Fruit harvesting was performed at the green stage of ripening. Marketable characteristics for California peppers were defined as: extra: uniform color, good health state, square shape and weight greater than 190 g; Class I: uniform color, good health state, nonsquare shape, and weight greater than 225 g; Class II: uniform color, good health state, nonsquare shape, and weight of 224 to 170 g; Class III: uniform color, good health state, nonsquare shape, and weight of 100 to 170 g; and nonmarketable: remaining rotten fruits, fruits with more than 20% of their surface having blossom-end rot (BER) or lighter than 100 g (del Amor, 2006). To analyze pericarp firmness and color, 20 fruits were harvested randomly for each substrate and season. Fruit color was determined with a Konica-Minolta CR-300 colorimeter (illuminant C; Japan) with three measurements along the equatorial perimeter. Firmness was determined on fruit with intact skin by using a Bertuzzi FT011 penetrometer (Fruit tester; Alfonsine, Italy) fitted with an 8-mm diameter probe. All data were analyzed for significant differences by one-way analysis of variance and Duncan's multiple range test at $P < 0.05$ using the STATGRAPHICS centurion Version 15 statistical package (stat point TECHNOLOGIES Inc., Warenton, VA).

Results and Discussion

The vegetative growth parameters had a similar pattern during the 3 years; thus, CC gave the greatest plant height, especially when compared with the RH substrate amended with polyacrylamide (Table 2). By contrast, the differences between CC and UF were not always significant over years. A similar tendency was observed for the stem diameter and the total leaf and stem fresh weights. Clearly, when compared with CC, under the more restricted irrigation supply in the last year (2007), RH significantly reduced plant height by 12.8%, stem diameter by 11.8%, total leaf FW by 20.8%, stem fresh weight by 27.5%, and leaf area index by 15.7%. Additionally, a reduction of the sum of intercepted radiation of 4.8% was observed. Under a Mediterranean climate, Prieto et al. (2007) obtained less leaf area in hydroponic culture (54% lower compared with our plants grown in CC). In similar cultivars and plant cultures, Assouline et al. (2006) obtained values of leaf area index (4.3 $m^2\cdot m^{-2}$) slightly higher than ours. Our data agree with those of Pinker et al. (2007), who found that plants on coconut dust were significantly taller and more vigorous, whereas Lee et al. (2000) reported reduced growth of pepper seedlings on substrates containing fresh hulls, which agrees with our findings. Thus, the physicochemical proprieties of the substrate could reduce plant growth, especially when the substrate has a low water-holding capacity and can alter root development under water stress conditions, reducing water potential in stems, leaves, and fruits.

Table 1. Volume of irrigation and percentage of drainage irrigation (% DR) at different days after transplanting (DAT) for the three crop seasons and substrates.

Season and substrate	% DR avg			Irrigation avg ($mm\cdot d^{-1}$)		
2005 (DAT)	0–75	75–117		0–75	75–117	
Coconut coir	30	22		2.00	4.22	
Urea formaldehyde	30	12		2.00	4.22	
Rice + polyacrylamide	30	29		2.00	4.22	
2006 (DAT)	55–84	84–114	114–167	55–84	84–114	114–167
Coconut coir	26	30	20	2.29	3.87	5.36
Urea formaldehyde	32	30	16	2.66	4.00	7.12
Rice + polyacrylamide	36	26	17	3.23	4.22	7.62
2007 (DAT)	0–119	119–165	165–215	0–119	119–165	165–215
Coconut coir	29	22	16	1.78	1.75	3.15
Urea formaldehyde	40	28	20	1.05	1.47	2.75
Rice + polyacrylamide	40	28	29	1.32	1.76	3.42

Accumulation of total plant dry matter (W, g/pl) as a function of accumulated water uptake (Qw, L/pl), at different plant harvests during the 2005, 2006, and 2007 seasons is shown in Figure 1A; this identifies the upper and lower limits of WUE (upper and lower lines). The water efficiencies for the plants grown on these substrates were between 2.7 and 5.0 g DW/L. Lower water efficiency was defined by the irrigation strategies imposed in 2005 and 2006, whereas higher efficiency was defined by the UF substrate during the 2007 crop season (irrigation limitation). Additionally, during 2006 (increased water application), UF and RH produced values

Table 2. Climatic and vegetative growth parameters of sweet pepper at the end of each crop season.^{z}

