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Automation and control of greenhouse implemented technologies: a review

Automatización y control de tecnologías implementadas en invernaderos: una revisión

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RESUMEN

Protected agriculture is a way of producing food by creating a microclimate that allows protecting a crop from the risks inherent in free exposure; in this sense, its purpose is to guarantee the optimal and appropriate conditions of internal variables to generate reproduction, development and growth of plants with quality and commercial opportunity. In this way, the application of technologies to crops has extended considerably due to the need to optimize this productive alternative: in this respect, there are multiple scattered investigations based on particular designs of elements such as greenhouses. Therefore, this article shows a review on protected agriculture aimed at the automation of greenhouses in countries that have implemented emerging technologies in this field and the consequent control generated in the stages of the production cycle through sensors, actuators, specific covers or robots designed to perform tasks such as spraying or harvesting, among others. Key analysis elements are presented on the modeling of the phenomenon that underlies the implementations, so that systems with the necessary adaptation are achieved for any crop, taking into account its type, cost and location, defining a baseline on the technologies that make it functional and efficient.

ABSTRACT:

La agricultura protegida es una manera de producir alimentos creando un microclima que permite proteger un cultivo de los riesgos propios de la libre exposición; en este sentido, tiene como finalidad garantizar las condiciones óptimas y apropiadas de variables internas para generar la reproducción, desarrollo y crecimiento de plantas con calidad y oportunidad comercial. De esta manera, la aplicación de tecnologías a cultivos se ha extendido considerablemente por la necesidad de optimizar esta alternativa productiva: al respecto se encuentran múltiples investigaciones dispersas basadas en diseños particulares de elementos como los invernaderos. Por lo anterior, el presente artículo muestra una revisión sobre agricultura protegida orientada a la automatización de invernaderos en los países que han realizado implementaciones de tecnologías emergentes en este campo y el consecuente control generado en las etapas del ciclo productivo a través de sensores, actuadores, cubiertas específicas o robots diseñados para realizar tareas tales como fumigación o cosechado, entre otras. Se presentan elementos de análisis clave sobre el modelamiento del fenómeno que subyace a las implementaciones, de manera que se logren sistemas con la adaptación necesaria para cualquier cultivo teniendo en cuenta su tipo, costo y ubicación, definiendo una línea de base sobre las tecnologías que lo hacen funcional y eficiente.

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1. Introduction

The increase in population and climate change have generated, as never before, the need to find sustainable solutions to rationally conserve natural resources -especially water resources- as well as to produce food efficiently and effectively; all in order to use raw materials in a controlled manner, develop production systems that are not exclusively extractive, and moderate individual and collective consumption.

In the case of food production, the objective is to guarantee it throughout the year and increase it without the need to use more space than required, avoiding raising fixed, variable or operational costs. For this reason, research has been devoted to the study of so-called protected agriculture or controlled environment agriculture (CEA) [1]. This way of producing establishes an advantage over the traditional method of open-air crops: it creates a barrier between the crop to be protected and the outside environment; that is, it creates a microclimate that allows the crop to be protected from the risks inherent to free exposure production, such as damage caused by rain, wind, frost, pests or animals that can harm it. Therefore, protected agriculture aims to ensure optimal and appropriate conditions of internal variables such as radiation, temperature, humidity, carbon dioxide, among others, to generate reproduction, development and growth of plants by increasing production in quantity, quality and commercial opportunity [2], [3], [4].

Of the above, the element that is qualitatively the most important in this production system is the greenhouse. In addition to housing the plants, fruits and air conditioning devices, depending on the type of crop and its reproduction demands according to the climate forecast in the region of interest, its construction requires determining the cost of electricity to operate it, so that power generation from alternative sources is a viable and less expensive option, as evidenced by the cases in which biomass is used [5], [6].

On the other hand, research on greenhouses -or closed and controlled production systems- has generally considered energy optimization and robotics, as well as information and communication technologies [7], [8], [9]; which indicates that, as technology advances, relevant innovations will continue to be incorporated to produce, without restrictions, all types of crops.

