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ENERGY EFFICIENCY OF AGRICULTURAL TECHNOLOGIES THROUGH THE CREATION OF A SUSTAINABLE MODEL: A CASE STUDY OF GREENHOUSES

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Abstract

Ecological sustainability in agriculture involves the responsible and efficient use of natural resources, promoting practices that protect the environment and ensure long-term productivity. The paper aims to achieve the conceptual design of an agricultural greenhouse, including the elements necessary for the automation of installations to accomplish optimal energy efficiency. A generalized input-output optimized model was developed for a controlled agricultural technological process of plant growth. The model can identify the functional links between the variables of an agricultural technological process and allows for the global or partial optimization of the process, based on economic-organizational and technical-ecological criteria. Considering the cycle of crop cultivation in protected spaces, a calculation is also presented regarding the optimization of the duration of the operating cycles, taking into account various factors, in order to maximize production and minimize costs, in a sustainable and economic framework. The integration of automated systems in agricultural greenhouses significantly improves efficiency, reduces energy consumption, and boosts productivity. By utilizing IoT, automation, and data logging, these systems enable optimal environmental control and remote monitoring, ultimately maximizing both economic and environmental benefits in greenhouse farming.

Key words: *energy efficiency, automation, agriculture, greenhouse, input-output model, economic sustainability*

INTRODUCTION

Sustainability in agriculture represents an integrated approach that ensures efficient food production while protecting the environment and resources for future generations (Çakmakçı et al., 2023) [3].
The concept of energy is not limited to large infrastructures but also focuses on efficiency, where reducing energy costs involves both changing ideologies and human behaviour, as well as adopting modern technologies (Sorrell, 2015) [27].
Agriculture in the Balkan region of Europe is characterized by high energy consumption due to harsh winters and significant greenhouse heating requirements (Knez et al., 2022) [11].
A major challenge in promoting a mindset shift among farmers and optimizing energy use for year-round crop production is the way energy is generated and managed in this region (Sulewski et Wąs, 2024) [29].
Agricultural greenhouses are robust structures built from durable materials such as glass, metal, or polycarbonate panels, supported by sturdy steel or aluminium frames. They provide superior thermal insulation, maintaining a constant temperature year-round, and are equipped with heating and mechanical ventilation systems to operate efficiently even in extreme weather conditions (Maraveas et al., 2023) [17].
They are mainly used for intensive crops, including flowers, vegetables, or exotic plants,

allowing full control over environmental factors such as temperature, humidity, light, and ventilation (Morgan, 2022) [20].

However, these benefits come at a high cost, both for construction and maintenance, due to the materials and automation equipment required.

Therefore, modernization of greenhouses cannot be carried out without investments (Kusz, 2014) [14].

The Romanian legislative framework regulating measures to increase energy efficiency across all sectors, including agriculture, alongside Romania's Energy Strategy 2020-2030, supports the use of renewable sources such as solar energy and biomass, and the modernization of agricultural infrastructure to reduce energy consumption (ME-RO, 2020) [19]. Additionally, agricultural projects focused on energy efficiency and the use of renewable energy are being promoted, and farmers are supported through subsidies for purchasing modern equipment and upgrading greenhouses (RO law, 2014) [25].

European regulations on energy efficiency in agriculture set measures to promote energy efficiency, with a target to reduce energy consumption by 32.5% by 2030, encouraging the use of modern technologies and renewable sources. The European Green Deal supports the transition to sustainable and efficient agriculture through the "Farm to Fork" initiative, focused on reducing emissions and increasing the use of renewable energy. The Common Agricultural Policy (CAP) 2023-2027 supports these goals with funding for farm modernization, installation of solar panels, and the digitalization of agricultural processes for more efficient energy use (Directive EU, 2018) [6].

Agricultural greenhouses allow the extension of the growing season, promoting the cultivation of plants outside their natural season, and improve yields by providing optimal growing conditions. At the same time, greenhouses contribute to resource efficiency by reducing water and energy losses through modern technologies, and offer effective pest control through isolation and monitoring (Al-Qudah et al., 2025) [2].

Intelligent systems dedicated to farmers, through which they gain complete control over agricultural greenhouses, involve automating functions that provide full control of the facility.

Important results have been achieved in tomato growing in protected areas (Jeca and Smedescu, 2023; Toma-Diaconu and Vochin, 2024) [10, 31], but they require investments in modern integrated greenhouses (Zbanca and Negritu, 2013) [36].

These systems allow growers to create optimal growing conditions for agro-food products, including smart electrical installations (lighting, outlets, interior or exterior blinds for shading/shutters, insulation systems, etc.), heating, ventilation, and air conditioning (HVAC) systems, as well as remote control of the greenhouses (Dhanaraju et al., 2022) [5].

Depending on the complexity of the greenhouse, the design of the installations, and their level of automation, energy consumption can be reduced by 20-30% (Muñoz-Liesa et al., 2022; Trépanier et al., 2025) [21, 32]. By automating the installations, the sources that power the equipment can be controlled, eliminating unnecessary costs (Tayefeh et al., 2024) [30].

