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MODELING OF GREENHOUSE STRUCTURE AND CHARACTERISTICS FOR AN IDEAL ECONOMIC STRUCTURE FOR GROWING VEGETABLES, FLOWERS OR FRUIT CROPS

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Abstract: The greenhouse is an agrosystem that presents important productive advantages in comparison with non-protected agriculture. Countries with bad environmental conditions (e.g. Holland and North Europe) need greenhouses with a high insolation capacity (glass cover) and with controlled climate conditions and lighting (high investments in equipments). Mediterranean countries, with a much higher brightness and a more favourable climatology, have, maybe, overlooked the environmental control of the greenhouse (plastic covers, many thermic losses and bad ventilation), so punishing the productivity, but decreasing drastically the operating investments. In the plastic cover's greenhouses, which are little efficient, there is an important margin to improve the quality and productivity of the agrosystem. We have focused our work on the study of the importance that the modelling of the greenhouses structures bas in the general productivity of the agrosystem, with no necessity of high investments. We emphasize in our work what characteristics have to bc demanded to make a good design to accomplish the functionality conditions that may have any greenhouse:

1. Capacity to modify the microclimates of the agrarian space that is delimited by its structure, to improve the crop efficiency.
2. Dynamie resistance to bear the crop weights, wind strength and other meteorologic phenomena that may affect them externally, and
3. Versatility to adapt itself to different crops (in harmony with the seasonal planification of the farmer), or to the addition of the new technologies to improve the global productivity of the system.

In conclusion, we show the structure that we have evaluated, after two years of measurements, as the most interesting from the productive point of view, with reasonable costs for the Mediterranean farmers of the southernest countries and we propose it as an alternative for the current structures, which are much less efficient.

INTRODUCTION

The most important difference that may be established between glasshouses (Durch type) and plastic-covered greenhouses is their construction cost. However, closely related to investment, there are also the consequences with respect to productivity: the greenhouse agrosystem presents important productive advantages with respect to non-protected cultivation. Generally, the better the system of protection and artificiality is, the higher are usually crop yields. For this reason, productivity achieved in glasshouses will never be obtained in plastic-covered greenhouses.

Originally, the greenhouse was simply a heat trap that tried to maximize caught radiation and minimize heat losses; although later the greenhouse became an integral system of forced production which includes crop protection (against external atmospheric agents, insects and pests) and optimization of resources (such as water availability in order to avoid high evapotranspiration, and gaseous fertilization with CO_2 which allows to force natural production) aimed at obtaining an environment that permits control under the most desirable technical conditions.

In areas with mild weather conditions, and particularly in the regions with Mediterranean climate, protection under plastic cover is the most advisable greenhouse option, mainly in view of its adaptability to the growers' economic possibilities, but also due to thermic crop needs being less than in Central and North European countries with cold climate. The permanent need of increasing productivity in free-market-economy systems obliges growers to introduce technological improvements in their production systems to continue being competitive and with regard to the prospects for the future. Consequently, it becomes necessary to look for new modalities of technological innovation that, being acceptable in cost, may be of benefit to the growers making their farms more profitable. This is the reason for which we have undertaken the research work we are presenting to this ***"Mediterranean Colloquium on Protected Cultivation".***

EVOLUTION OF THE UNHEATED GREENHOUSE IN THE MEDITERRANEAN REGIONS:

After the II World War, the industrialized European countries of cold climate (Holland, Belgium, Germany, Denmark or Great Britain) started to build glass-covered greenhouses, while Japan followed a similar way but using predominantly plastic cover. Proliferation of unheated greenhouses (with plastic cover) in the Mediterranean Basin began in the sixties, got established in the seventies, and became definitely generalised in the eighties.

The structures of the first unheated greenhouses were very rudimentary, and only acted as heat traps used to increase temperature during the crop-growing period, producing earlier crops. Fruit precocity meant better income, as higher prices were achieved on the markets due to less competition because of the absence of products grown in normal cycles.

As unheated greenhouses became more popular, the offer extended the normal period of market supply, so that the comparative advantage of the first greenhouses started to disappear. To maintain the profitability of the greenhouses, it was necessary now to incorporate new elements to increase productivity and profits of the farms. These new elements (structures, plastics, fertirrigation, modification of the atmosphere by CO_2 addition, control of temperature and relative humidity, etc.) are the result of technological innovation and deepening of agricultural knowledge.

The original unheated greenhouses are getting more and more similar to the Durch-type glasshouses. As more investment is made in technology, greenhouse yields are generally increasing, but it is necessary not to lose the perspective of the reason of the plastic covered greenhouse. The limits of this approximation (between glasshouses and plastic-covered greenhouses) will be established in terms of two parameters:

a) cost , the upper limit of which should be established with reference to the glasshouse, although once an approximation to the cost of this kind of typology is taking place, the interest in plastic covered greenhouses will decrease.

b) productivity, the lower limit of which should be adopted with reference to the productivity in field cropping, but it should not descend to the point that marginal profitability produced by the incorporation of a new technological element is lower than the one obtained by equal crop growing without this element.

VARIABLES TO BE CONSIDERED IN TECHNOLOGICAL IMPROVEMENT OF UNHEATED GREENHOUSES:

Radiation, which provides the necessary energy to generate vegetal matter in presence of chlorophyll, heat (linked to radiation and other climatic and physical factors), **water** as vital plant sustenance, which constitutes an essential element present in a high percentage in the plant tissue, and **fertilizers**, which may be organic or inorganic (in solid, liquid or gaseous state), are the basic variables that participate in crop elaboration. The fertilizer group may be regarded as a multivariable factor involving a great number of nutrient elements that might be considered as real, more or less interdependent variables.

