EXPERIENCES IN CULTIVATION INSIDE THE WATERGY PROTOTYPE OF A CLOSED GREENHOUSE FOR SEMI-ARID REGIONS

Guillermo Zaragoza
Dolores Buendía
David Meca
Jerónimo Pérez Parra
Estación Experimental Fundación Cajamar
Autovía del Mediterráneo km. 419
El Ejido – Almería, 04710, Spain
gzaragoza@cajamar.com

Martin Buchholz
Technische Universitaet Berlin
Department of Building Technology and Design
Str. des 17 Juni 135
Berlin, 10623, Germany
martin.buchholz@tu-berlin.de

Keywords: closed greenhouse, greenhouse cooling, closed water cycle, carbon dioxide fertilization

Abstract

A prototype of a closed greenhouse has been constructed in the semi-arid region of El Ejido in Almería, Spain. It is a plastic greenhouse which minimizes the use of water and energy. This work presents the agronomical evaluation of the system during the first three years of operation, when several cycles of cropping have been performed in different seasons, all of them in a closed water cycle with the recovery of evapotranspiration and drainage, and with an enhanced concentration of CO_2 in the air (1000 p.p.m.). Production data are given for two autumn and two spring cycles of beans (*Phaseolus Vulgaris*), as well as for one summer cycle of okra (*Abelmoschus Esculentus*). The yield results, together with those of the productivity of water, are compared with the standards for the region and, in the case of one spring cycle of beans (cv "*Strike*"), with a similar crop grown simultaneously in an open greenhouse.

INTRODUCTION

Environmental and economical issues recommend a more sustainable greenhouse production. The diminishing water resources in the areas where the greenhouse market is rapidly expanding and the limitations in the use of fossil energy demand technical solutions to provide a more resource-efficient production. Closed greenhouses are commonly discussed as more efficient ways of using water and improving the productivity in horticulture.

The main advantages of a closed greenhouse can be summarized as: (i) a considerable reduction of the requirements of water for irrigation due to closing the water cycle with the recovery of the evapotranspiration from the plants and soil; (ii) an effective CO_2 enrichment of the air inside, increasing the photosynthetic activity of the plants and therefore the production; (iii) a total avoidance of pest treatments due to the non penetration of insects in the closed greenhouse, enhancing the quality and the value of the production.

These benefits, however, face a challenge as keeping an optimum climate inside the closed greenhouse requires a considerable use of energy. This is especially high in the case of semi-arid regions, precisely the most attractive for closed greenhouses due to the limited availability of water for agriculture. The concepts of closed greenhouses developed so far (Opdam et al., 2005) are based on conventional air conditioning equipments like ventilators and heat pumps, therefore requiring the use of fossil energy. The available technology so far is not feasible for its application in warm Mediterranean climates unless associated with a very large energy consumption.

The Watergy prototype of a closed greenhouse for semi-arid regions minimizes the use of energy other than solar, taking advantage of the natural buoyancy to establish the internal air circulation between the vegetation area and a heat exchanger, and avoiding the use of a heat pump with a passive cooling system. This system removes the heat from the greenhouse during the day and discharges it during the night using the colder air temperatures. The cooling process involves a condensation of the air humidity, acting as a means of water recovery inside the greenhouse. Therefore, it allows growing with minimum demands of water.

The prototype is designed to work continuously during the whole year, even in the hot conditions of the summer in Southern Spain. The horticultural concept of the project contemplates a constant cultivation inside the greenhouse, using the technique of inter-planting to alternate cycles of crops which guarantee a constant presence of developed plants acting as a source of evapotranspiration. Fast-growing plants with a high leaf area index like beans (*Phaseolus Vulgaris*) were chosen for the whole year, with the exception of the hot season. During the summer, the high ambient temperatures of the area, frequently above 30 ºC, make it unfeasible to keep the closed greenhouse in a thermal level below the tolerance limit of most horticultural species. However, photosynthetic C4 plants are more resistant to high temperatures and therefore have been contemplated as a summer crop for the prototype. Okra (*Abelmoschus Esculentus*), which has a rapid and leafy growth comparable to beans, was chosen.

The prototype is working since autumn 2004. A description of the performance of the system was presented by Buchholz et al. (2006), showing that air temperature and humidity in the closed greenhouse can be kept inside a range which guarantees continuous plant production without using external energy except solar. What follows is a summary of the cultivation experiences carried out inside the prototype, describing the different growing cycles on the different seasons, the species and cultivars involved, their production and their efficiency in the use of water.