In this sense, there is a great deal of documented research on the development and implementation of greenhouses, despite the fact that the amount of land dedicated to this type of cultivation in the world is close to one million hectares [10]. Of these, nearly 700,000 are located in Japan, which is the country with the most hectares dedicated to greenhouses, followed by Spain, Italy, the United States, Mexico and Colombia [11].
To have an indicator of the impact of greenhouse implementation, for example: incorporating sensor and ventilation systems for the climatic conditions of some regions in Mexico, increased the efficiency and yield of a tomato crop of up to 13 kg/m2; after using automatic climate control and irrigation systems, yields of up to 40 kg/m2 were obtained. For the implementation of this same system in the Netherlands some crops obtained up to 78 kg/m2 [12], [13].

However, due to the difference in technological appropriations, knowledge and studies developed in the engineering area focused on protected agricultural systems according to situated characteristics, Latin American countries need to design and implement particular greenhouse methods, techniques and technologies to increase crop yields through models to predict the behavior of the different mechanisms that integrate them and their interactions with the controlled environment [14]. If in such implementations the design, construction, implementation, and adaptation of the greenhouse is optimized, then innovations in analysis methodologies, algorithms and control methods would be established [15].

On the other hand, in the case of Latin America, there are discrepancies in the data of the reported experience due to the accelerated growth and death of greenhouses; to which is added the absence of a classification of this practice from the point of view of the technologies, designs and implementations located according to the region, or the phytosanitary and climatic certainties. Therefore, reviewing the experiences developed in protected agriculture and systematically organizing them will derive in conceptual, technological and development and innovation baselines that are useful and relevant for future research in the area.

The article, then, is structured as follows: in the introduction, reference is made to the advantages and importance of protected agriculture with greenhouses; then the methodology of the review is presented using the index categorization method; next, in the knowledge framework, the information collected is described and its characterization and subcategorization is developed; then, the most appropriate method to increase effectiveness is established, taking into account the modeling of the phenomenon with the significant variables; then some industrial and educational applications are presented, and finally the conclusions and interpretations of the research are presented.

2. Methodology

Since the beginning of the 90's of the 20th century, many investigations have been carried out in the field of protected agriculture with the aim of proposing design methods to make a crop more efficient through the implementation of automation and control technologies. For this reason, a bibliographic search was carried out in the Science Direct, Google Scholar, IEEE and Scopus databases, where a search was made with the following keys: controlled greenhouse, protected agriculture and crop automation.

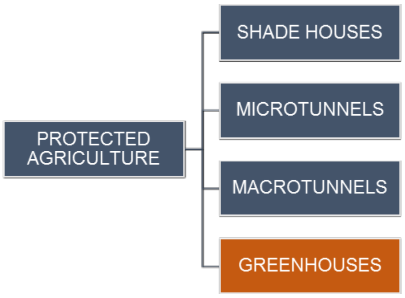

Figure 1. Diagram of the categorization of protected agriculture. Source: own

The results found were filtered in the most relevant worldwide, in Latin America and in Colombia, obtaining between 80 and 100 records in total; according to [16] some main categories were established, Figure 1. And from these some subcategories, Figure 2. The sources are interpreted within the framework of knowledge that classifies greenhouses technologically given by [17], a methodology validated by the SciBas and ORCA research groups.

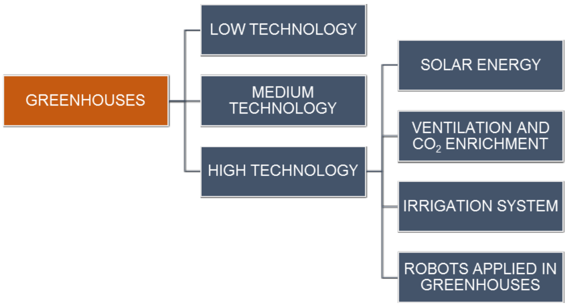

Figure 2. Diagram of the subcategorization of protected agriculture in greenhouses. Source: own

3. Knowledge framework

Protected Agriculture can be developed with crop techniques to control the microclimate of a plant, in which technologies and techniques are implemented to protect any crop from climatic and environmental changes that could damage it [17]; this can be implemented in different types of structures such as: shade houses, microtunnels, macrotunnels and greenhouses.

