SMART GREENHOUSE AND PLANT GROWTH CONTROL

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Abstract. Since the development of agriculture is an important problem for every state, huge funds are allocated to this industry. However, the problem of lack of fresh fruits/vegetables, that is, the problem of import substitution remains a pressing issue in many countries. The aim of the study was to inspect the growth of plants in a home-based mini-greenhouse, for which reason the following tasks were set: conduct a biological experiment; search for dependence of the influence of environmental conditions (microclimate) on growth. The paper highlights the problem of import substitution of vegetables in Kazakhstan, and suggests the best way to solve this issue. The proposed solution offers the development of mini-greenhouse that meets the criteria of price and quality. The developed system differs from other smart greenhouses, firstly, by its availability to a wide range of users (price criterion), and secondly, by ensuring agrotechnical, energy, and design requirements (quality criterion). These requirements are implemented through the use of promising technologies: phytomonitoring, intelligent technologies and open source software, the use of available construction materials and water saving technologies such as drip irrigation. The economic effect from the use of the proposed technology has amounted to 10,000 tenge, the payback period was 4 seasons.

Keywords: home-based mini-greenhouse, phytomonitoring, drip irrigation, optimum, plant growth dynamics, open source software.

Introduction

Throughout human history, agriculture has remained the most conservative branch of the economy. Low margins, high risks, an acute dependence on fluctuations in the prices of fertilisers, fuel, finished products (highly fragmented supply chain) impede the infusion of private investment. Up to 30% of the total budget of the European Union is spent on supporting European farmers [1]. Greenhouse industry is one of the leading branches of agriculture. The health of the population directly depends on the development of this sector of the economy. For the full development of the

human body, 80-100 kg of fresh vegetables (not counting potatoes) are needed for one person a year. For a family of 5, it is necessary to consume vegetables (kg): tomatoes (50), cabbage (50), onions (50), carrots (50), cucumbers (25), beans (25 kg), etc. [2; 3].

Since the development of agriculture is an important problem for every state, huge funds are allocated to this industry. However, the problem of lack of fresh fruits/vegetables, that is, the problem of import substitution remains a pressing issue in many countries [4-7]. The authors of the paper suggest the following solution. It is necessary to build a mini-greenhouse, which, although cannot give a large harvest, can provide for one family. The main advantage of mini-greenhouses from industrial ones is an affordable price for building materials, relatively low prices for household appliances and components, low costs for resources (electricity, water, etc.). It is assumed that if every citizen himself provides his family with fresh vegetables/fruits (growing in his own garden), then the state problem of import substitution will eventually fix itself [8]. There is also a problem of lack of personnel in the countryside due to the outflow of rural youth to the city. The training of rural personnel in the field of smart and precision farming, energy-saving technologies, as well as the widespread introduction of mini-greenhouses in the village will solve the last problem.

It is known that the key requirement for the development and implementation of technical systems is the price/quality criterion. Obviously, the higher the quality, the higher the development cost and vice versa. But how to assemble a system that provides both the required quality and low price at the same time? One of the key problems in the development of modern greenhouses is the construction of a system that meets the criterion of price/quality [4; 6]: 1 – improving the quality of service (accuracy and high speed of control); 2 – reducing the cost of construction and equipment (availability to the general user) of the greenhouse.

Phytomonitoring is one of the leading advances in the greenhouse industry, which performs direct and continuous monitoring of the plant growth process, aimed at improving the controllable yield factors. According to experts, in the near future, it is the use of phytomonitoring that will become the world standard for developed agriculture and change the approach of farmers to their work [4; 9; 10]. This technology includes three components: 1 – recurrent visual inspection by specialists, sampling of plants, evaluation of the general condition; 2 – systematic laboratory analyses of plants, soil, irrigation water; 3 – continuous processing of information coming from phytomonitoring stations (monitoring sensors). But, however, the widespread adoption of the latest technology is limited by several reasons. A plant is a living organism that implements several functions – maintaining a stationary inner state (immunity), on the one hand, and adaptation to external conditions (survival) [3; 11]. Therefore, there is still a problem of the complexity of analysing the state of the plant (biological problem), and the complexity of developing equipment for monitoring the state of the plant (technical problem) (Table 1).

Table 1. New technologies in the greenhouse industry

Technology	IT functions	Advantages and disadvantages (in terms of price-quality)	Accessibility to the general population
Phytomonitoring [10]	TP control	The quality is increased due to continuous monitoring of all stages of plant growth and development. The price is relatively high.	There is no mass production and widespread use of this technology yet.
Drip irrigation [12, 13]	TP management	The accuracy of water regime control is increased and the loss of water resources is reduced (by about 30-60%). Affordable price.	Yes.
Smart greenhouses [14, 15, 16]	TP management and control	Labour automation, accuracy and speed of data processing. Complexity of development. Requires special knowledge. The development cost is relatively high, requires an order to a specialist.	No.
AIoT platforms / AIoT applications	TP control	Control of data coming from sensors, equipment, and other devices.	Yes.
Agricultural robots	TP management	Unmanned aerial vehicles, drones for	No.

2

		monitoring the state of fields and harvesting, smart sensors.	
Hydroponics / Aeroponics [17, 18]	*	Improves the quality of harvesting by growing plants in water/air. Requires special knowledge in the field of biology and special equipment. The price is relatively high.	Yes.
Genetic engineering [4]	*	Improves the quality of obtaining crop varieties. Requires special knowledge in the field of biology and special equipment. The price is relatively high.	No.

*Note: * These technologies do not belong to IT technologies.*

For these reasons, most inexpensive greenhouses use control schemes without taking into account the state of the object of research – plants. This is a big drawback of such systems [5; 12; 14; 17; 18]. How to get out of the situation, is it possible to find an alternative solution that replaces the use of sensors for monitoring plant health? The authors propose to use intellectual technology instead of a phytosensor as part of the system, that is, two expert systems were used throughout the study. The first is used for control (phytomonitoring), the second – for object management.

The aim of the study is to inspect the growth of a plant in a mini-greenhouse. Research tasks: conduct a biological experiment; find the dependence of growth on the influence of environmental conditions (microclimate).

Materials and methods

In the life cycle (ontogeny) of the plant, four stages are distinguished: embryonic (seed development), juvenile (youth), reproductive (maturity), old age. Growth dynamics is determined by a growth curve that obeys a logarithmic law (Figure 1a) [3; 19]. The productivity of vegetable crops is largely determined by external conditions, that is, by microclimate conditions:

– climatic – temperature (day and night, total temperature), light (illumination, spectrum, photoperiod), air (composition, movement, humidity), magnetic field, mechanical impact (wind, etc.);

– soil (physical and chemical properties, soil air and moisture).