EXPERIMENTAL PROCEDURES

Closed greenhouse

The prototype of closed greenhouse was constructed at the Experimental Station of Fundación Cajamar in the province of Almería, Spain. It is located in the area with the highest concentration of greenhouses in Europe. The closed greenhouse, made out of galvanized steel with a plastic cover following the standards of the area, has an innovative element designed to provide cooling strategies mainly based on solar energy. A cooling tower in the centre of the greenhouse uses the effect of natural buoyancy for moving the air from the crop area through the roof area into the tower which contains a heat exchanger (Buchholz, 2000). To increase the energy and water content of the rising air, it can be humidified in the roof area by sprinklers on an inner roof plastic layer. The heat exchanger acts as a coolant fed by a storage outside the greenhouse which is filled with water and uses the ambient temperature differences between day and night as its source of cooling. Through the cooling process, the humid air condenses and the evaporated water from irrigation and from the sprinklers can be recycled (Buchholz et al., 2005).

The prototype is designed to maximize water treatment, using all the heat to upgrade water. Therefore, the heat is stored during the day outside the greenhouse and released back to the greenhouse during the night by the same heat exchanger. During the process, the heat exchanger is humidified by a sprinkling which increases the heat release with additional evaporative cooling. This system acts as a further means of water treatment, as this nocturnal evaporation results in further condensation when the rising heated air is cooled on the inner cover of the roof.

Condensation takes place on the surface of the heat exchanger during the day but also on the inner cover of the greenhouse. Therefore, a good anti-drip material is required for an efficient recovery of the condensation and to avoid unwanted reduction of transparency by reflection from the drops of condensed water on the inner surface of the cover. Commercial anti-fog plastics (200 µm width) have been used in the prototype. All of them are three-layer combinations of polyethylene on the outside and ethylene vinyl acetate (EVA) with tenso-active additives on the inside. Between 75 and 80% of the irrigation water is recovered. This distilled water is reused for irrigation, therefore closing the water cycle inside the greenhouse (Zaragoza et al., 2007).

Agronomical evaluation

Several growing cycles have been performed in the prototype since its construction. In all of them, carbon dioxide has been supplied to the closed greenhouse by a standard commercial injection system. A high concentration of CO_2 (about 1000 p.p.m.) has been maintained constantly inside the closed greenhouse during daytime. This is meant to enhance the photosynthetic activity and also to increase the tolerance of the plants to high temperatures.

In addition, no use of pesticides has been required at any time, due to the non penetration of insects inside the prototype.

The productive surface is a standard sand-mulching soil of about 200 m^2, which acts as a whole lysimeter with full recovery of the drainage.

The different crops grown inside the closed greenhouse are described in the next section, together with an analysis of the yield results (see tables 1 and 2).

RESULTS AND DISCUSSION

The growing cycles have been grouped in four, according to the continuity in the performance of the system. A preliminary run of the closed greenhouse took place in autumn 2004. After finishing the installation of the measurement system, a second run started in 2005 and was finished at the end of the year when the greenhouse was opened to change the plastic cover. A third run started in February 2006 and had to be stopped at the end of the year to change the cover again, starting a fourth run in January 2007.

1st period (Autumn 2004)

A preliminary cultivation started in September 10th 04 with a French bean cultivar ("*Donna*"). A density of 2 plants/m^2, higher than the standard of the area, was chosen to provide a very high leaf area index (LAI) which guarantees high values of evapotranspiration. It was too much, in fact. Due to the large vegetative growth of the plants inside the CO_2-enriched closed greenhouse (full coverage with LAI>3 was reached in only 7 weeks), the density proved too large and lead to extremely high humidity conditions and, furthermore, excessive shadows in the north area. During this cycle, the relative humidity in the north side was generally above 90%. Despite this permanent near-saturation, no fungal diseases appeared, likely because of the total closure of the greenhouse. In the northern half of the greenhouse, the final production was 1.5 kg/m^2. In the south half, with more radiation and better humidity conditions, production was 3 kg/m^2, which is slightly larger than that of a standard open greenhouse in the area for that season. During this first cultivation no measurements of the condensation or the irrigation were available, as the system for constant monitoring of these parameters was not fully implemented.