The main objective of the study is to provide a practical solution capable of reducing the energy costs of agricultural greenhouses, water usage, and crop yield while minimizing human intervention. The proposed greenhouse management system will integrate functions such as lighting control, temperature and humidity regulation, shade control system, CO_2 level monitoring, and remote-control capabilities.

MATERIALS AND METHODS

1.Smart Greenhouse: Key Components and Process

Equipment Used

The equipment used in the greenhouse automation process features a direct KNX connection, eliminating the need for any adapter interface.

KNX is a standard in the field of automation for industrial and agricultural buildings. It is regulated by the international standard

ISO/IEC 14543-3, the European standards CENELEC EN 50090 and CEN EN 13321-1, as well as the Chinese standard GB/Z 20965.

KNX has a significant connection with agricultural greenhouses, as it can be used for the automation and optimization of essential greenhouse systems. This open standard enables the automatic control of temperature, humidity, ventilation, and lighting, ensuring optimal conditions for plants. Additionally, KNX can manage automated irrigation by integrating soil moisture sensors, optimizing water consumption. Moreover, it can help reduce costs through efficient energy management and the integration of renewable energy sources. KNX facilitates connectivity with IoT devices and allows real-time monitoring of greenhouse parameters, thereby enhancing agricultural efficiency and productivity.

In order to ensure data transfer between all components of the greenhouse management system, a solution is needed to address the communication with isolated devices, ensuring that all components communicate in a unique common language: in short, a system such as the KNX BUS, independent of the manufacturer and the application domain. In the KNX environment, all devices are connected to the same BUS (twisted pair, RF, power lines, or IP/Ethernet), allowing them to communicate with each other.

KNX devices (Figure 1) can include: sensors or actuators required for controlling various building systems, such as lighting, interior or exterior shading/blinds, insulation systems, security systems, energy management, heating, ventilation, and air conditioning systems, signalling and monitoring systems, interfaces with building service and control systems, remote control, metering, audio/video control, household appliances, etc.

All these functions can be controlled, monitored, and signalled through a unified system without the need for additional control centers.

Moreover, the lighting can be automatically controlled based on the intensity of natural light, thus maintaining a specified minimum level in each location and reducing energy consumption (Lee et al., 2024) [15].

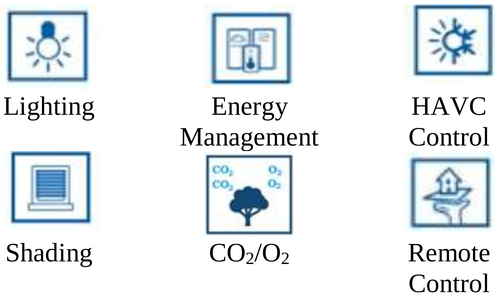

Fig. 1. Example of a KNX control system
Source: Own adaptation based on [13].

By interconnecting all communication devices into a single BUS, the design and installation time is significantly reduced. Engineering Tool Software (ETS), a manufacturer-independent software applicable across different domains, allows for the design and configuration of installations containing KNX-certified products. Since the software is manufacturer-independent, the system integrator can combine products from various manufacturers with different communication media (twisted pair, radio frequency, power line, or IP/Ethernet), all within a single installation. Additionally, a KNX installation can be easily adapted to new applications and is highly expandable. New components can be easily connected to the existing BUS installation (KNX RO, 2025) [12].

ETS (Engineering Tool Software) is a program that runs on the Windows operating system, allowing the development and configuration of control systems for the automation of smart agricultural greenhouses. In general, greenhouse software helps optimize design, management, and maintenance processes by leveraging advanced technological solutions.

Climate management software, such as Priva Compass, HortiMaX, and Argus Controls, enables automated control of temperature, humidity, irrigation, and lighting, while also providing real-time monitoring and reporting. For efficient water management, applications like Rain Bird IQ, Netafim CMT, and HydroPoint Baseline optimize irrigation and water consumption, reducing waste and improving efficiency. Sensor integration for monitoring and analysis is facilitated by solutions such as Climate FieldView, FarmLogs, and Grodan e-Gro, which analyze climate data and suggest optimal adjustments (Ray et al., 2024) [24].

Lighting Control

Lighting control in agricultural greenhouses is essential for ensuring optimal plant growth conditions, especially during periods of insufficient natural light or in covered greenhouses. Supplemental lighting, usually provided by LED lamps, helps extend photosynthesis periods, stimulating plant development and improving yield production. It aids in regulating growth rates, ensuring uniform plant development, and reducing stress caused by the lack of natural light. Additionally, optimizing lighting reduces energy consumption and costs, enhancing the overall efficiency of agricultural production.

Lighting control can be performed simultaneously based on predefined scenarios or separately for each lighting group. On/off lighting will be controlled using multifunction switches. By using LED bulbs, energy consumption can be reduced by up to 30% (Ganandran et al., 2014) [9].

Table 1 provides a comparison of the advantages and disadvantages of LED (Light Emitting Diode) lighting versus HPS (High Pressure Sodium) lighting.