Season and substrate	Culture time (days)	Sum heat integral^{y} (°Cd)	Plant ht (cm)	Stem diam (mm)	Total leaf FW (g)	Stem FW (g)	Leaf area index ($\mathrm{m^2_{leaf}/m^2_{floor}}$)	Sum intercepted radiation ($\mathrm{MJ/m^2}$)
2005	117	1,807						
Coconut coir			124 b	18.0 b	378 c	532 c	3.0 b	962 c
Urea formaldehyde			128 b	15.4 a	337 b	456 b	2.9 b	937 b
Rice + polyacrylamide			111 a	15.1 a	224 a	345 a	2.2 a	840 a
2006	167	2,131						
Coconut coir			129 c	18.7 b	354 a	737 c	3.3 a	1,149 a
Urea formaldehyde			115 b	18.0 a	347 a	515 a	3.0 a	1,119 a
Rice + polyacrylamide			104 a	18.3 a	350 a	606 b	3.2 a	1,144 a
2007	215	2,314						
Coconut coir			148 b	21.2 b	470 b	699 b	3.8 b	1,351 b
Urea formaldehyde			125 a	22.5 b	551 c	712 b	3.7 b	1,343 b
Rice + polyacrylamide			129 a	18.7 a	380 a	507 a	3.2 a	1,286 a

^{z}Within columns and for each year, means followed by a different letter are significantly different at the 0.05 P level according to Duncan's multiple range test.

$^{y}T_b$ = 10 °C.

FW = fresh weight.

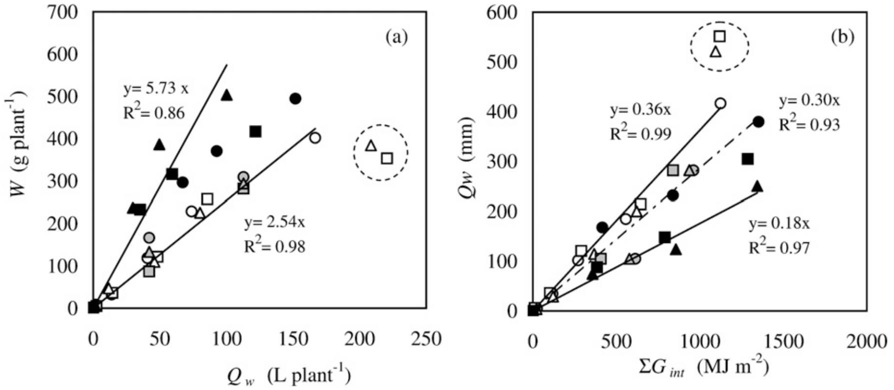

Fig. 1. (**A**) Accumulated dry matter, W, as a function of accumulated water absorption, Qw, and (**B**) accumulated Qw as a function of intercepted radiation, ΣG_{int}, along the 2005 cycle (gray symbols), 2006 cycle (open symbols) and 2007 cycle (closed symbols), in coconut coir (⊙), urea formaldehyde foam (Δ), and rice hull mixed with polyacrylamide (□). Upper and lower limits of water use efficiency and energetic water use efficiency (—), average CC energetic water use efficiency (-··-). Data outside efficiency limits (—).

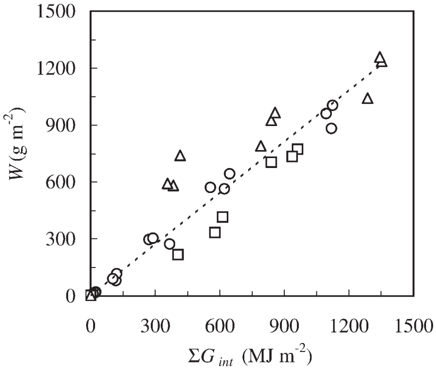

Fig. 2. Total plant dry matter, W, as a function of intercepted radiation ΣG_{int} in the three substrates in the 2005 (O), 2006 (□), and 2007 (Δ) growth cycles and light use efficiency, LUE (–), obtained from the fit of pooled data (W = 0.91 ΣG_{int}; r^2 = 0.94).

outside the efficiency limits (Fig. 1A). In 2007, W [accumulation of total plant dry matter (DM)] was higher on CC and UF than for plants grown on RH. Under a Mediterranean climate, González-Real et al. (2009) found for winter-season sweet pepper grown in perlite, lower shoot DM than our values (47% to 56%) for the 2007 season. Evans and Gachukia (2004) found higher W values when RHs were used for tomato. The variability observed for W was the result of the generative stage (the large fluctuations in plant fruit load). Sweet pepper is characterized by large fluctuations in fruit yield, even under constant climate conditions (Marcelis et al., 2006). Moreover, during the 2007 season, UF and RH gave significantly higher Qw values (Fig. 1B) as expected in this year as a result of the fertilization strategy (limited irrigation). Additionally, Qw was compared with the integral intercept radiation (ΣG_{int}, MJ/m^2) and a energetic water use efficiency was obtained (Fig. 1B); for this analysis, similar behavior was observed, including the same outside values for UF and RH. Moreover, a unique fitting was performed for the CC data in the 3 years, obtaining a high correlation coefficient (Fig. 1B).