2nd period (2005)

With the measuring system operating in full, another crop cycle started in March 4th 05 with French and bush beans in inter-planting. Although the vegetative growth was very lush and healthy, production failed because the flowers faded. This was due to a handicapped performance of the cooling system, even after whitening the greenhouse cover for further cooling. During the spring and summer of 2005 the night-time sprinkling which helps the heat de-loading at night was not included in the automation. Without the evaporative cooling caused by the latter, the heat release inside the thermal isolated tower is not enough to unload the heat storages and the availability of coolant for the following day was very limited. Therefore, unacceptable high peaks of temperature were reached during the flowering stage, jeopardizing the development of fruits. Figure 1 shows that the limiting temperature of 35ºC was surpassed too often during the flowering period in the spring of 2005.

Okra was introduced in June 05 gradually replacing the beans. The growing of okra during all summer was very healthy, with an impressively lush and fast vegetative growth. As more emphasis was put on acquiring experience in the agronomical management of okra inside the greenhouse, with continuous tests being performed, no production figures can be taken as representative from this first summer cycle.

After the summer, another cultivar of bush beans ("*Parker*") was sawn gradually replacing the okra. At this stage, the anti-dripping property of the plastic was completely gone and the transmission of light through the cover of the greenhouse was reduced 50%. Nevertheless, the production was about 2 kg/m^2, which falls on the upper range of the local growers' standards for that season. This optimum production despite the decrease of radiation input is very likely due to a compensating effect of the CO_2 enhancement increasing the photosynthetic efficiency. With a closed water cycle, the productivity of water for this crop was about 100 kg/m^3, which is 5 times greater than those usual of open greenhouses in the area for that crop and season (Orgaz et al., 2005).

3rd period (2006)

In the beginning of 2006, the plastic cover of the greenhouse was changed to a new anti-dripping one and a new growing cycle was started, alternating two different crops. First, bush beans ("*Strike*") were sawn on February 24th. Then, on March 9th the intermediate lines were filled with okra, sawing 6 different cultivars. "*Cajun Delight*", "*Red Burgundy*", "*Green Velvet*", "*Star of David*" and "*Clemson Spineless*" were compared with a non-identified cultivar of Asian origin. The production of "*Strike*" beans reached 1.2 kg/m^2 on June 1st, when the yield was stopped by an early heat wave, leaving a considerable amount of fruits on the plants not yet fully developed. In spite of this, the yield obtained is comparable with the optimal for local open greenhouses on that season. Productivity of water was estimated as 51 kg/m^3, considering a proportional distribution of the total drainage between the two crops. If all the drainage was assigned to the okra crop, the productivity of water for the beans crop would be 40 kg/m^3. Inversely, if all the drainage was assigned to the beans crop, the value would decrease to 54 kg/m^3. In any case, the productivity of water on this spring cycle for the beans was between 4 and 5 times larger than for an open greenhouse in the area during that season (Orgaz et al., 2005).

The yield of okra fruits, on the other hand, was constant during the summer and unaffected by the high temperatures. The most productive cultivar on the first stage was "*Cajun Delight*", although the quality production was larger for "*Red Burgundy*". "*Green Velvet*" also gave a high amount of top quality fruits on the first cycle (see table 2). A severe pruning was performed on July 16th, discontinuing the production until August 25th. The purpose was to analyze the regeneration capacity of the okra plants by comparing the production of the old plants with that of a new crop sawn on July 31st (replacing the beans). In this latter case, only three cultivars were sown, "*Cajun Delight*", "*Red Burgundy*" and the unidentified from Asia. The production of the new plants started on October 9th, and was better for "*Cajun Delight*" than for "*Red Burgundy*" during this season, in both cases much larger than the Asian cultivar. Furthermore, the total yield of the second period for the "*Cajun Delight*" and "*Red Burgundy*" cultivars exceeded that of the old plants after the pruning by 40% and 28% respectively. For the Asian cultivar, on the other hand, the yield of the old plants after the pruning was 41% larger than that of the new plants. Other cultivars proved to be more adapted to lower temperature conditions, as the "*Clemson Spineless*" and "*Star of David*" started giving significant yields only on the autumn season after the pruning.