Table 1. Advantages and Disadvantages (LED vs. HPS)

Description of characteristics	LED	HPS
Lifespan (average 10 hours/day)	>50,000 h	22,000 h
Additional consumption (start, stop, cool)	NO	YES
Energy efficiency (electricity converted into light)	90-95%	18-23%
UV radiation and toxic material content	NO	YES
Light dispersion without a reflector	YES	NO
Multiple optional color temperatures	YES	NO
Instant ignition and "0.0s" cooling times and operating frequency	YES	NO
Possibility of low voltage power supply	YES	NO
Higher mechanical shock resistance	YES	NO
Constant light flux and flicker-free	YES	NO

Source: Own adaptation based on [35].

In access and auxiliary areas, dimmable lighting is recommended, with the possibility of adjusting light intensity and/or maintaining a constant intensity.

Energy savings of between 28% and 66% can be achieved by maintaining the lighting at an intensity of 500-700 lux, depending on the season, weather, and the building's geographical location.

However, in industrial or plant areas, stronger lighting of over 1,000 lux is required. This is also relevant for agricultural greenhouses, especially for plants that need strong lighting to support photosynthesis and rapid growth. In greenhouses, supplemental lighting is often used to compensate for the lack of natural light or to extend daylight periods under insufficient lighting conditions (Singh et al., 2014) [26].

For example, for plants growing in a greenhouse, such as vegetables or flowers, a light intensity between 1,000 and 2,000 lux may be necessary to support optimal development, especially during active growth stages or in winter periods when natural light is limited.

Stronger lighting can also be used to stimulate certain processes, such as flowering or fruiting, depending on the needs of the specific crop.

However, it is important for the lighting to be properly adjusted, as too strong or too weak light can negatively impact plant development.

Temperature control

Temperature control can be done zonally by closely monitoring a set of temperature values, either from multifunctional switches or a mobile phone.

Additionally, there is the possibility of simultaneous control of multiple rooms or based on pre-established schedules according to requirements, such as winter/summer mode, day/night mode, freeze temperature alarm, and overheating alarm.

The temperatures mentioned earlier are examples; for each type of space, temperatures will be set according to needs. In each room, the required temperature can be adjusted by +/- 5°C locally, from the temperature controller's buttons.

Cooling of the spaces will be done by automatically controlling the windows/blinds or the ventilation system.

Temperature control in agricultural greenhouses is essential for ensuring optimal conditions for plant growth and development, directly influencing their health, production, and quality.

Correct temperatures stimulate physiological processes, prevent heat stress, and reduce the risk of diseases, ensuring seasonal flexibility and energy efficiency. Thus, careful temperature management contributes to producing uniform, high-quality products and increasing the sustainability of protected agriculture (Akpenpuun et al., 2023) [1].

Shading control

The automation solution can include control of interior or exterior electric blinds for shading.

Control can be done both locally and remotely. This type of control can also be paired with time schedules for automatic operation. The greenhouse management system will also allow the operation of the blinds through specific software.

With the help of a weather station, an automatic shading system for areas directly exposed to solar radiation can be implemented. Automatic shading of certain sections or greenhouse walls involves the automatic control of blinds/shutters based on the position of the sun.

The weather station determines the position of the sun and the solar radiation on a building facade, thus determining the optimal position of the blinds. Additionally, the position of the blinds' slats is crucial.

In the summer, during the hottest periods of the day, the blinds/shutters are lowered to reflect heat, and the slats are rotated to allow as much natural light as possible into the greenhouse. In contrast, in the winter, the blinds/shutters are opened when the sun shines to capture heat.

This automatic control mode can be turned off at any time, and the blinds/shutters will remain in the desired position.

By using interior or exterior shading blinds, shutters, or insulation systems, energy savings of up to 40% can be achieved (Eigbrett, 2015) [8].

The control of blinds or shutters in agricultural greenhouses plays a crucial role in regulating light and temperature, protecting plants from overexposure or heat loss.

These systems prevent heat stress, optimize the photosynthesis process, and contribute to energy efficiency by reducing reliance on other cooling or heating methods.

By maintaining a balanced microclimate, the blinds and shutters ensure healthy plant growth and improve production quality.

CO_2 level control

Monitoring gases such as carbon dioxide, oxygen, ammonia, carbon monoxide, and nitrogen oxides are essential in an agricultural greenhouse to ensure an optimal growing environment.

CO_2 stimulates photosynthesis, while oxygen supports the respiration of plants and microorganisms in the soil.

Pollutants such as carbon monoxide or ammonia can become toxic at high concentrations, affecting plant health and productivity.

Maintaining optimal concentrations, monitored by specialized sensors, is crucial to prevent plant stress and maximize agricultural production.

Monitoring and controlling CO_2/O_2 levels in spaces is an important aspect when considering plant health, safety, and energy efficiency. The air inside greenhouses must maintain an optimal level, typically between 400-1,000 ppm, to stimulate plant growth and productivity.

Humidity control

Humidity control in both the atmosphere and soil in greenhouses is essential for maintaining an optimal environment for plant growth, preventing diseases, and maximizing production.

Atmospheric humidity influences the plant transpiration process and gas exchange, and excessive levels can encourage the growth of mold and fungal diseases.

On the other hand, insufficient humidity can lead to plant dehydration and water stress.

Regarding the soil, the moisture level plays a crucial role in water absorption by the roots. Soil that is too dry can hinder plant development, while excessive water can cause root rot and the growth of pathogens.