Besides the aforementioned variables biotic and abiotic agents, external to the needs of the growing process, are involved and act as parasitic degraders of this process: they are what we know as **pests or diseases**, which are combated by means of plant health techniques.

The greenhouse agrosystem increases or reduces the performance of each one (factors or variables) in relation to their natural horizon, as shown in Figure 1. While global radiation and PAR (Photosynthetically Active Radiation), the spectrum of which perceptively coincides with the one of visible light (between 400 and 700 nm for PAR and 380 to 760 nm for visible light), theoretically decrease inside the greenhouse because there is a barrier (the greenhouse cover) which absorbs or rejects certain energy, heat, however, is higher inside of the greenhouse, where there is no diffusing effect of the wind and where the diathermic characteristics of the cover materials (glass or plastic film) act as a heat trap, as they do not allow radiation of short wave length, i.e. soil-reflected radiation, to go across. On the other hand, while water use is more efficient inside the greenhouse, because evaporation and evapotranspiration are limited due to air circulation being considerably reduced in a closed environment, gaseous fertilization with CO_2 is very limited as plant consumption is not compensated for by an additional CO_2 supply from the outside atmosphere, which means penalization of plant growth and crop production. Finally, while the healthiness of the crop should improve due to dust suspension in the air being reduced, athmospheric phenomena which are harmful for the plants being avoided, and entry of insects being hindered, on the other hand, the high temperatures and relative humidity are an excellent medium of cultivation for pathogen germs that succeed in getting into the greenhouse, thus favouring the development of diseases caused by bacteria, virus, fungi, etc.

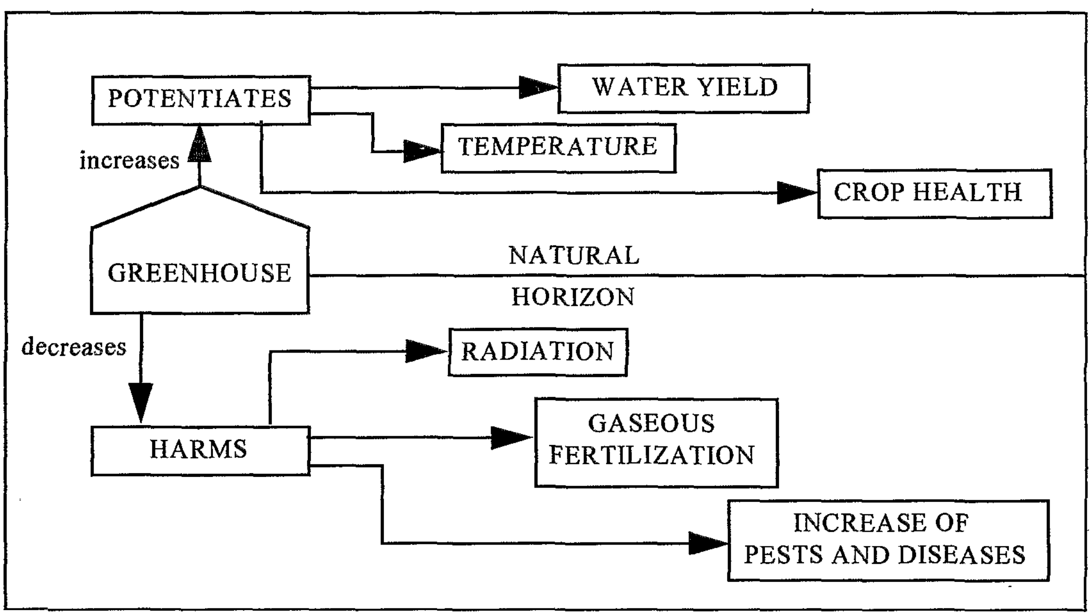


Figure 1. Effects of the greenhouse agrosystem on crop variables

This means, in the proportion we are potentiating favourable variables and hindering negative variables, we shall be improving productive crop yields. In view of the fact that the closed environment of the greenhouse permits a certain control of these variables, without excessive costs of the necessary modifications, we may consider it feasible to introduce in the greenhouse agrosystem technological improvements that will benefit crop production, by modifying the variables in the most favorable way for plant growth and fruit quality, which could not be done easily in an open environment.

IMPORTANCE OF GREENHOUSE STRUCTURE AS MODIFIER OF PRODUCTIVE VARIABLES:

Each one of the variables that influence the process of agricultural production may be subject to change and modifications for the purpose of obtaining the most favourable values for crop interests. Intervention of variables can be carried out in different ways: for example, heating is used to achieve higher temperatures; special lamps are employed to increase the light that favours photosynthesis or radiation energy; by means of addition of CO_2 a more favorable atmosphere is obtained for vegetative development; application of insecticides and other chemical products reduces the impact of pests and diseases.

However, these measures are usually very expensive and therefore the competitivity of the products on the market decreases. Optimum productivity of the system does not always compensate for the rise in productive cost. The economy of the growers of the Mediterranean countries is not as powerful as in the case of growers from more industrialized countries, so that they cannot afford to pay the expenses which are necessary to modify the variables by direct actions, such as the aforementioned ones.