3.1. Shade houses

These are used to protect the crop from insects, birds and rodents, as well as being useful against solar radiation, rain and too strong winds. It consists of a metal structure covered with plastic mesh to allow rainwater to enter the interior [18].

3.2. Microtunnels

These structures tend to be small (maximum 1m high) formed by tubes or hoses, with a mesh or screen cover that provides protection to the crop, in addition to being easy to install and very economical, which makes them ideal for many farmers with few economic resources; or at least for the first stage of some crops to avoid pests and extreme weather changes [19].

3.3. Macrotunnels

Macrotunnels are structures built with bamboo arches, PVC or galvanized iron tubes, covered with one or more layers of plastic, agrotextile or anti-insect mesh. They are large structures, ranging from 3 to 3.5m in height, so unlike microtunnels they allow access to one or more people inside and of course to plants with greater growth [20].

Unlike greenhouses, these macrotunnels are mobile structures, which helps with crop rotation; in addition, they have no control over environmental conditions and have no actuators for ventilation, so manual rolling of the tunnel sides is used to allow air circulation [21].

3.4. Greenhouses

The greenhouse, as in other systems designed for crop protection, allows the control of the climatic conditions that act in the development of these; an optimal and balanced process of the plants, depends on the way in which some factors like the illumination, humidity and temperature affect them in a favorable way.

A greenhouse is usually a metal or wooden structure with a transparent cover that allows the entry of

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[3] Research groups attached to the Research and Scientific Development Center of the Universidad Distrital Francisco José de Caldas (CIDC), and recognized and categorized before COLCIENCIAS

sunlight and the process of photosynthesis, while allowing little energy to escape, so that this balance helps to modify the internal environment in order to allow the development and growth of plants inside [22], [23]. These are divided into three categories, low technology, medium technology and high technology [24].

3.4.1. Low technology

These are very rudimentary protection structures, such as plastic tunnels on supports like tubes that only protect the crops against rain, drought and excessive heat. Most of the crops produced with this technology are destined for the local market, as they are produced by small farmers. With the implementation of this technology, productivity is improved without investing too much and with the advantage of being able to maintain prices without having economic losses.

3.4.2. Medium technology

This category includes greenhouses that are almost completely isolated from the air, irrigation is not always controlled, and in some, precision nutrients are applied, so not all greenhouses are considered hydroponic. Commonly, crops produced with this technology are for domestic consumption, although they can be marketed if they meet health standards for pesticides, pathogens and residues.

3.4.3. High technology

There is documentation about greenhouse automation since the beginning of the 21st century, so many companies today provide these services allowing the user to visualize the measurements at all times and to control the actuators on site to regulate the environment and maintain adequate conditions for the crops [25].
In some places they have thermal screens that use a system to monitor through a digital timer or through radiation and illumination probes; in addition to the heating of air and water that measures a suitable temperature for the place of the culture making the yield to be to the maximum.

High technology crops are implemented in completely closed greenhouses, with inert substrates instead of soils; precision drip irrigation, micro-sprinkler or fertigation, water automation and precision fertilizers are therefore hydroponic systems [17].
This technology is quite expensive, so to generate profits they are mainly used to export the crops. One advantage of this -as opposed to the average technology- is that it helps farmers meet the Food and Drug Administration's (FDA) stringent health requirements, as well as preventing crop losses and ensuring year-round production.

The following variables intervene in high technology, which when automated, allow the stability of the microclimate of the greenhouse:

- Covering

Greenhouses are sometimes equipped with heating systems that provide an additional contribution of heat at certain times of the year, as well as other elements that help to regulate the internal climate, artificial lighting and ventilation systems [26].

To be productive, the roof used has to allow, to some degree, the passage of light and prevent the output of heat, which is known as the greenhouse effect. During the day, the effect is evident, especially on cold days. At night the interior temperature tends to drop to a value close to the outside temperature, providing very little protection against frost.

Plastic covers can be flexible films, rigid plates or meshes, although approximately 80% usually use flexible films, which are considered better for their thickness and density characteristics [27].