For effective control, specialized sensors are used to continuously monitor moisture levels and enable automated interventions. Atmospheric humidity sensors, such as DHT22 or SHT31, measure relative humidity and send data to a centralized system. Meanwhile, soil moisture sensors, like YL-69 or SEN0193, detect the water content in the soil and can activate automated irrigation.

The automation system receives the data from the sensors and controls the equipment.

When atmospheric humidity exceeds the optimal threshold, fans or dehumidifiers can be activated, and if the soil becomes too dry, the system can automatically start irrigation.

Remote control

The visualization solution provides the ability to read the status of greenhouse functions and send commands from within the greenhouse or adjacent spaces via a Wi-Fi network or remotely through an internet connection.

Such a solution is designed for convenience, allowing full access to all greenhouse functionalities (lighting, setpoint temperature, blind/shutter control, scenarios) via a tablet or mobile phone.

The proposed equipment is the Wiser for KNX, which allows communication between multiple protocols such as IP, KNX, ModBus, and BACnet.

With this logic controller, it is possible to control the lighting, blinds or shutters, as well as the heating and ventilation systems, thus ensuring optimal conditions to meet all the specific requirements of the plants in the greenhouse.

Distinct time schedules can be created depending on the type of crops or time period. Since the KNX system can record consumption data for gas, water, and electricity, this data can be retrieved in the visualization and displayed in graphs that show consumption over time, whether by week, month, or year.

RESULTS AND DISCUSSIONS

1. Development of a Generalized Input-Output Model for Greenhouse Cultivation

Greenhouse vegetable cultivation technology may or may not include operations such as fertilization, irrigation, phytosanitary treatments, plant support, artificial pollination, and climate control, depending on the crop requirements and the type of protection used.

Achieving high-yield production depends on factors such as the correct selection of varieties, optimal management of environmental conditions, appropriate application of fertilizers and phytosanitary treatments, as well as efficient control of irrigation and pests.

Figure 2 shows the general diagram of vegetable cultivation in a protected system.

From this phytotechnical flow diagram, it can be concluded that the process of vegetable cultivation in greenhouses is generally complex and tailored for each type of vegetable.

The technological phases require control using a process computer with high reliability.

Its communication with the process is achieved through process interfaces with a maximum of x inputs and y outputs (x - the number of parameters taken from the process as response variables, r; y - the number of commands generated to control the process, c).

Starting from the generalized technological action system, the construction of the optimization system begins with defining a generalized input-output model for the agricultural process of obtaining vegetable crops.

The structure of the generalized input-output model, for which the following groups of variables are introduced, considered as vector variables:

I. Input variables (factors of the process) that play the role of causes, which are, from a technical standpoint, controlled and commanded quantities, structured into the following groups:

a)Input variables related to the greenhouse infrastructure (I), such as strength, reliability, and equipment, which influence the overall system performance and the efficiency of operations, ensuring optimal conditions for plant development and protection from external factors.

b)Input variables related to the plants (P), such as appearance, size, taste and aroma, texture, environmental resistance, and nutritional content, which determine the quality of the final product and the plants' ability to adapt to greenhouse growth conditions, thereby influencing yield and crop viability.

c)Input variables related to the environment (E), such as temperature, atmospheric humidity, soil moisture, and light intensity, which directly influence plant growth and development, having a significant impact on production and crop quality.

d)Input variables related to actions (A), such as greenhouse preparation, planting, plant care (irrigation, fertilization, pest protection), and harvesting, with each action being essential to ensuring optimal and healthy production.