The agricultural researcher has the obligation of looking for alternatives that, improving the tendencies of the variables in the sense that most favours the crops, do not suppose excessively high investment.

In various previous experiments we have observed that greenhouse structures are an important factor that conditions the variables which influence production. For this reason, acting on these structures would be an efficient and more economical way to change these variables in a positive sense.

Measures taken with regard to the greenhouse should have the following objectives:

1. Increase the value of variables which are negatively affected as a consequence of the existence of the greenhouse (light, radiation and levels of CO_2 in the atmosphere)

2. Optimize the variables that have been reforced by the existence of the greenhouse (temperature, relative humidity, and plant health).

Knowledge of Physics and the information obtained from the measurements carried out on the experimental plots committed to the care of our team in Almeria (latitude: 36° 50'N), have allowed us to establish the following relationships between the structures and the variables of most importance for crop production in greenhouses.

1. **Light,** which is of primary importance for plant growth, will improve as structural obstacles hindering the transmission of sunlight are reduced and light catching surfaces are enhanced. For this reason, a good structure should have the following characteristics:

a) Larger proportion of cover surfaces (including the surface of the greenhouse walls) in relation to the ground surface occupied by the greenhouse. This underlines the importance of :

- *high greenhouses* (walls of 3.5 m up to 6.0 m are recommended) as they favour light conditions without excessively increasing the dynamic risk with regard to the wind (depending on the situation of the greenhouse and the speed reached by the strongest gusts of wind generally registered), or

- The interest in *roof orientation and geometry* (E-W orientation and asymmetry of slopes, with a larger catching surface in the south-oriented slope) because the closer the angle of incidence of the rays of sunlight gets to perpendicularity the more radiation and light will be available inside the greenhouse. Curved surfaces always offer a line of perpendicularity to sunbeams.

b) Substantial reduction of opaque components of the structure, be that pillars, framework, gutters or wires. The less the iron weight (or the weight of alternative materials as wood and aluminium) per m^2 of covered extension is, the smaller will be the surface of elements hindering light catching. On the other hand, as the big greenhouse-covered surfaces are usually built in multispan version, luminosity will be enhanced by increasing span width (always taking into account the limits established by the dynamic resistance of the greenhouse, which would not permit construction of excessively wide spans).

c) Reduction, or elimination, of non-structural opaque components as there are heating pipes, thermic screens or shading nets which are generally hung up on the structure. At the same time, inside luminosity may be enhanced by soil reflection (covering the soil with a white plastic sheet) or reflection from pillars or components of the structure (painting them in white colour).

d) Use of cover materials that are very transparent to the spectrum of visible light and, especially, to radiation comprised within the range from 600 to 700 nm (the light red one) which is the most efficient radiation for the development of photomorphogenesis. As we are concerned with plastic-covered greenhouses, we should use those types of plastic material offered on the market that best suit our needs. The plastic films with best transparency for PAR transmission are PF (polyfluoride), PVC (polyvinyl chloride, EVA (ethylene vinyl acetate) and PE (polyethylene) which has the same transparency as glass.

2. **Temperature**, which may be a limiting factor for productivity, both due to excess or lack, should be controlled starting from the structure in order to offer the most favourable effect for the grower's interests at any given moment: In winter full performance of the thermic trap has to be achieved so that the temperature inside the greenhouse is notably higher than outside, and sufficient to satisfy plant needs; on the contrary, during the period in which air temperature is high enough, it should be tried to minimize the greenhouse effect and make the temperature decrease, if possible below the outside temperature, in case the latter is too high. A structure which pretends to bring about such performance, should get near the following characteristics:

a) It should favour the penetration of solar radiation, for which purpose it has to comply with the aforesaid requirements. Great part of the radiation caught by the greenhouse (both ultra-violet and visible and, especially, infrared radiation) is degraded into calorific energy which heats the atmosphere of the greenhouse, the cultivated soil and the plant itself. This energy also brings about vaporization of the water emitted by the plants or provided by crop irrigation.

b) It should reduce thermic losses, for which reason the greenhouse has to be as airtight as possible, without holes and uncontrolled openings, so that it may be isolated from the exterior when the temperature of the atmosphere is too low. This condition of being hermetically closed will also avoid rainwater to enter into the greenhouse. Both its transparency for solar radiation (of short wave length) and opacity for infrared radiation (emitted by the soil and the plants inside the greenhouse), depend on the kind of cover material, i.e. the plastic used, which therefore should be chosen among those which best comply with the agronomic requirements.

c) A powerful ventilation system which allows renewal of the hot air, by convection, for which zenithal and lateral openings are required to establish draughts. The structure should allow controlled opening for ventilation in order to graduate the air volume to be renewed and to modify the temperature according to physiological crop needs.

d) Utilization of complementary systems integrated into the structural greenhouse ensemble, such as double walls and inflated roofs (both of which improve thermic insulation although they are detrimental as far as transparency for incoming radiation is concerned), thermic screens (to maintain the heat) or shading nets (to lower temperatures), air cooling and fogging systems, which obtain notably lower temperatures by means of incorporated water vaporization, establishing at the same time a ventilating system.