From the data in Figure 3, it is assumed that the ideal material to be implemented as a cover should be photo-stable, so as not to lose its properties due to long periods of exposure to the sun; transparent to visible radiation, to allow the plants in the crop to carry out photosynthesis; opaque to infrared radiation, to prevent heat loss from radiation during the night; and hydrophilic, so that water condensation does not form in the form of drops [28].

From the 1940s onwards, the use of polyethylene for greenhouse covers began with the idea that it was the ideal material [29], [30]; however, if we analyse the characteristics of this and what a good cover should have, it is not so suitable; as it is not very photo-stable, very transparent to infrared radiation, hydrophobic and not transparent to the visible.
Currently, polyethylene is used for roofing since all the characteristics it does not have are applied by means of additives, such as light stabilizers to make it more photo-stable, mineral charges to make it more opaque to infrared radiation and surfactants that make it hydrophilic [28].

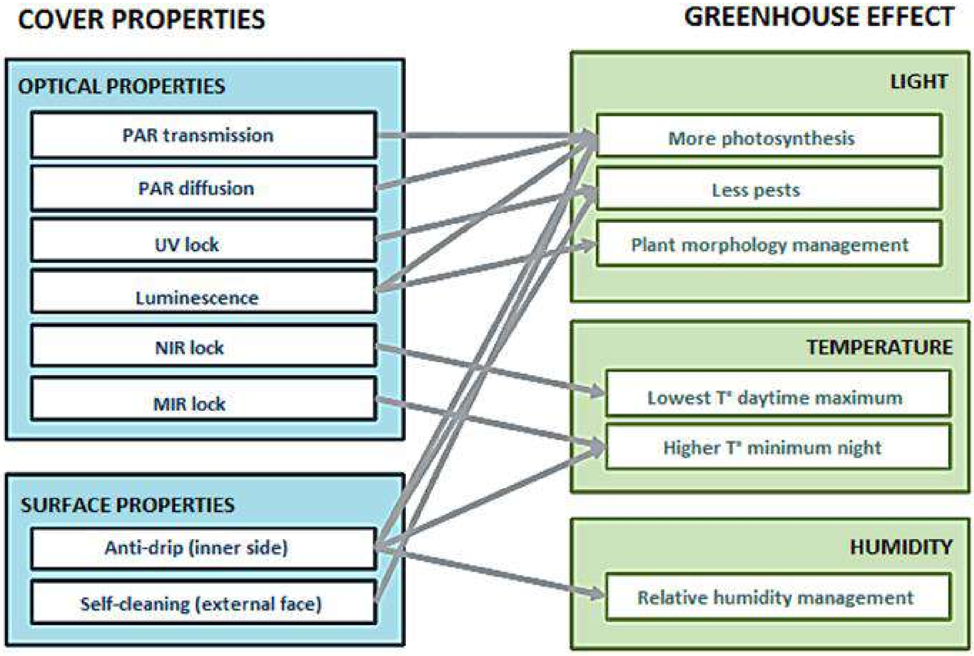

Figure 3. Relationship between roof properties and greenhouse effects [28].

The accuracy of irrigation, its temperature, frequency, amount of light entering the greenhouse and other conditions can be controlled through automated systems such as programmable controllers, with which farmers would improve the productivity of their crops when combined with the correct irrigation, lighting and ventilation techniques [31].

- **Solar energy**

Solar energy is a type of renewable energy that is supplied by the sun through its electromagnetic radiation (light, heat and ultraviolet rays) and from this it is possible to generate electricity -photovoltaic energy- or the heat of the sun to generate heat -thermo-solar-. It is obtained by means of panels and mirrors [32].

Although the development of solar technologies began around the 1860s, the availability of non-renewable sources such as coal and oil stopped growing in the early 20th century [33].

It was the oil crisis -between 1973 and 1979- that triggered a change in world energy policy, to finally have its great boom in 1998 -which continues to this day- prompted in 1997 by the Kyoto protocol - an agreement within the United Nations Framework Convention on Climate Change with the aim of reducing emissions of greenhouse gases that cause global warming [34].

Solar energy emerges, from the above, as a new option for energy consumption without affecting the environment, quite the opposite, to non-renewable energy.