4th period (2007)

Before starting a new cultivation, the plastic cover had to be changed again due to the short duration of the anti-drip effect. A new crop of bush beans ("*Strike*") was sown on January 25th 07 inside the closed greenhouse. This crop cycle was performed in parallel with another in an open greenhouse in the same experimental site. Both crops started their production at a similar time (8 weeks from seeding) but total yield was larger in the closed greenhouse (1.9 kg/m^2) than in the open greenhouse (1.4 kg/m^2). Another difference was that the larger vegetative growth associated with the enhanced CO_2 concentration of the air inside the closed greenhouse allowed the plants to regenerate and continue their flowering after the first yield period. Plants in the open greenhouse were removed totally exhausted after a 1-month old yield period on April 30th 07, which marks the end of the cycle considered. Nevertheless, inside the closed greenhouse the plants remained healthy for a longer time, regenerating and even starting a new productive period in mid-May, although it was not successfully yielded due to the high temperatures (see figure 2) holding up the fruit development.

The most remarkable differences between the open and the closed greenhouse are those of the productivity of water. In the open greenhouse the productivity was 13 kg of fruits per each m^3 of water consumed in irrigation. In the closed greenhouse, on the other hand, the productivity of water was 106 kg/m^3. That means an efficiency of the use of irrigation water about 10 times higher in the closed greenhouse for a comparable growing cycle in the open greenhouse.

CONCLUSIONS

A summary of the growing cycles carried out in the Watergy prototype of a closed greenhouse for semi-arid regions has been presented. It has been proved that a continuous cultivation can be performed, obtaining high value pesticide-free production during the whole year with minimum water consumption.

Beans have given yields larger or similar to the best obtained in open greenhouses of the area for the corresponding growing cycles. French beans ("*Donna*") suffered from excess humidity and shading, especially in the north, but nevertheless gave a high production in the south half of the greenhouse. Bush beans ("*Parker*") performed also very well during the autumn, despite a reduced light transmission of the plastic due to the short duration of its anti-drip properties. During the spring, bush beans ("*Strike*") gave yields larger than those of open greenhouses and with extended yield periods. The best results were obtained when sowing in late January (in year 2007), ending before May with a production that exceeded that of an open greenhouse by almost 40%.

The closure of the water cycle allowed a productivity of water much larger than that in the open greenhouses of the area. During the autumn cycle the figure for "*Parker*" beans was 100 kg/m^3, 5 times larger than the best in open greenhouses. During the spring, "*Strike*" beans gave a value 5 times larger in 2006 (51 kg/m^3), and 10 times larger in 2007 (106 kg/m^3), in this latter case comparing directly with a similar crop grown simultaneously in an open greenhouse.

During the hot season it was also possible to obtain horticultural production inside the prototype, using a photosynthetically C4 species like okra to gradually fill the gap between a spring and an autumn cycle of beans. Of the different cultivars analyzed, "*Red Burgundy*" has given the best quality production during the summer, with "*Cajun Delight*" and "*Green Velvet*" following. A severe pruning has been tested as a method for regenerating the plants in order to obtain a continuous production without waiting for a new seeding to grow. Production was slightly decreased, however. More investigations should be done for optimizing the pollination of okra inside a closed greenhouse in order to improve its production.

The results obtained are very satisfactory, and successfully support the goals of the Watergy project of developing a closed greenhouse which operates in semi-arid climates. The agronomical design of the project has been validated for a continuous production inside the closed greenhouse, though further work should be carried out with other species in order to extend the possibilities of the prototype. In order to improve the agronomical performance inside the closed greenhouse, the contribution of physiologists is much desired. Wide knowledge exists about the behaviour of plants in open greenhouses, both for temperate and arid climates, and the best cultivars have been selected for each case, with suited management. However, not so many studies have focused on the growth of horticultural species inside closed environments, especially with the climatic characteristics of the Watergy prototype (high humidity but also high temperature and enhanced CO_2 concentration).

Literature cited

Buchholz, M. 2000. Climate control in greenhouses and solid state fermentation systems as a source of water and energy. Proceedings of the World Renewable Energy Congress VI, Renewables – The Energy for the 21st Century, Brighton, 1-7/7/2000, Ed: Sayigh, A.A.M., Kidlington, Oxford.

Buchholz, M., Jochum, P., Zaragoza, G. and Pérez-Parra, J. 2005. Concept for water, heat and food supply from a closed greenhouse – The Watergy project. *Acta Horticulturae* 691, 509-516.