3. **Water**, which is of primary importance in the regions with arid climate, both due to the shortage or bad water quality (high salinity) in this type of climates, which makes water a limiting factor, and the transcendental importance of the same in plant physiology, due to the fact that it represents more than seventy-five percent of plant tissue composition, as all biochemical reactions are produced in an aqueous medium and, moreover, because it is an essential basic material for transformation of luminous energy into chemical energy which organizes the vital system of the plants. The plant takes the water it needs from the soil (through its roots) or from the air (through its leaves and aerial tissues). In view of the fact that in the greenhouses there is no more soil water than the water provided by irrigation, and the water contained in the air proceeds from plant transpiration, it becomes necessary to regulate these supplies so that the conditions for plant growth are the most appropriate ones for each crop. In order to be able to control plant water demand and consumption, we have to know the water balances of the soil and of the greenhouse atmosphere and, therefore, the structures have to meet the following requirements:

a) Water-tightness, which avoids uncontrolled inflow of water during rainy days (which would saturate the humidity of the greenhouse atmosphere and of the soil, and require singular actions in each case to eliminate it); on the other hand, it reduces water losses by evaporation while the ventilation windows remain closed. Water-tightness will be all the more necessary, the more differences exist between the atmospheric conditions outside the greenhouse and the suitable ones for the crop.

b) Efficient ventilation to eliminate excessive humidity when necessary. Proper zenithal windows together with low lateral windows, to facilitate convection, are characteristic of an adequate structure.

c) Plastic cover material which does not permit the formation of condensation drops ("anti-drip plastic") to avoid inside dripping on the plant which has ominous effects with regard to diseases.

d) Availability of structural complements, such as heating, fogging and cooling devices, which allow a better control of relative air humidity inside the greenhouse.

4. **CO_2**, which is the essential component of gaseous fertilization as it is an indispensable basic material for photosynthesis. It penetrates into the plant through the stomata and moves towards the chloroplasts of the plant cells, making plant growth possible in concentrations ranging from 100 to 2,000 ppm (parts per million) in volume, or otherwise expressed, from 0.2 to 4.0 g per m^3 of air. During its respiration, the plant produces CO_2 but at a rate which is lower than its consumption during photosynthesis. Therefore, in the closed atmosphere of the greenhouse, an oscillation, in volume, is produced, which ranges from 100 ppm (at noon) to 450-500 ppm (at dawn). In the atmosphere of the exterior, mean concentration is fairly stable, lightly oscillating around 350 ppm, which would be sufficient for a "normal" plant growth, although for yield improvement twice this

concentration or even higher amounts (up to five times the normal concentration) are necessary and, therefore, an additional source of CO_2 has to be provided for the crop.

The most suitable greenhouse structure for improvement of gaseous fertilization will be the one which combines the following conditions:

a) Air-tightness to allow control of the CO_2 volume in the greenhouse atmosphere raising it above the concentration of this gas in the exterior, which will make it possible to obtain a significant increase of productivity. This implies addition of complementary doses of CO_2 either insufflating carbonic gas into the greenhouse or by means of the gases emitted by the "humus" of organic soil fertilization (which is less productive but constitutes a good method to follow in case the grower's possibilities to invest are very limited).

b) Efficient ventilation which allows to maintain the concentrations of carbonic gas during daytime at the level of the exterior atmosphere. This is of special interest in the hot seasons as, at the same time, it permits cooling of the greenhouse.

5. **Protection of plant health** may be improved without the necessity of fighting pests and diseases with chemicals. The improvement of greenhouse structures acts as preventive therapy. The following characteristics of a greenhouse have a positive effect with regard to crop health protection:

a) Adequate water-tightness to avoid water inflow, which favours the appearance of diseases produced by fungi, or to establish an effective barrier against the entry of insects which act as vectors of bacteria or virus propagation.

b) Efficient ventilation to maintain temperature and relative humidity in tune with crop requirements, avoiding the existence of unhealthy conditions which favour multiplication of crop parasites.

Our working hypothesis established that **determined actions on the structures could significatively improve variable behaviour**, which means that we are able to influence crop quality and productivity through improvement of the structural properties of the greenhouses.

ANALYSIS OF THE RESULTS OBTAINED IN OUR EMPIRICAL STUDY ON DIFFERENT STRUCTURES OF UNHEATED GREENHOUSES

In our experimental work we have proved the importance of greenhouse geometry with regard to radiation catching, both if we refer to "global" radiation or focus in a more specific way on PAR. We have measured the mean global radiation values of four greenhouse typologies, more advanced in evolution than the conventional one ("parral" type) of the province of Almeria, and we have found significant differences between them, which prove the efficiency of an adequate structure in lighting and energetic yield of the greenhouse. All compared units were multispan greenhouses, with two or three spans, crop surfaces ranged between 600 and 1800 m^2, and their typologies were as follows:

a) "Symmetric" greenhouse, with two north-south oriented naves, a covered surface of 22.5 x 26 m, equivalent to 586 m^2. Pillars were 2.5 m high, the maximum roof height being 4.5 m above soil surface and the minimum height 3.3 m. Its structure was metallic, though the cover was not rigid, the plastic film being fastened by means of a classical wiring system of the "parral" type. (Type I in Figure 2, similar to the *Canarian type* or the type called "*Raspa*" in Almeria).