- **Ventilation and CO2 enrichment**

In many regions the temperatures during the first hours of the day are extremely low and, nevertheless, the levels of CO2 are restrictive for the development of the culture; for that reason, in time of winter in cold climates where the diurnal ventilation is not economically profitable, it is necessary to contribute Carbon dioxide to the plant for its optimal growth. Likewise, if the ventilation system is blocked before sunset, due to the drop in temperature, the CO2 levels continue to be reduced due to the photosynthetic activity of the plants.

Ventilation may be regulated, either automatically or manually, by opening the sides and the cover, sometimes supported by internal ventilation or by extractors, since this results in a drop in humidity and in the control of certain diseases [35].

- **Irrigation system**

For the operation of a greenhouse there are water supply tanks that are conducted through pipes to the plants. The criteria for watering the crop depends on how the plant is doing, based on accumulated radiation or by analysis of drainage curves. However, in any form of irrigation it is essential to measure the electrical conductivity of the water, volume and pH, since these indicators show whether it is suitable for the plants [36].

However, in cases where water is not recirculated, drainage should be provided at a rate of 10% to 30% of the amount applied to the crop with irrigation [37].

- Robots applied in greenhouses

Using computer vision (CV), robots can recognize the environment around them by having a video camera system, in addition to appropriate software capable of filtering and processing the information; it must then make decisions and take the necessary actions [38], [39]. For example: detecting a plant and analyzing its particularities, examining the size, color and level of maturity; calculating the state of the plant to classify it and know if it is in optimal condition or if it has some inconvenience and needs special care.

According to the above, the robot would need to be able to move freely through the crop, so the VC should also be used to avoid obstacles [40], and to perform tasks with some type of tweezers on the plants, such as harvesting fruits and vegetables, or cutting flowers [41].

4. Models and methods

In a greenhouse, the external factors that intervene in the crop such as wind speed, sunlight and humidity must be taken into account, so they are considered complex non-linear MIMO systems; these factors are important to improve the operation of the system with the soil, the covering material, the sensors and actuators used and above all with the crop; For greenhouse control, some types of algorithms have been used, such as proportional-integral-derivative (PID), non-linear, robust, fuzzy logic (FL), neural networks and hybrid control algorithms [42]; the above to be clear about the specifications and limitations to which one is exposed by having the appropriate model [43].

In other words, to achieve optimal control, it must be based on a reliable model in which all possible variables must be incorporated [44], counting on the system's ways of coupling to make it functional and without failure [45]; which means that a strategy must be used to reduce the amount of parameters while counting the most important variables [46].

Therefore, under normal conditions the greenhouse is taken as a hybrid system, in which continuous signals - such as environmental factors - and logical switching states - such as the covering or ventilation system - interact, making it necessary to have modeling techniques in programming with mixed integer variables, for which the modeling structure of mixed dynamic and logical systems (MLD) has been investigated [47], [48], which suggests a better modeling and prediction technique that can be the basis for the development and implementation of virtual greenhouses, so that the user can perform scenario simulations for different crops and climatic conditions.

A wide variety of protected crops can be found around the world, such as the solar greenhouses in China, which have an energy storage system in the walls of the structure [49]. On the other hand, there are the closed greenhouses found largely in Western Europe, where storage is a form of innovation for sustainable energy that helps maximize its use with seasonal storage [50], [51]. In a completely closed greenhouse, there is no ventilation, so this heat can be stored to meet the heating demand at any time [32], making it an ideal closed greenhouse, a controlled environment, with air conditioning, heating, circulation and air distribution within the greenhouse [52] as shown in Figure 4. Due to the climate conditions and the cost that it can mean, most of the researches have been made to increase the efficiency of the greenhouse design and to optimize the production [35], [53], [54], [55]; it was concluded that it was necessary to integrate biological and physical models with the climate conditions of any place of the world, making use of a quantitative compensation with economic return for the construction, maintenance and operation of the greenhouse facilities.

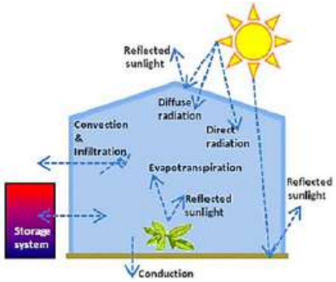

Figure 4. Heat transfer model in the closed greenhouse concept [32].