The level of plant response to exposure is determined by three values: optimum (most favourable), minimum and maximum (extreme) values of the factor at which plant life is possible. Closer to the optimum, the normal growth is observed, and closer to the minimum and maximum, the growth of individual organs slows down or accelerates, and as a result, the growth is defective. The closer to the optimum, the shorter the lag and the steeper the logarithmic part of the curve (Figure 1b).
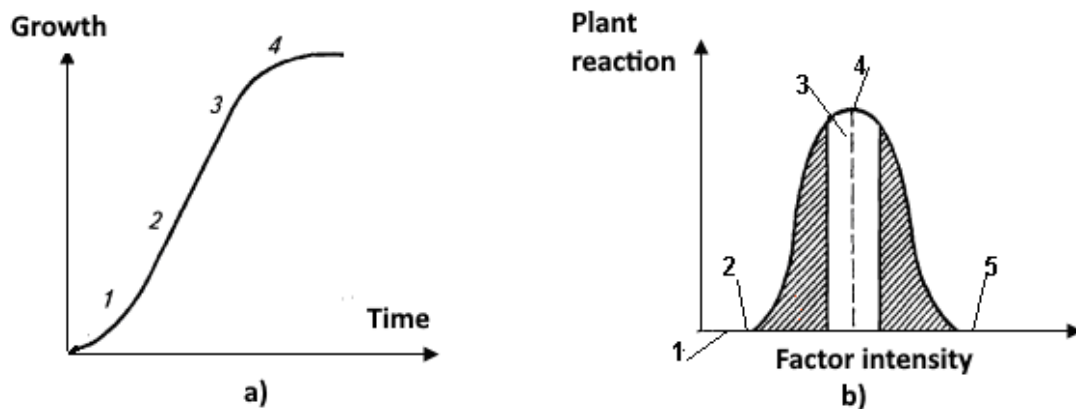
Fig. 1. Plant growth dynamics: a) logistic curve: 1 – lag period, 2 – intensive growth phase, 3 – slow growth phase, 4 – steady state phase; b) the plant's response to environmental factors: 1 – minimum, 2 – pessimum zone, 3 – optimum zone, 4 – optimum, 5 – maximum.

Optimisation of conditions for growing vegetable crops in sheltered ground depends on the level of technical equipment that provides heating, lighting, maintaining a gaseous regime, watering, feeding and caring for plants, phytomonitoring.

The purpose of the experiment is to investigate the dynamics of plant growth in a home mini-greenhouse. The tasks of the experiment: to determine the dependence of growth on the influence of three factors of the microclimate environment: temperature, watering and illumination. Experiment characteristics:

1. Experiment site: home-based mini-greenhouse.
2. Time of the experiments: spring-summer season.
3. Period of the experiments: the full growing season.
4. Biological characteristics of the plant: tomato variety "Pink giant". Mid-season variety (harvest in 110-120 days). The plant is semi-determinate. The normal height of the stem is 45 cm. Planting of seedlings in 40-45 days. Fruits are flat and round, fleshy, low-seeded, very large, weighing 350-500 g, good taste. Productivity 20-24 kg/m^2. Recommended for open and sheltered ground.
5. Cultivation technologies: greenhouse soil, composition – biohumus; drip irrigation.
6. Growing scheme: plot area – pot with of area 1 m^2, total area – 2 m^2. Each pot contains 4 plants (total planted 8).

The agrotechnical work plan is presented in the Table 2.

Table 2. The agrotechnical work plan

No.	Designation of the works	Implementation date
1	Sowing seeds	April
2	Lining-out	April
3	Seedling hardening	April
4	Planting seedlings	April
5	Installation of supports and trellises	May
6	Manual plant care (loosening the soil, weeding, hilling, watering)	the entire growing season
7	– visual inspection, measurement, processing of measurement data; – analysis of the work of the expert system and adjustment, if necessary	every 7 days during the growing season
8	Control and management of plant growth using the "Microclimate GH" mobile application	the entire growing season
9	Combatting plant diseases	May-July
10	Removal of side shoots	May-July
11	Harvest	August

The 7th and 8th stages of the work plan represent the use of intelligent technology. In the course of the 7th stage, the following indicators of plant growth are measured: number and length, colour of leaves, length and thickness of the main stem. The 7th stage is the training mode, and the 8th stage is the usage mode of the expert system.

The figure below provides the process flow diagram of the mini-greenhouse (Fig. 2). The system implements three technological processes (TP): cooling, watering and lighting.
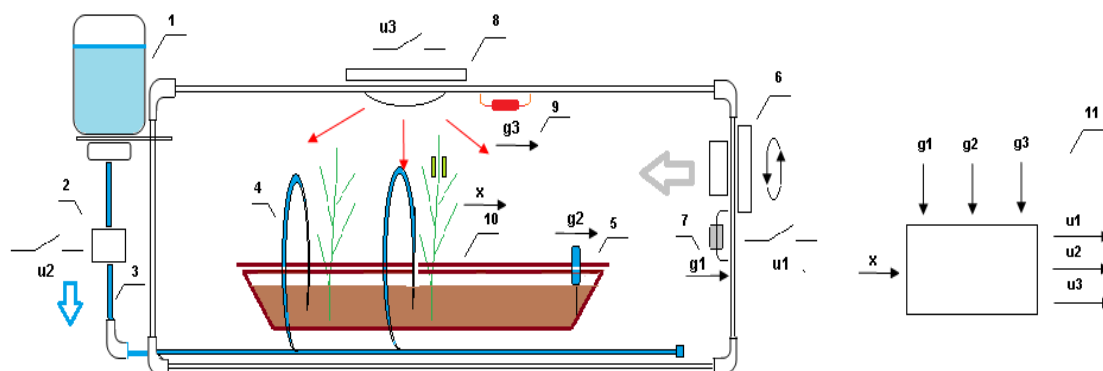
Fig. 2. Technological processes in the mini-greenhouse

145   The drip irrigation system works in the following way. Water is filled into the tank (1). The
146 control unit (CU) (11) regulates the water supply (control action $u2$), that is, opens/closes the water
147 valve (2) by turning on/off the controller relay. When the valve is open, water flows downward
148 (blue arrow), passing the main pipeline (3) and the drip chamber (4), and watering the plant in the
149 pot (brown vessel). Information about the state of the soil $g2$ is measured by the moisture sensor (5)
150 and transmitted to the controller by the control unit. The cooling system is described as follows. The
151 control unit regulates the air supply to the greenhouse, forming a control action $u1$, by turning
152 on/off the fan (6) through a relay. The air supply is indicated by a grey arrow. The temperature
153 sensor (7) measures the greenhouse air temperature $g1$ and transmits the data to the CU controller.
154 The lighting system controls the light conditions in the greenhouse. The control unit generates a
155 control action $u3$, which turns on/off the lamp (8) via the controller relay. The light intensity data $g3$
156 is measured by the light sensor (9) and transmitted to the CU controller.
157   Data on the state of the object x is measured by a phytosensor (10) and transmitted to the CU
158 controller. Based on these data, the CU makes a decision on the management of the object. Let us
159 consider in more detail the connection of the Control Unit with the technological processes of the
160 greenhouse (Figure3).