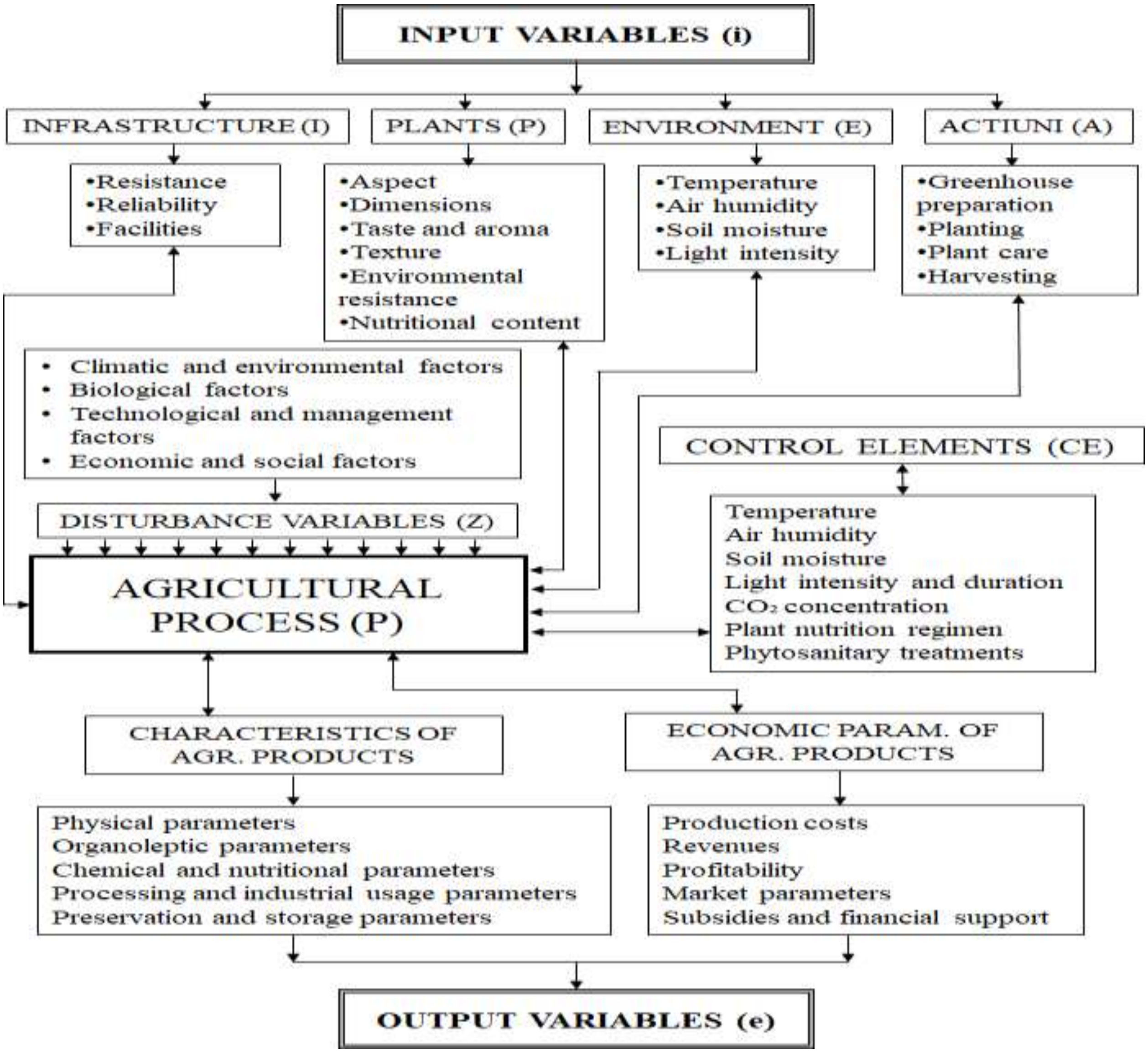

Fig. 2. Generalized input-output model for the greenhouse plant cultivation process
Source: Own contribution.

II.Output variables that characterize the state of the agricultural process, depending on the changes in the input variables, also known as state variables.

III. Control elements (CE) are the equipment through which the measurement, control, and command of the input-output variables in the agricultural process within a greenhouse are carried out. The regulation of variables is done through mathematical relationships that form the feedback component of the system, allowing the adjustment of environmental conditions and cultivation technologies to optimize production.

The variables that can be controlled include:

-*Temperature* – regulation is achieved through automated heating, cooling, or ventilation systems, which adjust the temperature based on plant requirements and external conditions.

-*Atmospheric humidity* – controlled through humidification and dehumidification systems, to maintain an optimal level, preventing fungal diseases or plant dehydration.

-*Soil moisture* – managed by irrigation systems based on moisture sensors, ensuring balanced water distribution, avoiding excess or water deficit.

-*Light intensity and duration* – controlled through the use of blinds/shutters or artificial lighting, to supplement natural deficiencies, optimizing photosynthesis.

-*CO_2 concentration* – controlled by carbon dioxide dosing systems, maintaining an optimal level for plant growth stimulation.

-*Plant nutrition regime* – controlled by controlled fertilization systems, ensuring the necessary nutrient supply based on plant needs and growth stage.

-*Phytosanitary protection* – achieved through monitoring and applying treatments against diseases and pests.

These control variables ensure an integrated management of the agricultural process, contributing to the system's stability and maximizing the yield of greenhouse crops.

IV.Disturbance variables or disturbances (z) are other factors that can negatively influence the system, such as:

-*Climatic and environmental factors* play a crucial role in plant development. Sudden temperature variations can cause thermal stress, while improper atmospheric humidity either favours fungal diseases or leads to plant dehydration. Soil humidity must also be maintained at an optimal level, avoiding both excess water, which can cause root suffocation, and deficiency, which affects nutrient absorption. Light intensity and duration influence photosynthesis, and fluctuations in CO_2 concentration can limit plant growth.

-*Biological factors* can be a constant threat to crops. Pests, such as insects and mites, along with diseases caused by fungi, bacteria, or viruses, can damage plant health and significantly reduce production. Additionally, overcrowding in the greenhouse can create excessive competition for light, water, and nutrients, affecting the uniform development of the crops.

-*Technological and management factors* directly influence the efficiency of the agricultural process. Equipment malfunctions, such as issues with irrigation, heating, or ventilation systems, can compromise optimal growing conditions. Moreover, errors in applying fertilizers and pesticides can affect plant health and even pollute the soil. Delays in performing essential agricultural tasks, such as planting, fertilizing, or harvesting, can reduce yield and quality.

-*Economic and social factors* influence the sustainability of agricultural production. Fluctuations in the prices of seeds, fertilizers, energy, and labour can increase production costs and affect profitability. Furthermore, market demand and supply play an important role, and overproduction or a decrease in demand can negatively influence prices and the profitability of the business.