An example of an optimization algorithm capable of designing a greenhouse for growing tomatoes with a large number of climate and economic conditions is shown in Figure 5, which has eight design elements: the type of greenhouse structure, the type of roof, the external shade screen, the lime, the heat screen, the heating system, the cooling system and the CO2 enrichment system [56]; It also details the effects of the exterior and interior climate and the design of the greenhouse, with these characteristics the model proposed is capable of predicting the climate, temperature, humidity and CO2 concentration with great precision, in this way the model should be a set of differential equations of first order [57], [58], [59], [60], [61], [62].

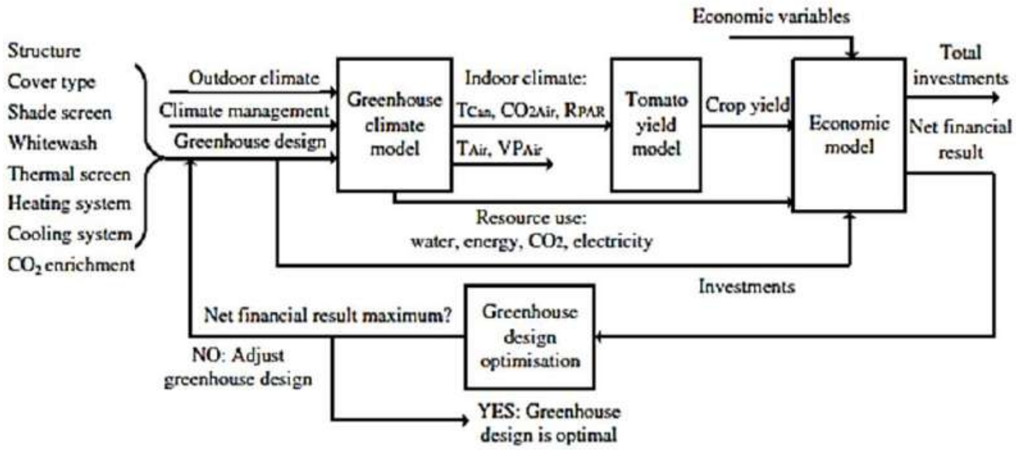

Figure 5. Optimization method for the design of a greenhouse [56].

In 2010, a greenhouse model was developed for academic purposes, which was capable of adapting different configurations depending on the conditions that were presented to it. This model was validated and approved in a large number of greenhouses with different characteristics and climates, such as: a temperate marine climate (northwest of the Netherlands); a Mediterranean climate (Sicily, Italy); and a semi-arid climate (Arizona and Texas, USA) [63].

The elements required for the greenhouse design method are presented in figure 6, with these the various energy and mass flows are incorporated.