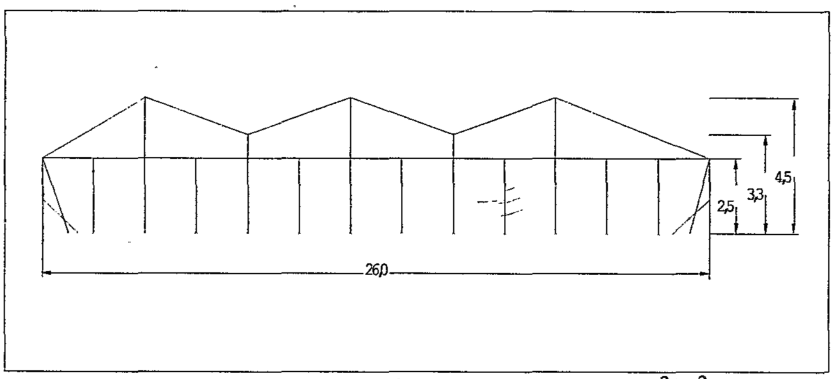
b) Module with curved roof, supported by an inverted wire catenary (as shown in the drawing of type II in Figure 2), which we call "Invernave". Pillars were 2.5 m high and the maximum height was 4.25 m. The greenhouse was formed by three 14.4 m wide and 40 m long naves covering a total extension of 1.728 m^2.

c) Asymmetric greenhouse, with two naves, each one of 11.25 m width, east-west orientation, covering a total area of 1.126 m^2. Pillar height of 3.0 m, the maximum roof height being 4.5 m. It had a metallic structure and a plastic cover, the plastic film being fastened by means of a classic wiring system of the "parral" type. (Type III in Figure 2).

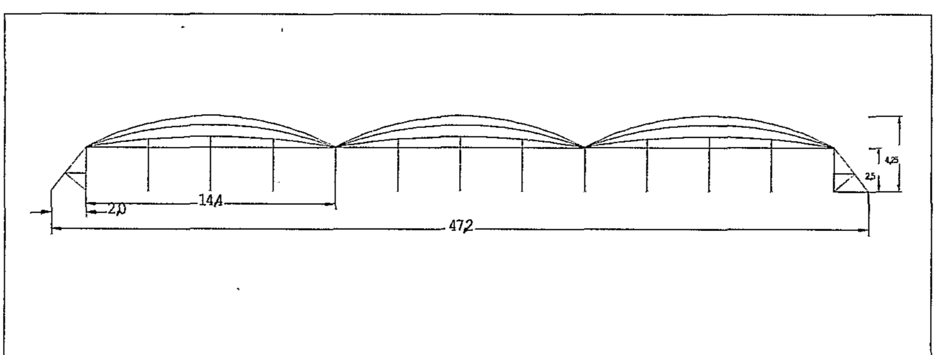
d) Curved symmetric greenhouse, of the tunnel type, with only one nave of 8,4 m width, east-west orientation, 50 m length and covered surface of 420 m^2. Pillar height of 3.0 m, the maximum height being 4.0 m. Metallic structure and plastic cover, the plastic film being fastened by means of a system of "omegas" which form part of the proper structure (Type IV in Figure 2).

e) Curved asymmetric greenhouse, named INAMED, with three 7.5 m wide and 42.5 m long naves, east-west orientation. The total covered surface amounts to 956 m^2, pillars are 3.0 m high, the maximum height being 4.6 m. It had a metallic structure and plastic cover, the plastic film being fastened by means of a system of "omegas" forming part of the structure as such (Type V in Figure 2). This greenhouse was not put into operation until 1996 and its construction was due to the results obtained by the evaluation and control of previously existing greenhouses.

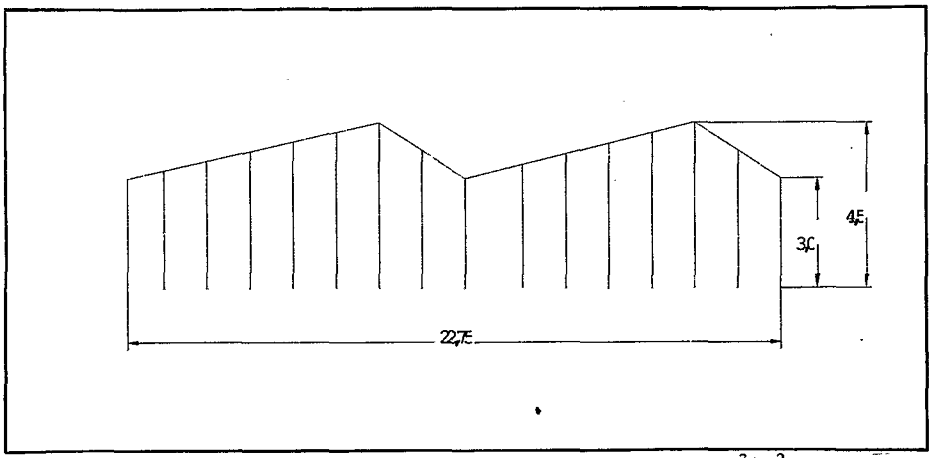
In the first place we made an evaluation of the physical variables of major agronomic interest in each of the different greenhouse typologies that exist on the market. Afterwards we would set up the chart of recommendations on which the new norms of design are to be based in order to improve the plastic-covered greenhouses to be offered on the market in the future. The results have been the following:



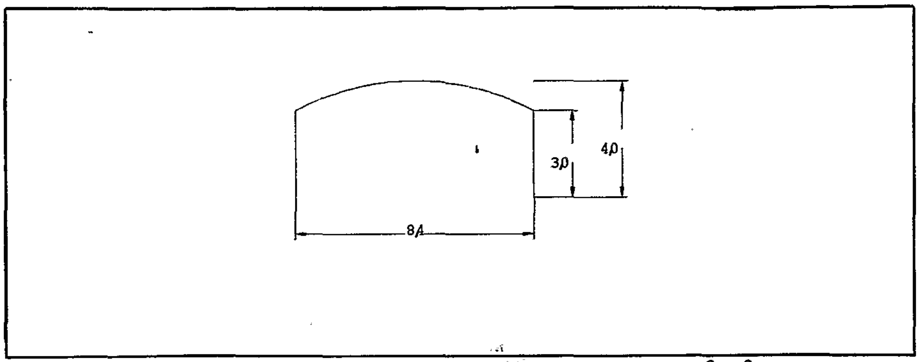
TYPE I: "Raspa" greenhouse. Volume: 3,525 m^3/m^2



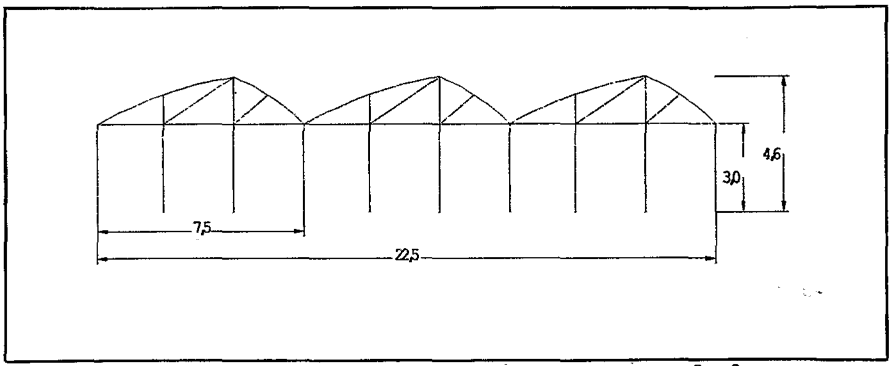
TYPE II: Invernave greenhouse. Volume: 3,191 m^3/m^2



TYPE III: Asymmetric greenhouse. Volume: 3,749 m^3/m^2



TYPE IV: Tunnel greenhouse. Volume: 3,676 m^3/m^2



TYPE V: Inamed greenhouse. Volume: 3,964 m^3/m^2

Figure 2. Typologies and format of the analyzed greenhouses

BEHAVIOUR WITH REGARD TO RADIATION

We started from the assumption that incident radiation outside the greenhouse is superior to the radiation that passes through its cover and enters into the greenhouse. The most suitable structure would be the one that permits transmission of the largest possible proportion of radiation. It would even be better if, during the summer months when there is an excess of incident radiation, its opacity would be greater than during the winter months.

The data for 1995 indicate that mean Global Radiation outside the greenhouse ranged from 1.99 $Kw.h/m^2$.day in December to 7.23 in July, while inside the greenhouses it oscillated between 60 and 73% of the incident radiation, as shown in Table 1.

Table 1. Global Radiation Values

Months	Outside Radiation (e) Kw.h/m^2.day	Greenhouse Type I (*)	Greenhouse Type II (*)	Greenhouse Type III (*)	Greenhouse Type IV (*)
January	2.95	64.1	62.4	60.3	(**)
February	3.54	61.3	63.8	64.4	(**)
March	4.65	68.2	69.7	69.5	(**)
April	6.13	72.3	72.8	70.3	(**)
May	7.10	65.6	58.7	60.8	(**)
June	7.23	63.5	57.0	62.0	(**)
July	7.30	64.7	38.4	67.0	71.0
August	6.61	64.3	45.5	62.5	67.0
September	5.37	62.9	67.6	63.3	68.0
October	3.84	69.5	68.2	64.1	69.0
November	2.67	65.7	67.0	61.4	73.0
December	1.99	(**)	66.8	63.3	(**)
Annual mean	4.96	65.6	61.5	64.1	(**)

(*) Percentage of the radiation measured outside the greenhouse (e).
(**) Without valid values, due to errors of the measuring sensors.

Generally it may be observed that there are few differences in transparency efficiency for Global Radiation between the different structures. Nevertheless, type II, which is a prototype developed by our collaborators, is hardly somewhat more efficient during the cold months (2%), but much more opaque during the hot months (17% less transparent from May to September). Separate consideration should be given to greenhouse Type IV that had problems derived from the electrical feeding system and, therefore, we had to neglect too many data. Nevertheless, we inferred that the curved roof without a wire network for plastic fastening is much more transparent than in the rest of the analyzed greenhouses.

The acquired experience allowed us to construct another greenhouse, which we called INAMED (curved asymmetric Mediterranean type greenhouse, which constitutes Type V of the analyzed greenhouses), and which has proved more efficient than the previous ones according to the data presented in Table 2. Its capacity of catching Global Radiation is 4% higher than in case of the most efficient of the previously analyzed greenhouses; but where it becomes even much more interesting is with reference to PAR (the radiation of most interest from the agronomic point of view), where very high differences have been reached (Table 3).

Table 2. Global Radiation absorbed during the first four months of 1.996 in each one of the analyzed greenhouse typologies

Months	Outside Radiation (e) Kw.h/m^2.day	Greenhouse Type I (*)	Greenhouse Type II (*)	Greenhouse Type III (*)	Greenhouse Type V (*)
January	2.29	76.0	66.8	72.5	75.1
February	3.58	67.6	69.3	73.7	75.7
March	4.71	76.2	74.3	68.8	75.6
April	5.86	70.8	72.5	73.4	76.1
Mean value of the four months	4.11	72.6	70.7	72.1	75,6

(*)Percentage of the radiation measured outside the greenhouse (e).