161
162   a)   b)
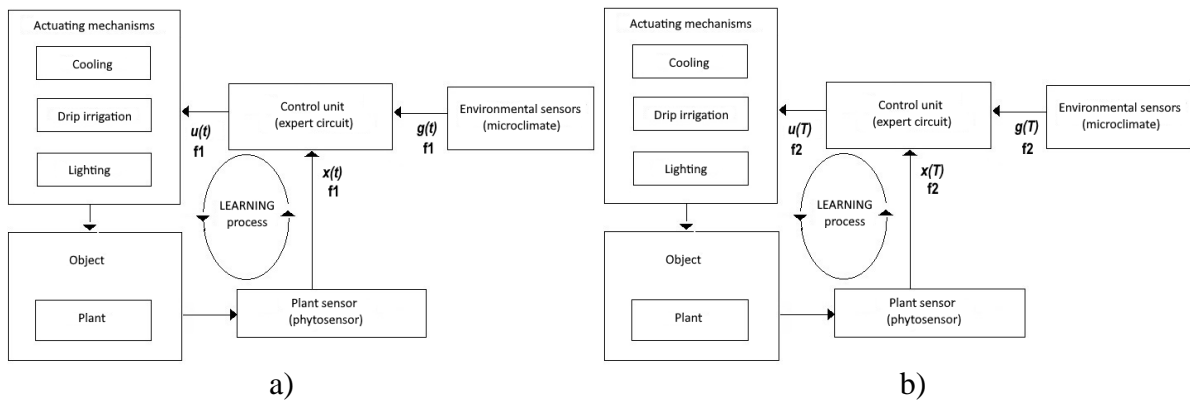
163   **Fig. 3.** Control unit and data processing: a) in usage mode (*f1*); b) in training mode (*f2*)

164   The signals $g1(t), g2(t), g3(t)$ from the sensors of the greenhouse environment (5), (7), (9), the
165 signal $x(t)$ of the plant sensor (10) are received at the input of the control unit. The frequency of
166 reception of these signals and the frequency of processing by the microcontroller are different – the
167 growth rate of a plant is much slower than the speed of reaction to environmental factors. This is
168 due to biological and physiological processes in plants [3; 19]. The frequency of receiving
169 environmental signals is assumed to be $f1=1$ min (this is the frequency of updating the Database).
170 The frequency of receiving signals from the plant sensor (10), describing the growth rate, is taken
171 equal to $f2=7$ days (7*24*60=10080 min). This is the frequency of updating the Knowledge Base.
172   The developed model "Plant-Environment-Situation-Control" allows solving two types of
173 problems: assessment of the state of an object (environment and plants) and the choice of a control
174 mode for NLC. To assess the state of an object, the Environment block and the Plant block are used.
175 The regulator (NLC) implements the function of selecting technological control depending on the
176 situation in the Situation-Control block. The circuit that functionally implements the described
177 model is shown in Fig. 4. It consists of the main blocks: a) Control object, in the centre of which the
178 Plant is located; b) Information and measuring system; c) Actuating mechanisms; d) Control
179 devices (CD) based on NLC. The system is controlled by the CD, which generates a control action
180 based on the rules of the expert (the law of optimum) and based on the assessment of the current
181 situation, calculated on the basis of information received from the measuring sensors and sends it to
182 the appropriate actuating mechanism. Data exchange also occurs through the CD, which sends data
183 to the Cloud Data Storage. Data from cloud storage for machine processing goes to the Matlab
184 script, after processing it goes back to the CD through the Cloud storage. Monitoring data are stored
185 in the storage for the entire growing season.
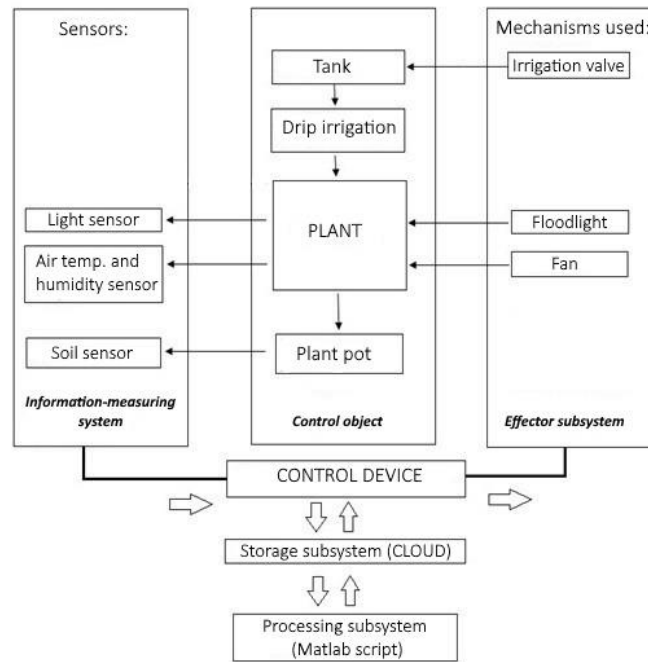
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187 **Fig. 4.** Functional diagram of an intelligent system

188   An experiment was carried out on a small scale, that is, in a home-based mini-greenhouse.
189 This paper also presents an experiment on a large scale in a greenhouse for scientific research. For
190 the purpose of the experiment, a diagram of the third block of the research greenhouse of the Al-
191 Farabi Kazakh National University (Fig. 5). The block area is 3 hectares (length 60 m, width 5 m,
192 height 3.6 m). The growing area contains 4 rows, each row contains 3 blocks. The total number of
193 blocks is 4x2 = 8. One block is one plot, 3 plants can be planted in it. Each of the 8 blocks has its
194 own watering valve (shown as a white open square). Water supply can be controlled by
195 opening/closing the corresponding irrigation valve. Through each valve, through three irrigation
196 droppers, water flows to an 8x3 = 24 plants. To monitor the state of the plant, each plant in the
197 vicinity of the soil zone has its own transmitter with built-in sensors: temperature and humidity,
198 illumination and soil moisture.
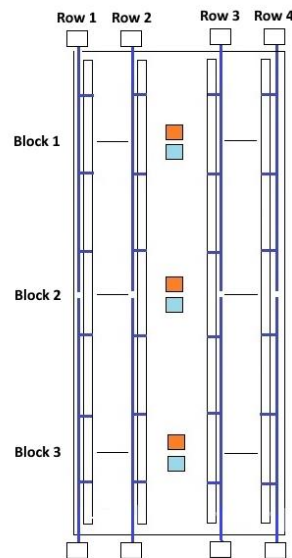
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200   **Fig. 5.** Arrangement of the third block of the greenhouse of the Al-Farabi KazNU

201   In the centre of the greenhouse, between the second and third rows, there are floodlights
202 (highlighted in orange) and fans (highlighted in blue). There is free space between the rows for the

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possibility of performing agrotechnical manipulations, for example, visual inspection, etc. The total number of transmitter boards is 24. The total number of receiver boards with relays is 5. Of these, three are for turning on/off fans and floodlights. And the other two are for turning on/off the irrigation valves.