Buchholz, M., Buchholz, R., Jochum, P., Zaragoza, G. and Pérez-Parra, J. 2006. Temperature and Humidity Control in the Watergy Greenhouse. *Acta Horticulturae*. 719, 401-408.

Buendía D., Zaragoza, G. Gázquez J.C., Pérez-Parra, J. 2007. Resultados del cultivo en diferentes estaciones dentro del invernadero cerrado Watergy. Proceedings of XI Congreso Nacional de Ciencias Hortícolas – Agriculturas Minoritarias, Albacete 24-27/4/2007, Ed: SECH, Madrid.

Opdam, J.J.G, Schoonderbeek, G.G., Heller, E.M.B., de Gelder , A. 2005. Closed Greenhouse: a Starting Point for Sustainable Entrepreneurship in Horticulture. *Acta Horticulturae* 691, 517-524.

Orgaz, F., Fernández, M.D., Bonachela, S., Gallardo, M., Federes, E. 2005. Evapotranspiration of horticultural crops in an unheated plastic greenhouse. *Agricultural Water Management*. 72(2), 81-96.

Zaragoza, G., Buchholz, M., Jochum, P., Pérez-Parra, J. 2007. Watergy Project: Towards a rational use of water in greenhouse agriculture and sustainable architecture. *Desalination* 211, 296-303.

Tables

Table 1. Production of beans (*Phaseolus Vulgaris*) inside the prototype in each cycle. Total fruit yield is indicated, together with the value of the productivity of water (PW), expressed as kg of fruits per m^3 of water consumed.

Crop cycle (from seeding to cutting)	Cultivar	Production	PW
10 Sep 04 – 7 Dec 04	"*Donna*"	north: 1.5 kg/m^2 south: 3 kg/m^2	(not accounted)
30 Sep 05 – 23 Jan 06	"*Parker*"	2 kg/m^2	100 kg/m^3
24 Feb 06 – 1 Jun 06	"*Strike*"	1.2 kg/m^2	51 kg/m^3 *(40 - 54 kg/m^3)* (*)
25 Jan 07 – 30 April 07	"*Strike*"	1.9 kg/m^2	106 kg/m^3

(*) during this *interplanting* with okra the drainage has been split between the two species according to their development; nevertheless extreme values of PW are indicated, for the cases of assigning the whole or nothing of the total drainage to the bean crop.

Table 2. Production of each cultivar of okra (*Abelmoschus Esculentus*) evaluated in the different crop cycles, together with the percentage of first category fruits obtained for each one (from Buendía et al., 2007).

Crop Cycle	Cultivar	Production	1st category
9/03/06 - 16/07/06 (first seeding)	"*Cajun Delight*"	0.9 kg/m^2	45%
	"*Red Burgundy*"	0.7 kg/m^2	82%
	"*Green Velvet*"	0.5 kg/m^2	63%
	"*Star of David*"	0.3 kg/m^2	80%
	"*Clemson Spineless*"	0.1 kg/m^2	40%
	unidentified *(Asian)*	0.2 kg/m^2	11%
25/08/06(*) - 11/12/06 (continuation of first seeding)	"*Cajun Delight*"	1.7 kg/m^2	78%
	"*Red Burgundy*"	1.8 kg/m^2	75%
	"*Green Velvet*"	1.0 kg/m^2	52%
	"*Star of David*"	1.0 kg/m^2	70%
	"*Clemson Spineless*"	1.5 kg/m^2	57%
	unidentified *(Asian)*	1.7 kg/m^2	61%
31/07/06 - 11/12/06 (new seeding)	"*Cajun Delight*"	2.4 kg/m^2	82%
	"*Red Burgundy*"	2.3 kg/m^2	74%
	unidentified *(Asian)*	1.0 kg/m^2	63%

(*) since it is a continuation of the crop after severe pruning for regeneration, the start of the new yield period is indicated.

Figures

Figure 1. Comparison of the temperatures inside the closed greenhouse during spring-time for three different years. For each day, bars represent the percentage of the daytime that the temperature inside the greenhouse is above 35 ºC, while the line indicates the average difference (ºC on the right Y axis) between the diurnal temperature inside the closed greenhouse and outside. Shading marks in each case the periods when the greenhouse was whitened for cooling (light reduction about 40%).