Therefore, proper management of these factors is essential for maintaining an efficient agricultural process and ensuring the production of high-quality crops in a protected system (Perju et. al., 1998) [22].

V.The characteristics of the agricultural product influence both its quality and its market destination. These properties are analyzed from multiple perspectives, each playing a crucial role in determining the product's value and use.

1. Physical parameters. The size and weight of the agricultural product are essential characteristics for handling, packaging, and transportation, influencing logistical efficiency and associated costs. The commercial appearance, including colour, shape, and uniformity, plays an important role in the product's attractiveness to consumers. Additionally, texture and firmness are decisive factors for both direct consumption and industrial processing.

2. Organoleptic parameters. Taste and aroma are key elements that determine consumer acceptance of the product. Consistency and juiciness are also relevant, especially for products used in gastronomy and the food industry, influencing quality perception and consumer experience.

3. Chemical and nutritional parameters.

The water content of an agricultural product affects both its shelf life and the applicable preservation methods. Nutritional value, expressed through the concentration of proteins, carbohydrates, lipids, vitamins, and minerals, influences health benefits and demand in the food market. The level of sugars and acidity determines the final taste of the product and processing possibilities, being essential factors in the juice and jam industries.

4. Processing and industrial use parameters.
The processing capacity of the agricultural product determines its adaptability to industrial processes such as peeling, chopping, or drying. Extraction yield is an important economic factor, indicating the proportion of usable product after processing, which is crucial for industries such as oil and juice production.

5.Preservation and storage parameters. Shelf life defines the period during which the product maintains its quality without degradation. Resistance to transportation and handling is a crucial aspect for efficient distribution, especially for products intended for export or long-distance sales.

These parameters are essential for determining the commercial value of the agricultural product and for adapting it to market and consumer requirements, thereby contributing to the optimization of the production and distribution chain (Căta et al., 2006) [4].

VI. Economic parameters of the agricultural process are essential factors that influence the efficiency, profitability, and sustainability of agricultural activities. They enable better resource management and production optimization based on market demands and associated costs.

1. Production Costs. Production costs are key elements that influence the profitability of an agricultural enterprise. These costs are divided into fixed and variable costs. Fixed costs are expenses that do not vary with production volume, such as equipment depreciation, infrastructure costs, or land taxes. On the other hand, variable costs depend directly on production volume and include expenses such as seeds, fertilizers, water, energy, and seasonal labour. Total costs represent the sum of fixed and variable costs for a production cycle, serving as an essential indicator for the economic analysis of the farm.

2. Revenues. Revenues from agricultural activity are fundamental for evaluating economic efficiency. Gross revenue represents the total amount obtained from the sale of agricultural products, without considering production costs. Net revenue is determined by subtracting total costs from gross revenue, reflecting the farm's actual profitability. Another important parameter is productivity per unit of area, which indicates the ratio between the obtained yield and the cultivated area, expressed in kg/m² or t/ha.

3. Profitability. The profitability of the agricultural process is essential for maintaining the farm's economic viability. Profitability represents its ability to generate profit and is calculated as the ratio between profit and total costs. Return on Investment (ROI) indicates the efficiency of capital utilization by measuring the ratio between the profit obtained and investments made in infrastructure, equipment, and technologies. Another key parameter is the unit production cost, which reflects the average cost required to obtain one unit of product, expressed in cost/kg.

4. Maret Parameters. Market conditions play a decisive role in the success of an agricultural business. The selling price of an agricultural product is influenced by the relationship between supply and demand, product quality, and industry competition. Demand elasticity represents consumers' sensitivity to price changes and can directly affect sales volume. Another essential factor is market accessibility, meaning the farmer's ability to sell products through local markets, supermarkets, exports, or other distribution channels.

5.Subsidies and Financial Support. Financial support can significantly impact the economic viability of agricultural farms. Government aid and subsidies are forms of support provided by the state to reduce production costs and increase competitiveness. Additionally, access to credit and financing is crucial for farm development, enabling investments in equipment, infrastructure, and modern technologies. These economic parameters are essential for strategic decision-making, optimizing the agricultural process and ensuring the sustainability of the agricultural business. Effective management of these factors can lead to increased profitability and the development of competitive agricultural production on the market.

The main criterion for grouping the variables was determined both by the order of their determinations and involvement in the process, as well as by the existence of implicit relationships between them.

Based on the presented variable blocks and information from the literature regarding the agricultural process of growing vegetables in greenhouses, the possible connections between these groups of variables—also referred to as direct links—are outlined.

The analysis of these connections leads to the conclusion that there are extensive possibilities for controlling the vegetable cultivation process in a protected system (through a high number of variables). At the same time, the complexity of the process is remarkable, highlighting the clear necessity for highly qualified personnel.

The analysis of the generalized interpretation system of the greenhouse cultivation process has led to the development of a generalized input-output model. This model serves as a starting point for designing an experimental framework to determine the functional relationships between different variables, aiming to establish dependency relations. These relations can later be used for optimization through mathematical models, based on one or more criteria, under various conditions. The optimization of the greenhouse cultivation process can be applied either globally or partially, integrating not only technical optimization criteria but also a set of economic-organizational and hygienic-ecological criteria (Țucu et al., 1998) [33].