Characteristics of the biological experiment: the goal and objectives – to conduct a laboratory-vegetation experiment to study the dynamics of growth and assess the environmental conditions for optimum; place of the experiment – research greenhouse of the Al-Farabi KazNU; the time of the experiment is the spring-summer season; the period of the experiments is the entire growing season, including the initial phase, the phase of vegetative growth, flowering and the reproductive phase (fruiting).

Experiment configuration:

1. Growing scheme: the size of the plots – 1 m^2 (2 pots), the number of replications is 5-6.

2. Cultivation technologies: greenhouse soil, composition – biohumus.

3. To regulate the microclimate processes, three modes are implemented: a) cooling/heating mode: ventilation; b) lighting modes: natural and artificial; c) irrigation mode: drip irrigation.

Biological characteristics of the plant: hybrid cucumber variety "Junior Lieutenant". High-yielding early maturing parthenocarpic bundle gherkin hybrid with a female flowering type. It is characterised by intensive growth, good regrowth of lateral shoots in combination with the second type of self-regulation of branching. In the nodes, from 2-3 to 5-7 or more ovaries are formed. Buttons are bright green, lumpy, with white-thorns, 9-12 cm long. High taste and canning qualities. The hybrid is resistant to mildew, cucumber scab, mosaic virus, tolerant to downy mildew. Recommended for open and sheltered ground. The agrotechnical work plan is presented in the Table 3.

Table 3. The agrotechnical work plan

| No.	Designation of the works	Implementation date
1	Sowing seeds	April
2	Lining-out	April
3	Seedling hardening	April
4	Planting seedlings	April
5	Installation of supports and trellises	May
6	Manual plant care (loosening the soil, weeding, hilling, watering)	Initial and All stages
7	– visual inspection, measurement, processing of measurement data; – analysis of the work of the expert system and adjustment, if necessary	every 7 days during the growing season
8	Control and management of plant growth using the "Smart Greenhouse" mobile application	All stages
9	Combatting plant diseases	May
10	Removal of side shoots	May
11	Harvest	Fruiting stage

The experimental data was obtained on specially designed equipment of the "Home Smart Greenhouse" system (the system configuration is given in the Table 4).

Table 4. Technological equipment, materials and programmes

Equipment and materials	Model	Characteristics
Communication device		
Mobile phone	Samsung (1 pce)	Model SM-T239. Operating system Android 4.4.4
Control unit with built-in transmitter and receiver		
Microcontroller + Transmitter	ESP32 WiFi&Bluetooth CP2104 DHT11 Soil (24 pcs)	ESP32 WiFi&Bluetooth development board, support Nodumcu / Arduino DHT11 temperature and humidity sensor CP2104 communication chip Micro USB port Soil probe (long) soil temperature and humidity detection module LM393 based photosensor

Microcontroller + Receiver	ESP 32 WiFi + Bluetooth + battery (5 pcs)	ESP32 WiFi&Bluetooth development board, support Nodumcu / Arduino CP2104 communication chip USB to TTL Micro USB port 18650 Lithium Battery Holder Powered (Battery is not included)
MK programming environment	Arduino IDE (1 pce)	version 1.8.10
Mobile coding environment	Blynk (1 pce)	version 2.27.6

Figures 6 and 7 show experimental data on the environment and plants for 75 days. This is the daily average of the environment and the average of each plant. The average yield was 3-4 kg/plant. By maintaining optimal conditions in the greenhouse, several yields can be obtained in 2-3 months.
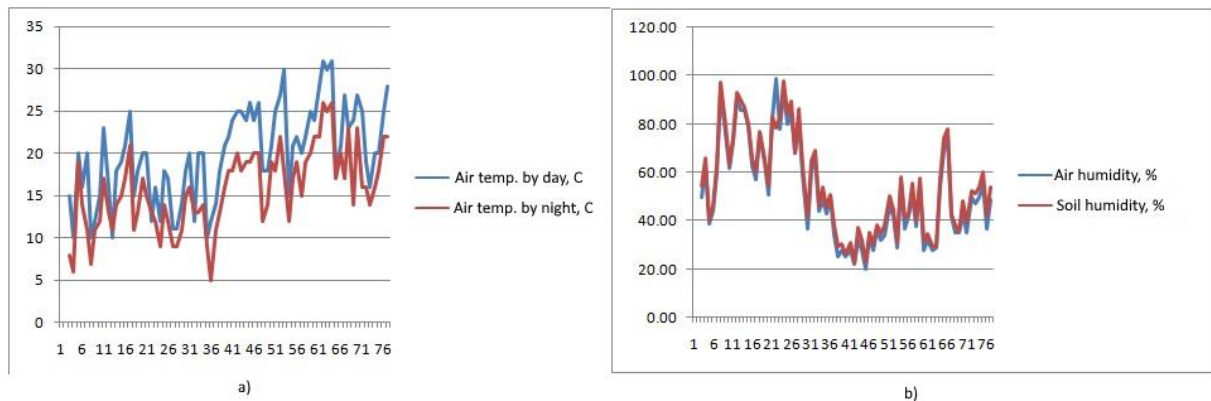
Fig. 6. Data from monitoring air temperature (a) and humidity (b)
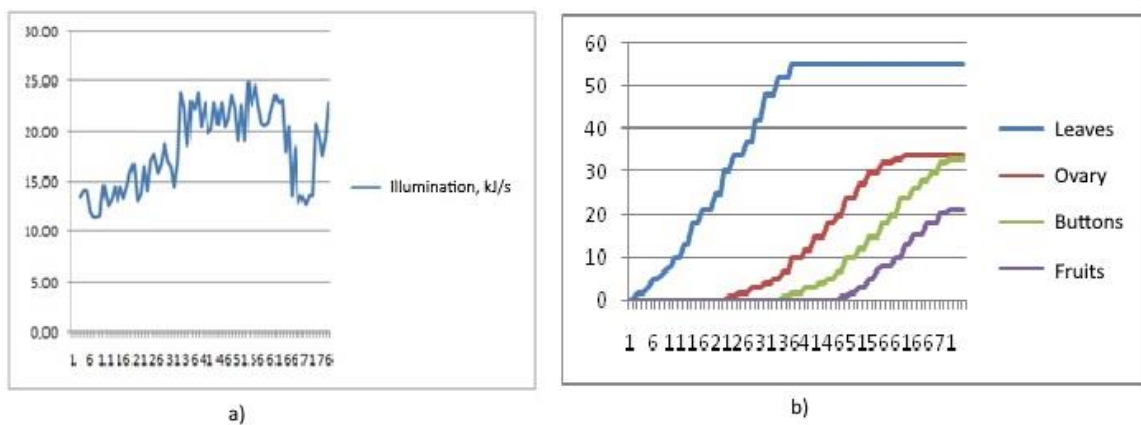
Fig. 7. Data from monitoring illumination (a) and growth dynamics (b)

2. Results and discussion

A mathematical model of the "Plant-Environment-Situation-Control" system is proposed. It consists of blocks: Environment, Plant, Situation, and Control:

1 – Block Environment characterises the state of the microclimate on a daily basis (Atmosphere – air temperature, relative air humidity; Soil – relative soil humidity; Light – illumination). The state of the environment is described by the vector F.

