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

Francisco M. del Amor
Instituto Murciano de Investigación y Desarrollo Agrario y Alimentario (IMIDA), Dpto. Calidad y Seguridad Alimentaria, C/Mayor, s/n. La Alberca, 30150 Murcia, Spain

Maria D. Gómez-López
Universidad Politécnica de Cartagena, Dpto. de Ingeniería de Alimentos y del Equipamiento Agrícola. Paseo Alfonso XIII, n° 48, 30203 Cartagena, Murcia

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/m²/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.

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 mmoles): 12 NO₃⁻, 1.5 H₂PO₄⁻, 3 SO₄²⁻, 7 K⁺, 4.25 Ca²⁺, and 2 Mg²⁺. 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), and urea formaldehyde foam (UF) consisting of amipnolast (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-L 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.
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°C; RH_{max}: 85.4 ± 1.7%; RH_{min}: 19.3 ± 9.6%, average inside solar radiation: 9.37 ± 1.4 MJ m^{-2} 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:

\[
G_{int} = G_0 [1 - e^{-k_{LAI}}]
\]

where \(G_{int}\) = intercepted canopy radiation (W·m^{-2}), \(G_0\) = incident canopy radiation (W·m^{-2}), \(k\) = attenuation radiation coefficient (0.78; Heißner, 1997), and \(LAI\) = leaf area index, m²/leaf/m²-floor.

Water uptake, \(Q_w\) (m³/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·L⁻¹) was calculated from the ratio of dry matter production to water uptake and an energetic WUE (mm/m²/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/m² and high = 650 KJ/m²); 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·d⁻¹ [0 to 75 d after transplanting (DAT)] to 4.22 mm·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·d⁻¹ and 7.6 mm·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).

**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 m²·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 properties 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.

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 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·d⁻¹) |
|----------------------|----------|-------------------------|
| **2005 (DAT)**       |          |                         |
| 0–75                 | 75–117   | 0–75 – 75–117           |
| Coconut coir         | 30       | 22                      |
| Urea formaldehyde    | 30       | 12                      |
| Rice + polyacrylamide| 30       | 29                      |
| **2006 (DAT)**       | 55–84    | 84–114                  |
| 114–167              | 55–84    | 84–114                  |
| 114–167              |          |                         |
| Coconut coir         | 26       | 30                      |
| Urea formaldehyde    | 32       | 30                      |
| Rice + polyacrylamide| 36       | 30                      |
| **2007 (DAT)**       | 0–119    | 119–165                 |
| 165–215              | 0–119    | 119–165                 |
| 165–215              |          |                         |
| Coconut coir         | 29       | 22                      |
| Urea formaldehyde    | 40       | 28                      |
| Rice + polyacrylamide| 40       | 28                      |

Table 1. Volume of irrigation and percentage of drainage irrigation (% DR) at different days after transplanting (DAT) for the three crop seasons and substrates.
Table 2. Climatic and vegetative growth parameters of sweet pepper at the end of each crop season.

| Season and substrate | Culture time (days) | Sum heat integralb (°Cd) | Plant ht (cm) | Stem diam (mm) | Total leaf FW (g) | Stem FW (g) | Leaf area index (m²/m²) | Sum intercepted radiation (MJ/m²) |
|----------------------|---------------------|--------------------------|---------------|---------------|------------------|-------------|------------------------|-----------------------------------|
| 2005                 |                     |                          |               |               |                  |             |                        |                                   |
| Coconut coir         | 117                 | 1,807                    | 124 b         | 18.0 b        | 378 c            | 532 c       | 3.0                    | 962 c                             |
| Urea formaldehyde    |                     |                          | 128 b         | 15.4 a        | 337 b            | 456 b       | 2.9                    | 937 b                             |
| Rice + polyacrylamide|                     |                          | 111 a         | 15.1 a        | 224 a            | 345 a       | 2.2                    | 840 a                             |
| 2006                 |                     |                          |               |               |                  |             |                        |                                   |
| Coconut coir         | 167                 | 2,131                    | 129 c         | 18.7 b        | 354 a            | 737 c       | 3.3                    | 1,149 a                           |
| Urea formaldehyde    |                     |                          | 115 b         | 18.0 a        | 347 a            | 515 a       | 3.0                    | 1,119 a                           |
| Rice + polyacrylamide|                     |                          | 104 a         | 18.3 a        | 350 a            | 606 b       | 3.2                    | 1,144 a                           |
| 2007                 |                     |                          |               |               |                  |             |                        |                                   |
| Coconut coir         | 215                 | 2,314                    | 148 b         | 21.2 b        | 470 b            | 699 b       | 3.8                    | 1,351 b                           |
| Urea formaldehyde    |                     |                          | 125 a         | 22.5 b        | 551 c            | 712 b       | 3.7                    | 1,343 b                           |
| Rice + polyacrylamide|                     |                          | 129 b         | 18.7 a        | 380 a            | 507 a       | 3.2                    | 1,286 a                           |

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

\(^{\text{a}}\)FW = fresh weight.

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The classic way to obtain the average light use efficiency (LUE, g/MJ) is by expressing the accumulated dry matter (W, g) as a function of intercepted radiation (ΣGint), along the 2005 cycle (gray symbols), 2006 cycle (open symbols) and 2007 cycle (closed symbols), in coconut coir (□), urea formaldehyde foam (△), 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. 1. (A) Accumulated dry matter, W, as a function of accumulated water absorption, Qw, and (B) accumulated Qw as a function of intercepted radiation, ΣGint, along the 2005 cycle (gray symbols), 2006 cycle (open symbols) and 2007 cycle (closed symbols), in coconut coir (□), urea formaldehyde foam (△), 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 (—).](image1)

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 more 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

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![Fig. 2. Total plant dry matter, W, as a function of intercepted radiation ΣGint in the three substrates in the 2005 (O), 2006 (■), and 2007 (△) growth cycles and light use efficiency, LUE (—), obtained from the fit of pooled data (W = 0.91 ΣGint; r² = 0.94).](image2)

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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 values between 9% to 14%. In RHs, porosity’; thus, for CC, Lemaire et al. (1998) demonstrated a unique fitting was performed obtaining higher yields agreed with the studies of Costa-Dalla and Gianquinto (2002) and Dorji et al. (2005).

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![Image](image3)
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 fruit yield and quality, an average value of ρ (0.27 mm/m²/J) can be given for the 3-year period (0.22 to 0.32 mm/m²/J). 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.

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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