The classic way to obtain the average light use efficiency (LUE, g/MJ) is by expressing the accumulated dry matter (W) as a function of the integral intercept radiation (ΣG_{int}) (Monteith, 1977), and the slope of the linear fitting (W versus G_{int}) is the average LUE. The slopes obtained, LUE, were 0.91 g/MJ (r^2 = 0.94; Fig. 2). Therefore, this provides a robust way to predict the aerial DM of the plant at any plant stage of the crop cycle. Our values of LUE are higher than those obtained by Prieto et al. (2007) (0.42 g/MJ) but similar to those of Dorais (2003) (1.0 g/MJ).

Plants that were grown on the CC substrate showed higher total marketable yield than those grown on RH (Fig. 3) during the 2006 and 2007 seasons, but not in 2005. Substrate studies show different "air-filled porosity"; thus, for CC, Lemaire et al. (1998) found values between 9% to 14%. In RHs, Evans and Gachukia (2004) found values ≈69%. In the aminoplast substrate, Welleman (2005) found values ≈30%. Therefore, according to these data, water availability for the plant is higher for the CC substrate; obtaining higher yields agreed with the studies of Costa-Dalla and Gianquinto (2002) and Dorji et al. (2005).

Although no differences were obtained between CC and RH or UF during 2005 on a DW basis, the total marketable yield (FW) was reduced by 29% and 16%, respectively, and similar reductions in FW, compared with DW, were obtained for the 2006 and 2007 seasons (data not shown). Because pepper plants are most sensitive to water stress during flowering and fruit development (Katerji et al., 1993), substrate like RHs, holding less water, can reduce yield and quality. Thus, the water deficit can significantly reduce fresh yield in terms of FW of fruit per plant. However, total dry mass of fruit per plant was similar to optimal water availability. This indicates that water movement into the fruit may have decreased with progressive development of water deficit without affecting the translocation of DM into the fruit (Dorji et al., 2005).

The use of RH instead of CC implied a reduction in total generative DW of 27.2% and 20.4% for the crop seasons 2006 and 2007, respectively. It is remarkable that, under an increased irrigation schedule (2006 season), total generative DW was reduced for the UF substrate; however, this application resulted in a reduction in the

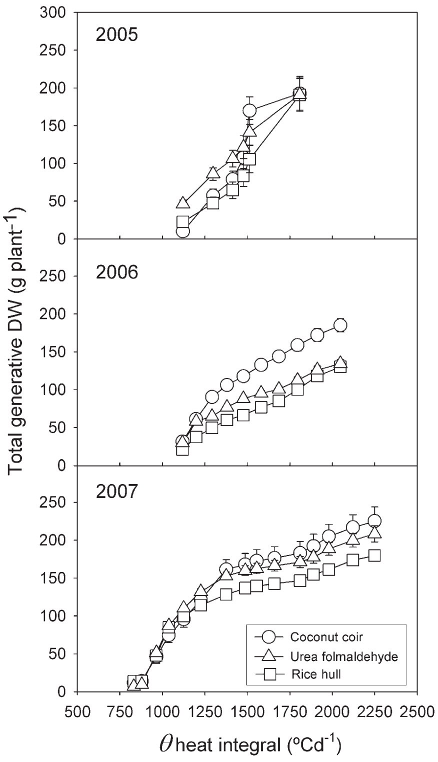

Fig. 3. Time course of total yield as a function of the thermal time ⊖ (T_b = 10 °C), in the three substrates: 2005 (**A**), 2006 (**B**), and 2007 (**C**).

Table 3. Fruit quality parameters of sweet pepper in the three growth years (2005, 2006, and 2007) and the three substrates (coconut coir, urea formaldehyde, and rice + polyacrylamide).[z]

		Color parameters		
Season and substrate	Pericarp firmness (N)	L	a	b
2005				
Coconut coir	39.49 b	51.9 a	4.5 a	30.6 a
Urea formaldehyde	29.23 a	51.9 a	3.5 a	30.4 a
Rice+ polyacrylamide	30.41 a	52.9 a	3.5 a	31.7 a
2006				
Coconut coir	32.47 a	41.13 a	4.5 a	20.18 a
Urea formaldehyde	37.47 b	59.47 c	5.5 a	28.51 a
Rice + polyacrylamide	30.80 a	50.94 b	7.0 b	29.87 a
2007				
Coconut coir	25.70 b	62.67 a	7.0 b	59.72 a
Urea formaldehyde	25.89 b	60.72 a	5.7 a	59.56 a
Rice + polyacrylamide	29.23 b	61.10 a	6.2 b	58.30 a

[z]Within columns and for each year, means followed by a different letter are significantly different at the 0.05 *P* level according to Duncan's multiple range test.

lowest drainage percentage (16%), mainly as a result of the very hygroscopic properties of this substrate. This behavior was completely different under the limited water application (2007) when a more effective response of total fruit yield was found for this substrate. Additionally, under water limitation (2007 season), with the same heat integral (2000 °Cd), total yield RH was similar (2006–2007 seasons), but UF showed higher yields, nearest to CC.