2 – The Plant block is the main block of the system (Control object) and characterises the state of the plant and is described by the vector X.

3 – The Situation-Control block characterises the state variables of the system and the choice of the control mode (ventilation, lighting, drip irrigation) depending on the specific situation S. In this block, the integral indicators of Environment and Plants are calculated.

The mathematical model of the system belongs to the class of continuous-discrete (hybrid) systems. This suggests that the system is characterised by both continuous and discrete behaviour. Despite the fact that in any physical system the time t is continuous, we can speak of discrete times t (i,j) as a subset of continuous time values. The developed model of the "Plant-Environment-Situation-Control" system and the process of regime control in accordance with a specific situation are shown in Figure 8. Before starting the simulation, the operation of converting continuous time into discrete time is performed: $t \rightarrow t$ (i,j). For example, the processes in the Environment Block are described in the diurnal time scale t (i), that is, they have the Day and Night states. And the processes of the Plant Block on a biological time scale t (j), this means that during the growing process, the plant passes through four phases (phenophases): initial (Sprout-Seedling), growth of the vegetative part, flowering and fruiting.
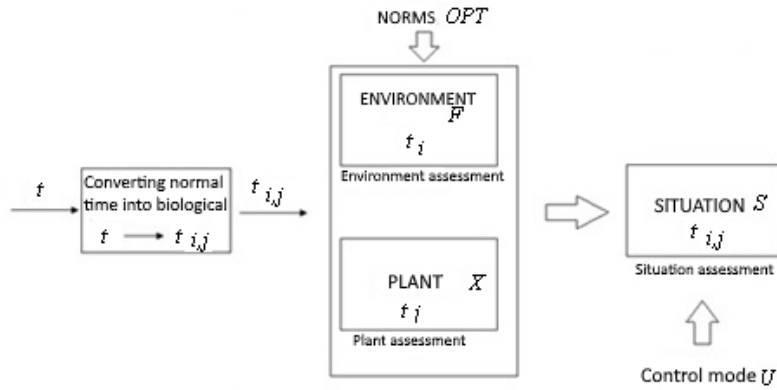
Fig. 8. Model of the "Plant-Environment-Situation-Control" system and regime control

Depending on the specific state of the environment and the state of the plant, the system transitions from one mode to another. These specific states are situations (events). They define the control modes. There are two types of modes: a) biological, which describe the transition of a plant from one phase to another; and b) technological, describing the transition from one technological process to another. The conditions for the transition from one mode to another are determined by the corresponding biological and technological standards [20-22].

The "Plant-Environment-Situation-Control" model is described in [2; 4] and is implemented as an expert system (ES). Its core is the Knowledge Base (KB), it is built on the basis of an expert's knowledge and formalised in the form of rules. In our case, knowledge base replaces the mathematical model of the control object. At the same time, the success of solving the problem largely depends on the structure and content of knowledge bases, as well as algorithms for their processing. At the disposal of the expert, with whose participation the biotechnological (biological and technological) control is formed, there is a database in which the state of plants $X(t)$, the state of the environment (climate) $F(t)$, operating parameters of technological operations u_k (t), $k=0,1,2,3$ (norm, ventilation, lighting and watering). The knowledge of the expert in assessing the situation S (X, F) will be used to select the control mode u_k.

The model of the "Plant-Environment-Situation-Control" system is specified as a sequence (Eqs. 1-6):

$$\langle X, F, S, OPT, U \rangle \tag{1}$$

$$X = \langle X_m(t_i), X_m(t_j) \rangle \tag{2}$$

$$F = \langle F_r(t_i), F_l(t_i) \rangle \tag{3}$$

9

$$282 \qquad S = \left\langle S_i(0, F_r), S_i(0, F_l), S_j(X_m, 0, t^*, t^{**}, t^{***}), S_j(X_m, F_l, t^*, t^{**}, t^{***}) \right\rangle \tag{4}$$

$$283 \qquad OPT = \left\langle OPT_i(0, F_r), OPT_j(0, F_l), OPT_j(X_m, 0, t^*, t^{**}, t^{***}), OPT_j(X_m, F_l, t^*, t^{**}, t^{***}) \right\rangle \tag{5}$$

$$284 \qquad U = \left\langle U_k(S_i), U_k(S_j) \right\rangle, \tag{6}$$

285   where:

286      $-X_m(t_i)$ – daily plant state – input parameter (data);

287      $-X_m(t_j)$ – biological state of the plant – input parameter (data);

288      $-F_r(t_i)$ – daily state of the environment – input parameter (data);

289      $-F_l(t_j)$ – biological state of the environment – input parameter (data);

290      $-S_i$ – assessment of the current situation (daily) – calculation;

291      $-S_j$ – assessment of the current integral situation (biological) – calculation;

292      $-U_k(S_i)$ – control mode in the current situation (daily) – calculation;

293      $-U_k(S_j)$ – control mode in the current situation (biological) – calculation;

294      $-OPT_i$ – optimal conditions and norms (daily) – task;

295      $-OPT_j$ – optimal conditions and norms (biological) – task.

296      $- t \in [0; T]$ – period.

297   Discrete moments of time t (i,j) are Boolean functions $D(t)$, $J(t)$ (Eqs. 7-8):

$$298 \qquad D(t) = \begin{cases} 1, t = t^{sосх} \\ 0, t = t^{зах} \end{cases} \tag{7}$$

$$299 \qquad J(t) = \begin{cases} 1, t = t^* \\ 2, t = t^{**} \\ 3, t = t^{***} \end{cases} \tag{8}$$

300   where: t^*, t^{**}, t^{***} – moments of the onset of the 1st, 2nd, 3rd phases of plant development; t^{srise}, t^{sset}-
301   the moments of sunrise and sunset; t – normal continuous time; $D(t)$ – discrete time (daily); $i = 0, 1,$
302   2; n – day number; $J(t)$ – discrete time (biological); $J = 0, 1, 2, 3$ – plant phenophase number.