From the values of this Table and, especially, from the ones of the following Table, it may be seen that just by modifying the structures substantial improvement of greenhouse yields may be achieved.

Table 3. PAR registered inside the greenhouses during the first four months of 1996

Months	Outside Radiation (e) Kw.h/m^2.day	Greenhouse Type I (*)	Greenhouse Type II (*)	Greenhouse Type III (*)	Greenhouse Type V (*)
January	0.70	61.4	67.1	84.3	98.6
February	1.07	54.2	67.3	84.1	93.5
March	1.39	69.1	77.0	84.9	99.3
April	1.71	74.8	82.5	85.4	99.4
Mean value of the four months	1.22	64.9	73.5	84.7	97,7

(*) Percentage of the radiation measured outside the greenhouse (e).

BEHAVIOUR WITH REGARD TO THE TEMPERATURE

Initially we presumed that there should be an important correlation between global radiation, PAR, temperature and relative humidity. For this reason we have calculated the correlation between these variables, in three different periods of the year, obtaining the values shown in Table 4:

Table 4. Correlation between the main physical variables which define the microclimate of the analyzed plastic greenhouses

Variables	Global Rad.	PAR	Humidity	Temperature
Global Rad.	1			
PAR	0.974	1		
Humidity	-0.948	-0.98	1	
Temperature	0.961	0.979	-0.961	1

We may therefore say that the global radiation caught by the greenhouses accounts, by itself, for more than 94.8% of PAR, 92.3% of temperature values and 90% of relative humidity. However, while PAR and temperature are directly related, relative humidity follows an inverse correlation. The ranking to be established for the analyzed greenhouses as far as temperatures are concerned would confer the utmost interest to greenhouse Type V, followed by types I, III and II. Type IV presumably would occupy the second place, but we lack reliable data throughout the whole year to enable us to sustain such an affirmation.

Obviously, the value of the temperatures also depends on the degree of greenhouse insulation with reference to the external environment. The ideal situation would be to minimize heat losses during the cold months and to manage to dissipate the greatest amount possible of heat to the exterior during the hot months. **This may be achieved with a structure that permits water-tightness but also possesses an efficient ventilation system that may be regulated at will by the grower.** Mean values during winter months indicate daily average thermic gains which range from 1 to 3°C, being the most efficient greenhouse type V and the coldest one type III. We understand that in the thermic aspect there is still room for substantial gains, although for the conditions of the climate of Almeria any of the greenhouse types is valid because the average value of daily minimum temperatures never has been lower than 12°C.

INFLUENCE OF THE STRUCTURE ON WATER CONSUMPTION

Evaluation of this aspect turned out to be much more complicated than in case of the aforementioned variables because, although water consumption depends on the temperature at which the crop is grown, it also depends on crop density, plant volume per m^2, rate of gas exchange and, of course, on the kind and typology of the crop. In order to avoid the complications deriving from a multifactorial study which tries to identify the relative influence of each variable, we have conducted an empirical study, defined in the system described below, which has proved the following:

1. In order to be able to establish reliable comparison, it is necessary to grow on substrates (soilless cultures), because when growing on soil there are considerable variations, even inside the same greenhouse. In the trial we used coconut fibre as substrate, placed in a polyexpan container, although we also made comparisons with rockwool, which was less efficient. We further conducted a trial with recirculating solution on arlite and on water sheet.

2. Drip irrigation is the most advisable system for greenhouse crop growing, being a method that allows a more homogeneous water distribution (if the system is correctly calibrated). We used two drippers per container or slab (in the case of rockwool) with a discharge rate of 2.5 l/hour. Irrigation was applied automatically by means of a control device for irrigation at demand. Recirculation of the irrigation water was employed in two experimental plots with no specially interesting results from the agronomic point of view, though the experiment was interesting in the environmental aspect.

3. Depending on the crop, certain structures are more efficient in water use. Structures of type IV and type II are more efficient than the ones of type I and type III, for tomato crops. On the other hand, for cucumber, type II and type I are more economical than type III and type IV.

4. The analyzed cycle corresponds to a winter crop, with duration from 24 September to 30 April, for tomato; while the crop cycle studied for cucumber lasted from 24 September to 7 February.

Water consumption and cost efficiency data are presented in Table 5 (tomato) and 6 (cucumber)..

In the case of tomato, it may be observed that the structure of type IV is significantly more efficient in water use, because it saves up to 30% of the water consumed to produce one kilo of commercial fruit, in comparison with the structure of type III which proves to be the less efficient one, probably due to its better ventilation.