Higher percentages of fruit in the quality categories "extra" and "I" (Fig. 4) were clearly obtained for the plants that had been grown in the CC substrate with the exception of Year 2005, when no differences were found among substrates. In that year, the percentages of "extra" and "I" fruits were very low, which may be attributable to the relatively shorter crop season. The strategies of high irrigation (2006) and low irrigation (2007) did not affect the percentages of "extra" and "I" fruits, and both the UF and RH substrates showed a dramatic reduction in quality compared with CC. In general, fruit firmness and color were not influenced much by the type of substrate (Table 3), the differences for each substrate being of little relevance from an agronomical point of view.

It could be observed that there is a different pattern in the irrigation behavior of the different substrates (drainages/plant growth). So an irrigation strategy can be proposed, according to our data, and based on the mechanism that involves the plant water absorption in which the amounts of water applied can be defined as E (mm·d^{-1}):

$$E = \frac{E_u}{(1 - D)} \quad (2)$$

$$E_u = \alpha \, \Sigma G_{\text{int}} \quad (3)$$

where E_u = water uptake or evapotranspiration (mm·d^{-1}), α = coefficient in mm/m^2/MJ, ΣG_{int} = daily accumulated, intercepted radiation (MJ/m^2), and D = drainage rate. It is interesting to remark that the α coefficient incorporates the energetic and plant growth components in agreement with Baille et al. (2005) regarding the recommendations for crop–climate coupling in greenhouse irrigation management.

The irrigation strategies to be applied can be linked clearly to the substrate and a different α coefficient can be defined for each one. Thus, for CC and for the 3 years, we obtained α = 0.30 mm/m^2/MJ. For the UF substrate, we can clearly identify the year when we obtained higher WUE and yield (2007 season), giving α = 0.18 mm/m^2/MJ. For the RH substrate, as a result of important reductions in fruit yield and quality, an average value of α (0.27 mm/m^2/MJ) can be given for the 3-year period (0.22 to 0.32 mm/m^2/MJ). To improve the plant water available, in UF, preferable E must be defined with a low irrigation time and high frequency. Although the irrigation strategies for each substrate have been defined in 3 culture years, it could be interesting for a future validation in different latitudes.

Conclusions

Our results show that these substrates may be suitable for sweet pepper production; however, the RHs substrate should be used carefully in sweet pepper because our results indicate an important decrease in yield and fruit quality. The UF substrate resulted in a response that was intermediate between those of RH and CC, but with a correct irrigation strategy, UF can save important quantities of water and fertilizer. Clearly, CC was the substrate that gave the best sweet pepper performance with high yield and fruit quality.

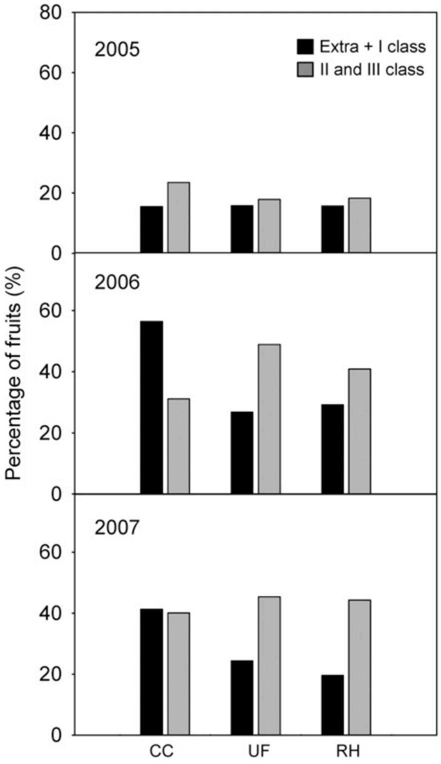

Fig. 4. Percentage marketable fruit qualities (extra and I, II, and III) of sweet pepper at the end of each season in the 3 growth years (2005, 2006, and 2007) and in the three substrates [coconut coir (CC), urea formaldehyde (UF), and rice hulls + polyacrylamide (RH)].

Further studies involving mixtures of RH with other substrates (increasing amounts of polyacrylamide could result in a very costly and nonprofitable solution) may allow the use of this substrate in areas where RHs are widely available at low cost.

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