303   The state of the plant $X_m(t_i)$ and $X_m(t_j)$ is defined through the variable $m = 1, 2, 3, 4$ – the
304   number of agrotechnical indicator; where the specified variable expresses, respectively, the number
305   of true leaves, the number of ovaries, the number of buttons, the number of ripe fruits in the daily t_i
306   and in the biological time scale t_i. The state of the environment $F_r(t_i)$ and $F_l(t_j)$ is defined through
307   the variables $r = 1, 2, 3, 4, 5$ – the number of the microclimate parameter and $l = 1, 2, 3, 4, 5$ – the
308   number of the integral indicator; where $F_r(t_i)$ expresses, respectively, the daytime air temperature,
309   night-time air temperature, air humidity, illumination, soil moisture in the daytime t_i; and the
310   variable $F_l(t_j)$ expresses the daytime total effective temperature, night-time total effective
311   temperature, total effective illumination, light period, and heat period in biological time t_j.

312   Control modes (technological solutions) $U_k(S_i)$ and $U_k(S_j)$ are defined, respectively, through
313   the variable $k = 0, 1, 2, 3$ – control mode number: norm, ventilation, lighting, watering; where the
314   variable $U_k(S_i)$ expresses the choice of the k-th mode in the current situation on a daily time scale;
315   and $U_k(S_j)$ expresses the choice of the k-th mode in the current situation on a biological time scale
316   for the j-th phase.

317   Mini-greenhouse is located in the apartment, under the window. The drawings were removed
318   in the evening. It can be seen that the apartment is dark, although it was light outside and there is a
319   lack of light. Therefore, most of the time the floodlight is switched on (Fig. 9).

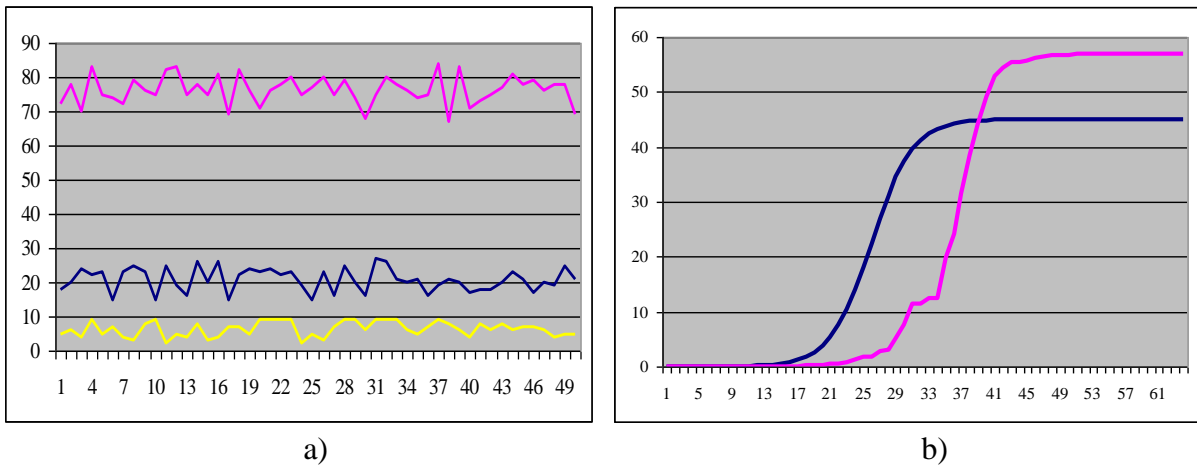a)   b)   c)
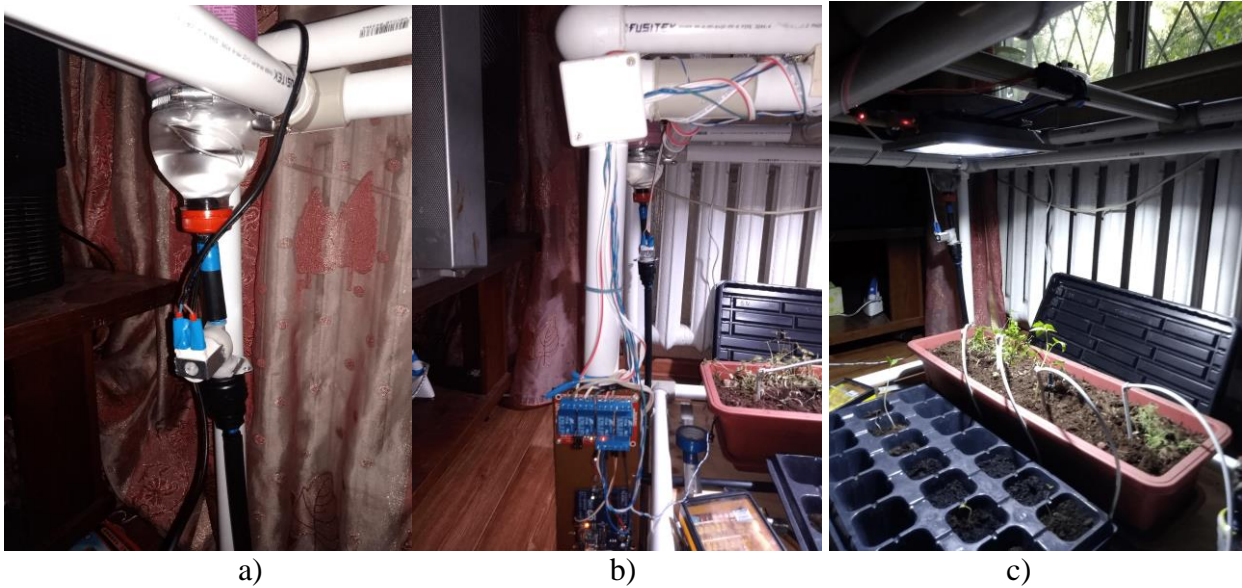
Fig. 9. Home mini-greenhouse: a) irrigation valve; b) control unit; c) plants in the greenhouse

Figure 10 illustrates the readings of the sensors for air temperature, soil moisture and light. These data reflect the law of variation of a random variable (temperature 20 ± 2 ºC, soil moisture $76 \pm 6\%$, illumination 5 ± 2 lm).

a)   b)

Fig. 10. Influence of environmental factors (microclimate) on plant growth: a) measurement data of microclimate parameters (pink line – soil moisture, blue line – temperature, yellow line – lighting); b) plant growth depending on the microclimate condition (blue line – growth under normal environmental conditions, pink line – growth under deviations of environmental conditions and control modes)

The results of the biological experiment are shown in the Table 5.