The importance of such an input-output model lies in its ability to be applied and customized to any agricultural process, regardless of its nature. This facilitates a deeper understanding and analysis of the process, ultimately enabling the implementation of optimal control.

2. Smart Greenhouse Process Design

Figure 3 presents the monitoring and control scheme of a greenhouse.

The Greenhouse Monitoring and Control System is an automated system that ensures optimal growing conditions for plants by continuously monitoring environmental factors and making necessary adjustments. The flowchart outlines how the system collects data, processes information, makes decisions, and controls various actuators.

The system collects real-time data from the following sensors: Temperature Sensor – Measures air temperature inside the greenhouse; Air Humidity Sensor – Monitors the moisture level in the air; Soil Humidity Sensor – Detects the moisture level in the soil; Light Sensor – Measures the intensity of natural light; CO_2 Sensor – Checks the concentration of carbon dioxide for plant growth.

Blinds Position Sensor – Determines the state of the blinds (open/closed) to regulate light and temperature.

The collected data are compared with predefined threshold values set for each environmental parameter.

The system evaluates the readings and determines the appropriate response: If Temperature is too High → Activate Cooling System (e.g., fans, ventilation); If Temperature is too Low → Activate Heating System; If Air Humidity is too Low → Turn on the Misting System; If Soil Humidity is too Low → Activate Irrigation System; If Light Levels are Low → Turn on Artificial Grow Lights; If CO_2 Levels are Low → Activate CO_2 Enrichment System; If Blinds Need Adjustment → Open or Close Blinds accordingly.

In the next step, the system activates the corresponding devices to adjust the environment as needed. Sensor readings and system responses are logged for future analysis. The data are displayed on a dashboard, allowing real-time monitoring. If critical conditions arise (e.g., extreme temperature, equipment failure), the system sends alerts via a mobile app, email, or SMS.

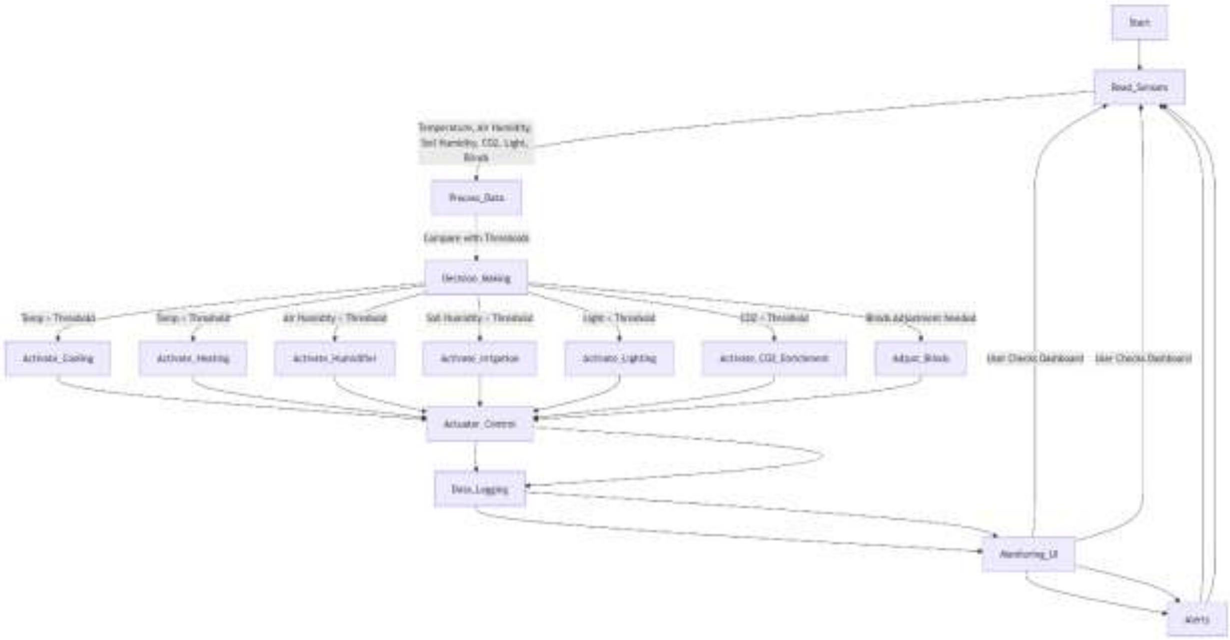

Fig. 3. The Greenhouse Monitoring and Control System
Source: Own contribution.

Users can manually check and adjust settings through the interface. The system continuously loops back to sensor readings to maintain optimal conditions.

The benefits that automation system bring are:

•Increased Crop Yield & Quality, by: maintaining optimal growing conditions, ensuring healthier plants and higher yields, preventing stress conditions (e.g., overheating, overwatering) that may damage crops.

•Efficient Resource Management, by water savings: automated irrigation ensures that plants receive just the right amount of water; energy efficiency: grow lights, fans, and heaters only activate when needed, reducing electricity consumption; CO_2 optimization: the CO_2 enrichment system boosts plant growth without excess waste.

•Reduced Labor Costs & Human Error: the system works automatically, reducing the need for manual monitoring and intervention and preventing mistakes such as overwatering, which can lead to root rot.