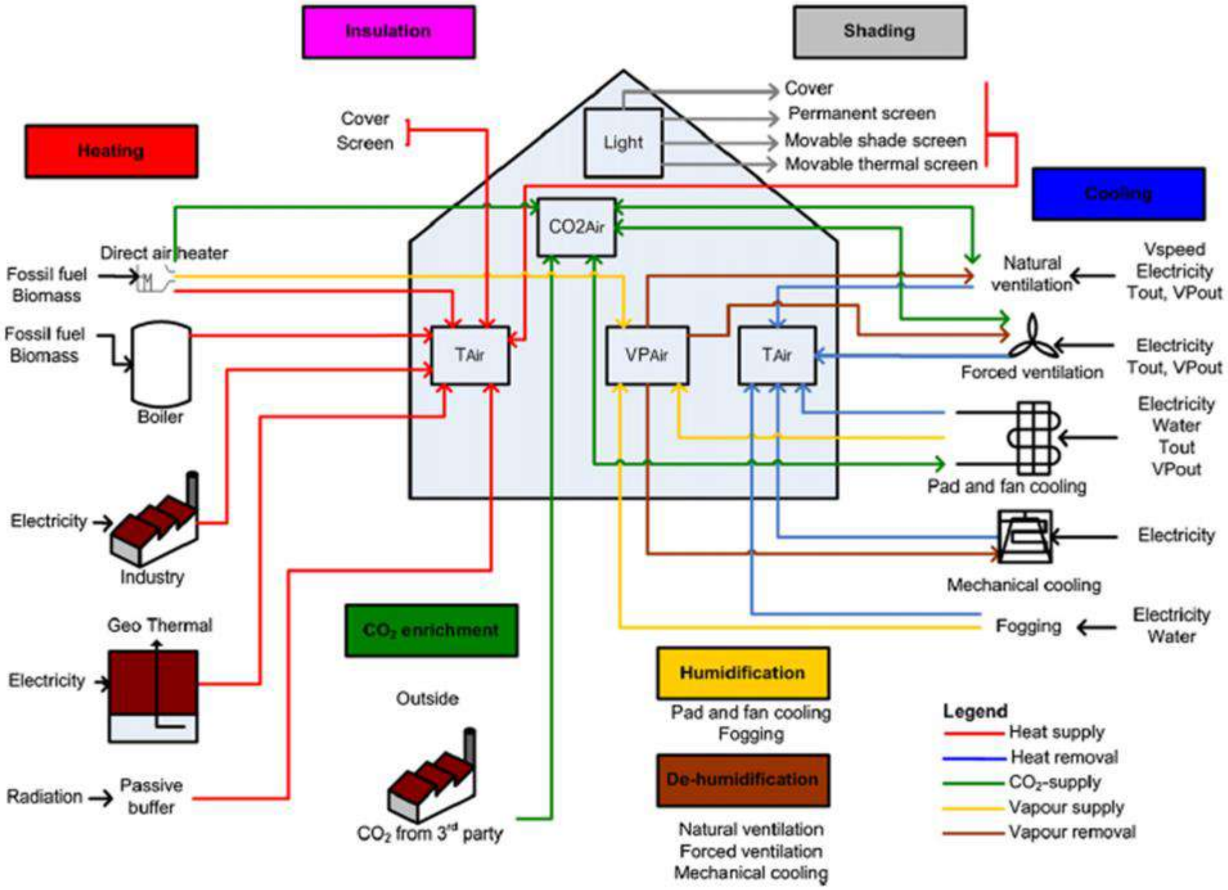

Figure 6. Greenhouse model flows [56].

In the model in Figure 6 a description of the roof is given to combine the impact of different cover layers in indoor climate and assuming that the temperatures of the outer cover are variable, the impact of the roof insulation on the indoor climate can be described; canopy and floor absorption depend on the optical properties of the roof and floor; Thus, for the optimization of the structure, the dimensions of the greenhouse depend on the roof, orientation and location of the vents; this model does not distinguish between diffuse and direct solar radiation and assumes that the transmission coefficient of the greenhouse does not depend on the solar angle [59].

On the other hand, robots have been used in greenhouses since the 1990s, with the AGROBOT project -of 1996- being one of the first to be publicized; this had a mechanical arm with the function of automatically harvesting ripe tomatoes and spreading pesticides throughout the crop [64].

In another case, it was shown that greenhouse robots are efficient because they do not require constant human supervision; in addition, they have precision sensors and actuators and through the VC they could determine whether the fruit or vegetable is ready for harvesting [65].

Therefore, the use of two cameras to interpret the information in three dimensions (horizontal, vertical and depth), using DC motors, rails, belts and other attachments, was proposed to achieve the correct functioning of the VC [66].

5. Applications

There are several automation options on the market, some very complex for larger greenhouses or with delicate crops that must have very specific environmental conditions; or also simpler ones that are perfectly suitable for small greenhouses or that do not need many environmental measurements for their correct operation.

In the case of larger greenhouses, there is equipment that helps to control important parameters for the crop and through alarms that have control of the air, humidity, temperature, or radiation at all times; all these variables can be read by the user in the recording systems that can be modified depending on each greenhouse [67].

INTA is a Spanish company that develops and installs advanced systems for the control of all types of crops, as well as the climate control of greenhouses. This company has the CLIMA-16 system that is capable of controlling the heating, ventilation, and screens, supported by an alarm system, which records the status of the greenhouse at all times; also the Sysclima software that is used for the management and control of a greenhouse from anywhere with an internet connection, as well as having reports that can be personalized to obtain the desired variables [68]. Figure 7 shows the interface of the Sysclima software.