Table 5. The results of the biological experiment (average)

| Control modes	Deviation of microclimate conditions		Zone	Growth quality
{1,1,1}	All three conditions are not met (3 deviations)	2%	Pessimum	Deviation 1
{1,1,0} or {1,0,1} or {0,1,1}	Two conditions are not met (2 deviations)	5%	Suboptimum 2	Deviation 2
{1,0,0} or {0,1,0} or {0,0,1}	One condition is not met (1 deviation)	26%	Suboptimum 1	Deviation 3
{0,0,0}	All conditions are met	22%	Optimum	Normal

From the biological characteristics of the plant, we know that normal growth is 45 cm, planting of seedlings in 40-45 days. The growth graph in Figure 10b shows the plant growth

11

function with deviations from Table 5. Plant growth in a home-based greenhouse with deviations from Table 6 was: stem height 56.93 cm (1.26 times higher), time delay about 10 days.

The calculated conditions for the onset of phases $t^* = 9$; $t^{**} = 31$; $t^{***} = 57$ and real moments of plant phases are correspondingly equal to $t^* = 11$; $t^{**} = 38$; $t^{***} = 65$. In Figs. 11-14 are histograms showing the values of the standard deviations from the optima for air, light, soil and plants. The values of the estimates are respectively equal to $O1 = 0.4008$, $O2 = 0.1797$, $O3 = 1.5159$ (Fig. 8a, 9b, 10a). The overall cumulative estimate is $O = 2.1105$ (Fig. 9a). Fuzzy inference graphs of the knowledge base FIS_OPTIM in Fig. 11b show that the integral state of the environment and the plant is located near the optimum zone, thereby providing favourable conditions for plants. The results confirm that the observed states correspond to the law of optimum throughout the entire period of plant growth and development.
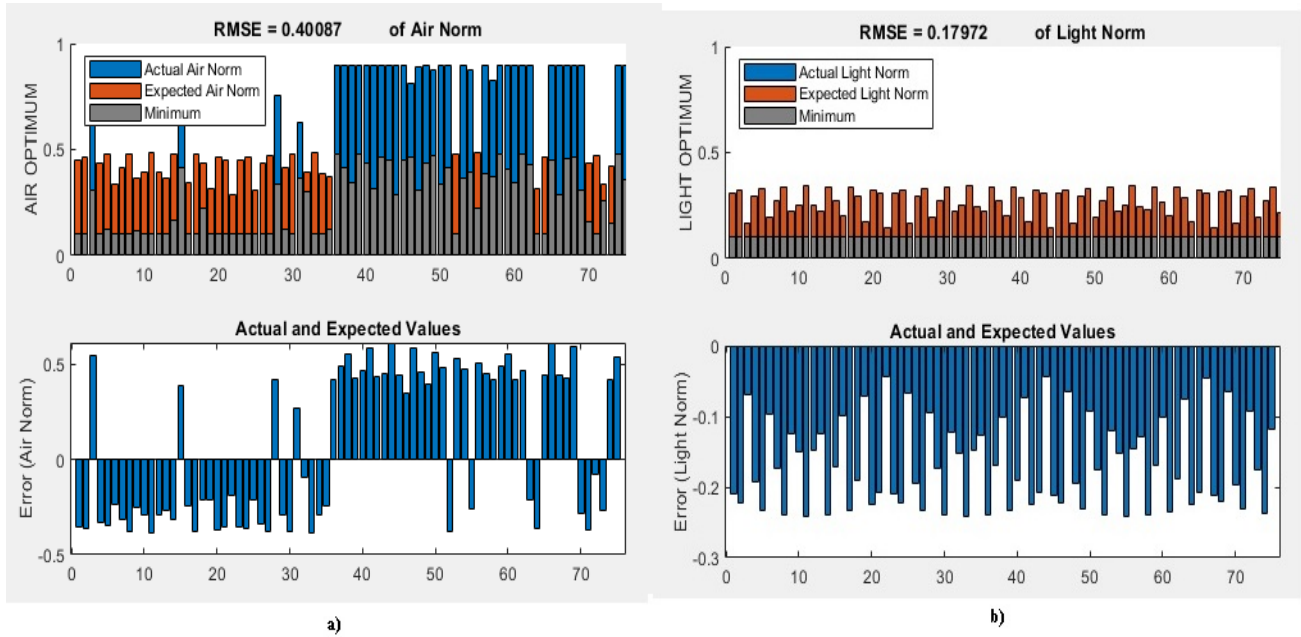
**Fig. 11.** Optimum assessment: a) air environment; b) illumination
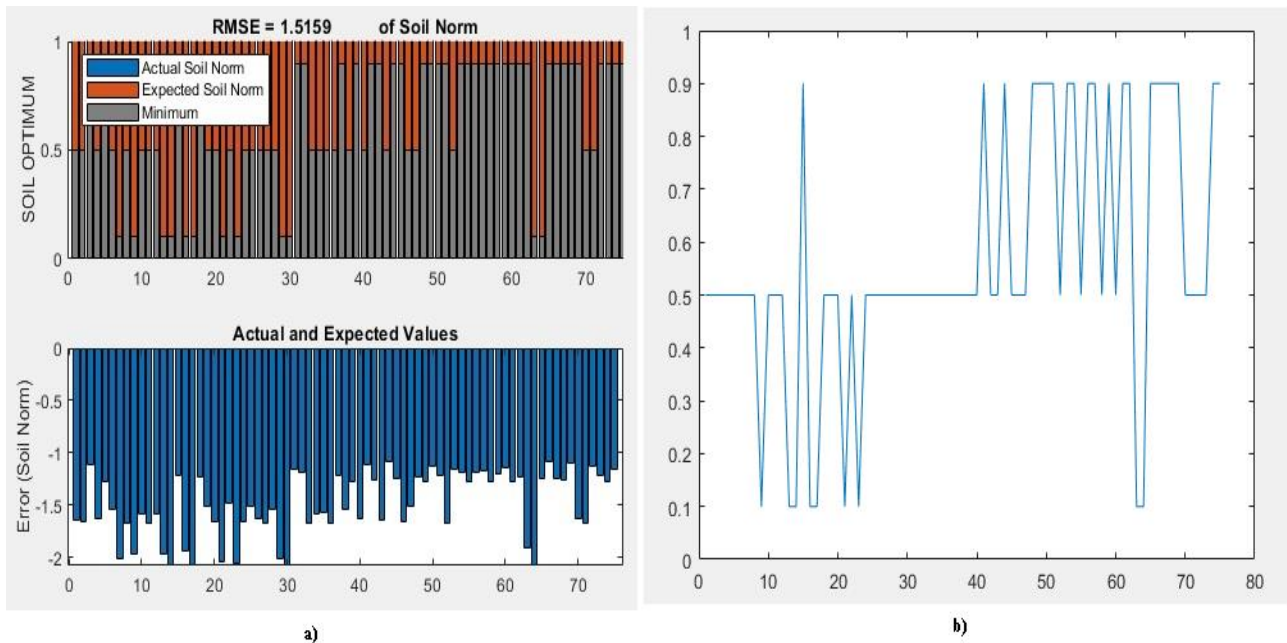
Fig. 12. Optimum assessment: a) soil environment; b) fuzzy inference of the soil environment FIS_OPT3