•Remote Monitoring & Control: cloud connectivity allows farmers to monitor conditions via a smartphone or computer. Alerts notify users about critical conditions, enabling quick intervention.

•Data Logging & Predictive Analysis: the storing of historical data for trend analysis and future optimizations helps farmers predict climate conditions and adjust settings accordingly.

•Scalability & Integration: the system can be expanded to multiple greenhouses or can be integrate with AI-based systems for advanced decision-making (Dorf et al., 2016; Puspitasari et al., 2018; Li et al, 2021; Visvesvaran et al., 2021; Soussi et al., 2024) [7, 23, 16, 34, 28].

3.Enhancing Greenhouse Agriculture Production through Optimization of Intervals Between Cultivation Cycles

Optimizing the cultivation cycles between two harvests and production yields in greenhouse agriculture can be achieved through a series of strategic and technological measures. First and foremost, the selection of adapted varieties is essential, with the recommendation to choose species and cultivars with shorter growth cycles, increased resistance to diseases and pests, and high productivity (Mihnea, 2011) [18]. Resource management plays a crucial role, through the use of efficient irrigation systems, such as drip irrigation or soil moisture monitoring technologies, and through the precise application of fertilizers, tailored to the crops' needs and soil analyses.

Microclimate control is another important aspect, achieved by adjusting temperature, humidity, and light levels with the help of automated systems and supplementing light with LED lamps when necessary. Careful planning of cycles and crop rotation significantly contributes to preventing soil depletion and the spread of diseases, ensuring optimal conditions for each crop.

Advanced technologies, such as precision agriculture, sensors, and artificial intelligence, enable real-time monitoring and adjustment of critical variables, thereby optimizing growing conditions. In addition, reducing unproductive intervals between cycles can be achieved by automating processes such as harvesting, soil preparation, and planting, as well as using modern substrates, such as coconut fiber or perlite, which facilitate rapid transitions between crops.

By applying these measures, greenhouse agriculture can become more efficient and sustainable, maximizing the use of space and resources while ensuring increased productivity in the long term.

The cultivation cycles between two harvests and production yields in greenhouse agriculture are essential factors in optimizing agricultural systems. Optimizing these cycles involves careful management of the duration of each cycle, crop rotation, and resources used, such as water, fertilizers, and energy. By implementing modern technologies and adapting agricultural practices to the specifics of each crop, maximum productivity per unit of area can be achieved, while simultaneously reducing costs and environmental impact.

In vegetable farming, the use of greenhouses allows for obtaining two, three, or even more annual harvests through early, main, and successive crops. Between harvest cycles, there are short intervals dedicated to activities such as harvesting the previous crop, soil preparation, applying fertilizers, checking soils, and ensuring an adequate water supply to support the next harvest.

Case study.

In an agricultural farm, a greenhouse is designed to support a cultivation cycle between two harvests, with a duration of t = 110 days, of which the actual cultivation cycle is t_{fi} = 100 days. To shorten the soil preparation period between two crops, a new method of harvesting, soil processing, and seeding is proposed, which reduces the preparation time to t_{r1} = 5 days. The fixed costs for the greenhouse in question are 9,000 lei/day, while the costs for soil preparation will increase from R_0 = 200,000 lei to R_1 = 263,000 lei. To calculate the minimum effective operating duration of the agricultural greenhouse that justifies the increase in soil preparation costs by 63,000 lei, we proceed with the following steps.

$$t_{fi} = \frac{(R_1 - R_0 + c_k \cdot t_{r1}) \cdot t_{f0}}{c_k \cdot (t_0 - t_{f0})} \text{ [days]}$$

$$t_{fi} = \frac{(263{,}000 - 200{,}000 + 9{,}000 \cdot 5) \cdot 100}{9{,}000 \cdot (110 - 100)}$$

$$t_{fi} = 120 \text{ days}$$

$$t_1 = t_{fi} + t_r = 120 + 5 = 125 \text{ days}$$

where:

t_{fi} – effective operating duration of the greenhouse, in days;

R – soil preparation costs;

C – fixed costs per greenhouse, in lei/day;

t_r – duration of soil preparation work, in days;

t_f – duration of the actual cultivation cycle, in days.

Therefore, the introduction of the new method of harvesting, soil processing, and seeding will be profitable if the operational intervals between two cultivation cycles increase from 100 days to at least 120 days. In the end, the cultivation cycle between two harvests is extended to 125 days. The extended growth period can provide the plants with more time to accumulate biomass and develop fruits or seeds, leading to increased productivity.

CONCLUSIONS

An automated agricultural greenhouse is safer, consumes less energy, and ensures high productivity. It provides complete control over the facilities: electrical installation, heating, humidity, ventilation, CO_2, and is easy to control remotely.

The Greenhouse Monitoring and Control System is a highly efficient, automated solution for maintaining optimal environmental conditions. It enhances productivity, reduces resource wastage, and allows remote monitoring. By integrating IoT, automation, and data logging, this system is essential for modern precision agriculture.

The integration of automated systems for monitoring and control, along with the optimization of cultivation cycles and resource management, leads to increased efficiency, reduced energy consumption, and enhanced productivity. Ultimately, this research contribute to maximizing the economic and environmental benefits of greenhouse farming.

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