Table 5. Influence of the greenhouse structures on water cost efficiency in tomato crops

Greenhouse type	Substrate	Litres of water/ m^2 crop area	Litres of water/ plant	Litres of water/ kg of commercial fruit
Type I	Coconut fibre	444.0	267.0	43.1
Type II	Coconut fibre	439.0	179.0	38.2
Type II	Water sheet	408.0	246.0	41.6
Type III	Coconut fibre	509.5	306.9	46.3
Type III	Rockwool	523.5	315.4	50.3
Type IV	Coconut fibre	431.9	260.2	34.6

Table 6. Influence of the greenhouse structures on water cost efficiency in cucumber crops

Greenhouse type	Substrate	Litres of water/ m^2 crop area	Litres of water/ plant	Litres of water/ kg of commercial fruit
Type I	Coconut fibre	210.0	168.0	26.9
Type II	Coconut fibre	197.0	158.0	21.9
Type II	Arlita	223.0	179.0	24.2
Type III	Coconut fibre	255.3	205.0	29.7
Type III	Rockwool	225.7	181.3	28.6

With reference to cucumber (which has not been grown in greenhouse structure type IV), the ranking according to efficiency is the same as for tomato, the most interesting structure being type II, followed by type I and type III. In any case, productivity per litre of water used in greenhouse irrigation is around 50% higher than in field cropping and, consequently, **the greenhouse is the most adequate formula for horticultural crop and ornamental plant growing in areas of arid climate, which is the case of the whole region of the Mediterranean Basin.**

ECONOMIC INTEREST OF GREENHOUSE MODELATION: PRODUCTIVE YIELDS OF THE DIFFERENT ANALYZED STRUCTURES

Using the computer as a tool to establish models of greenhouse behaviour with reference to radiation, light , temperature, water consumption, or total agricultural production of the farm, is of enormous economic interest because it allows us to define the best plastic-covered greenhouse model (without the necessity of constructing it previously) for the environmental conditions required by a determined crop, or crop family, in a region of a determined climate.

The models will help to establish the best greenhouse structure for each considered variable. However, in view of the close correlation existing between radiation and the other variables we may affirm, in a first approximation, that:

1. The best structure is the one which offers better transmissivity for radiation, which will influence caught PAR, temperatures reached inside the greenhouse and control of excessively high levels of relative humidity.

2. Other variables as the capacity of aeration or ventilation of the greenhouse also define a good structure, although they have not yet been studied in detail in our model. We may say that a good ventilation improves:

- CO_2 enrichment of the atmosphere inside the greenhouse, which will increase productivity,
- sanitary conditions inside the greenhouse, which means a reduction of expenses for phytosanitary products and an increase of the proportion of commercial fruits.

3. A good structure must be able to resist the dynamic force of the winds blowing in the area where the greenhouse is situated, and also crop load, fastened by strings to the structure for better plant growth and guidance.

From the production data of the experimental plots, shown in Table 7, we may obtain statistical inference, as there is a close correlation between global radiation measured inside the greenhouses and productivity per plant.

Table 7. Productivity of each one of the greenhouse structures in relation to global radiation, in a winter crop of tomato (Dec.-April)

Greenhouse typology	Used G.R.. (% of Re)	Relative cost of each structure	kg of product per ha	% of D referred to the less productive structure	kg of fertilizers applied per ha.
Type I	72.6	100	103,000	5.1	7,731.7
Type II	70.7	182	98,000	0.0	7,774.1
Type III	72.1	147	110,000	12.2	9,439.1
Type IV	73.5	162	125,000	27.5	7,853.5
Type V	75.6	131	137,000 (*)	39.8	?

(*) Expected production. It corresponds to an extrapolation of the observed tendency, in accordance with the linear regression established between global radiation (G.R.) and production (correlation coefficient 0.86) in the other analyzed greenhouses. The regression line would be represented by the function $y = -502.9 + 8.47 x$ (where y is the production and x is the global radiation measured inside the greenhouse).

It may be observed that used radiation has a greater effect on the amount of produced commercial fruit than the quantity of fertilizers supplied to the crop, which is related to water consumption. In any case, we have to point out that so far no reliable data are available on the agronomic yields of greenhouse type V and that, therefore, the indicated data are the result of calculating the regression in respect of radiation.

The differences in productivity detected between the different structures are really significant if we distinguish between:

a) greenhouses with metallic structure, water-tight, and with zenithal ventilation

b) greenhouses of the "parral" type, with a wiring net to support the plastic cover, which has many openings to the exterior,

c) the surfaces of curved roofs which offer a better perpendicularity to solar rays.

Finally, we have to point out that a very interesting aspect is the profitability of each structure, which, after all, conditions the grower's decision when building a greenhouse. Types V and I would be the most profitable ones, in terms of the initial cost; but greenhouses like type IV may be fully justified from the economic point of view because, with the prices reached by tomato in winter, the difference of the higher cost of type IV compared to type I, would be paid off after only two seasons.

If we analyze the structures from the point of view of their productivity when dedicated to cucumber growing, we obtain the data presented in Table 8.

Table 8. Productivity of each one of the greenhouse structures in relation to global radiation, in a winter crop of cucumber (Nov.-Feb.)

Greenhouse typology	Mean temp. during the growing period (°C)	Relative cost of each structure	kg of product per ha	% of D referred to the less productive structure	kg of fertilizers applied per ha.
Type I	17.6	100	78,000	0.0	4,551.8
Type II	18.6	182	90,000	15.4	4,274.1
Type III	17.4	147	86,000	10.3	5,543.5
Type IV	18.9	162	91,000 (*)	16.7	?
Type V	19.2	131	92,800 (*)	19.0	?

(*) Expected production. It corresponds to an extrapolation of the observed tendency, in accordance with the linear regression established between mean temperature inside the greenhouse and production (correlation coefficient 0.66) in the other analyzed greenhouses. The low correlation indicates that there are other factors which have not been taken into account.

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In any case, under this hypothesis of crop growing, productive advantages of more than 15 % may still be expected, which would justify a selection of a greenhouse structure of better quality than the ones of general use at present in the most arid areas of the Mediterranean regions (Almeria or North African and Canarian type).