T° Exterior 15,33 °C
Dir. Viento 154 °
Lluvia NO
Radiación Solar 79 W/m2
Vel. Viento 3,95 m/s
R.Solar Acumulada 1958 Wh/m2
Amanecer 06:40
Anochecer 19:41
Hum. Relativa 55 %
DX Exterior 7,32 gr/m3

Figure 7. Parameter monitoring with Sysclima software [68].

In 2007, a system was developed in Peru to obtain the physical variables of the greenhouse with telemetry, through a cell phone connected to a microcontroller that transmitted the variables with data calls using the Hayes standard (AT commands that are communication protocols) [69], [70].

Then in 2005, a robot with an arm located on a platform with elevation was planned; this had the function of carrying out the harvesting and pruning. The robot was an interesting invention since it was developed at low cost with the characteristics previously exposed [71].

5.1. Greenhouses in Colombia

The cultivation of flowers for export is the main use of greenhouses in the country; being the savannah of Bogota, Boyacá and Antioquia where they are concentrated. However, only low temperatures or rainy seasons are controlled, assuming that costs may increase because the greenhouse is not fully controlled [72].

According to ASOCOLFLORES, the main crops produced and exported were roses (48%), carnations (16%), mini-carnations (8%), chrysanthemums (4%) and others; however, most of these crops are grown in greenhouses that are not automated and therefore have a permanent risk of crop loss and must be constantly monitored; this means that there is not significant flower production in the department of Tolima [73].

On the other hand, the Ministry of Agriculture of Colombia created the first high-tech greenhouse of CORPOICA in Rionegro, -Antioquia- in 2009.

Approximately 4.5 billion pesos were invested in these facilities with crops such as tomatoes, sweet corn, lettuce, eggplant, colored peppers, cucumber and chili. The greenhouse is composed of thermal screens to regulate temperature and light, fans, relative humidity sensors and air extractors, automatic deployment sides, upper windows, irrigation systems and weather stations to monitor climate variables [74], [75].

By June 2018, the country's most modern intelligent greenhouse was inaugurated, with investment from the Dutch government. This horticenter has 430 plants and its technology is composed of two greenhouse wings, to carry out simulations and compare diverse climatic and atmospheric conditions, in order to identify the optimal means for the production of any crop, especially in Bogotá, where the difference in temperature during the day and night means that some crops do not develop properly, affecting the productivity of the farmers [76].

6. Conclusions

About 70% of the references consulted are from research carried out in Europe and Asia, while about 30% are from research carried out in Latin America. Of this 30%, approximately 9% correspond to research references in Colombia where the implementation and innovation in technologies applied to greenhouses is not systematized and is not generally advanced. In the countries of Europe and Asia, where the most documentation is found, it is observed that the dissemination of experiences is presumed due to the importance given to protected agriculture due to the changes in temperature that occur in those regions of the world in the winter or summer seasons, which does not favor the adequate growth of crops.

In Colombia, meanwhile, the projects found have been developed very recently and several with exclusively academic purposes; this is a great advance for the country since by focusing on them it is possible to assume as pilot experiences of greenhouses that, being in operation, can implement technologies and analyze their efficiency. From this perspective, innovations can be proposed aimed at the management of thermal energy savings available for the greenhouse through the exhaustive analysis of the parameters that can reduce energy losses, not forgetting that the main factor affecting the energy balance of a greenhouse is solar radiation, which can vary by location, structural design, thermal insulation and covering materials.

Most research proposes the use of solar energy to minimize the energy demand that would be needed with the implementation of technologies, focusing mainly on the heating seasons by adding solar energy to that collected by another energy storage system.

Finally, this article establishes a baseline so that with the model shown in Figure 5, a combination with a crop yield model and an economic model can be developed. There are many variants.

In summary, greenhouse models can be useful to significantly improve the understanding of the climate of an arbitrary greenhouse. By increasing their complexity, they provide a strategy for developing variants of indoor climate design and management. As a result of this exercise, the microclimate of any greenhouse could be monitored permanently, online, and with the possibility of instantaneous intervention.

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