Figures 13 and 14 also show the structure and rules of the knowledge bases of the fuzzy systems FIS_OPT3 and FIS_OPTIM, which are part of the "Plant-Environment-Optimum" expert system. Figure 10b shows the dynamics of plant growth and development, its graph clearly resembles the logistic growth curve (Fig. 2).
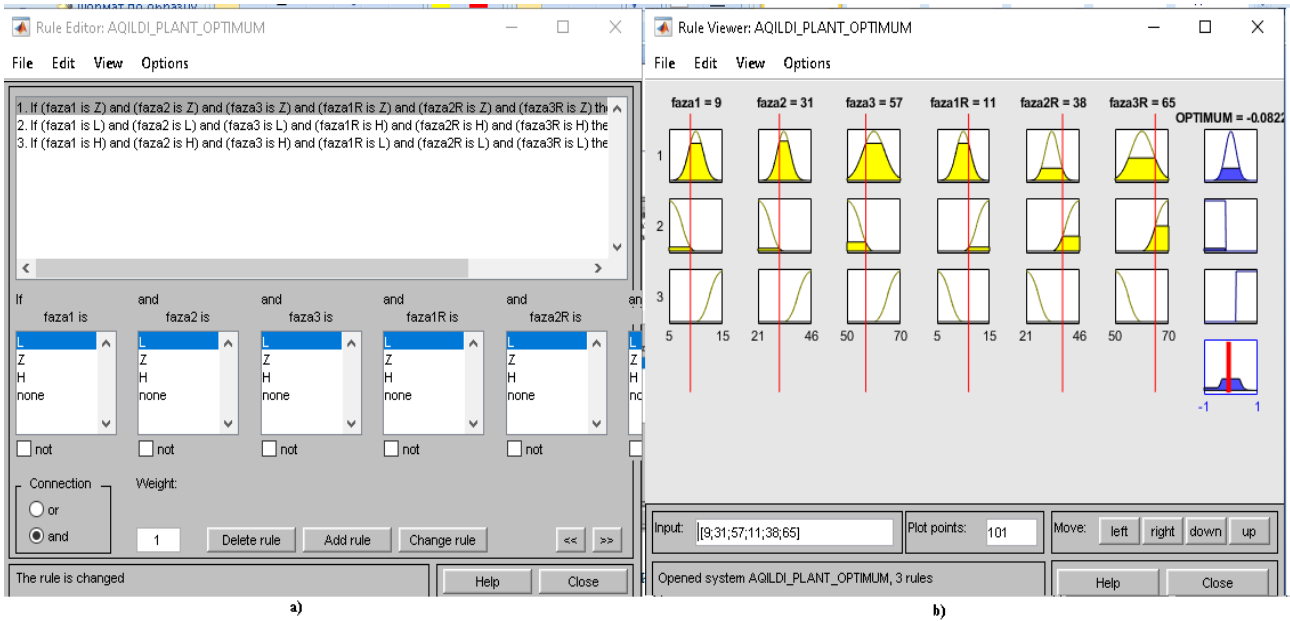
Fig. 13. The knowledge base of the integral estimation of the optimum FIS_OPTIM: a) Knowledge base rules; b) derivation of KB rules
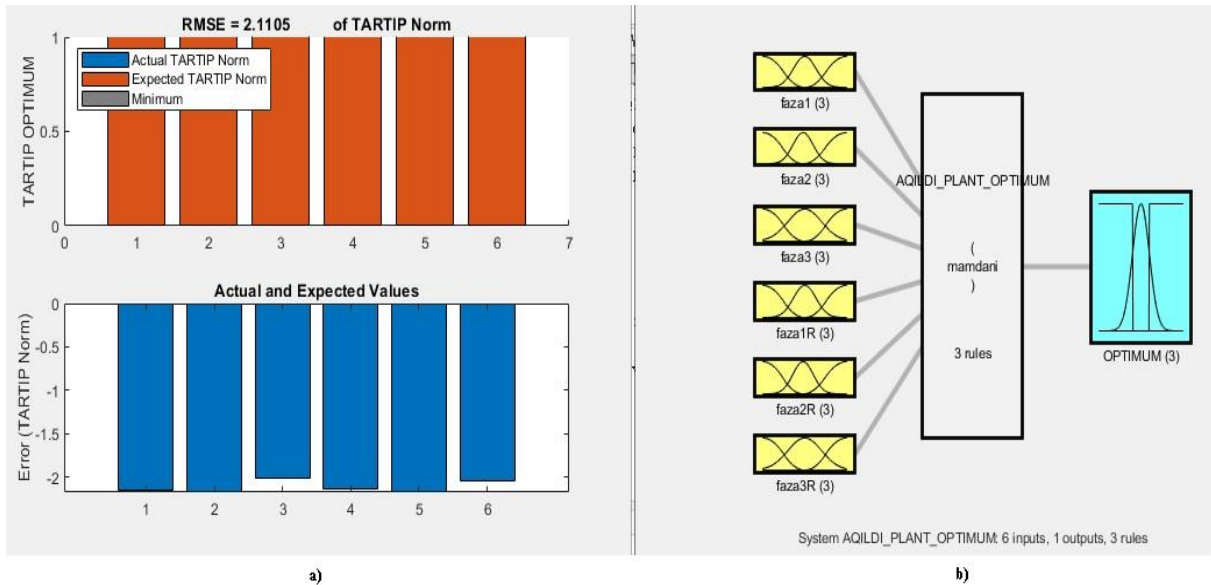
Fig. 14. Knowledge base FIS_OPTIM: a) integral assessment b) structure of the FIS_OPTIM system

Figure 15 shows the greenhouse of the Al-Farabi Kazakh National University during the growing season of cucumber crops.

13

Fig. 15. Greenhouse of the Al-Farabi KazNU during the growing season of cucumber crops

Conclusions

The task of developing mathematical models of complex agrotechnical and biological systems is an urgent problem for engineers and developers of software systems. This paper considers the model of the "Plant-Environment-Situation-Control" systems, proposed by the authors as an alternative version of the "Soil-Plant-Atmosphere" system. Unlike the Soil-Plant-Atmosphere system, which is a white box type model, the latest models are grey box type models, that is, based on the identification of experimental data. A feature of the system is its availability and simple operation, allowing the use of simpler methods than special allometric measurements to account for plant growth and development. It should be noted that the central place in the control of the state of the object and the management of agrotechnical systems will remain with the Man. The developed system is also a man-machine system with a rational separation of the functions of data preparation (computer) and decision-making (man).

In the course of the study, the following estimates were obtained: the state of the air environment to the optimum (process 1), the state of illumination to the optimum (process 2), the state of the soil environment to the optimum (process 3), and the overall integral assessment of the environment and plants to the optimum (process 4). The results obtained confirm that only at optimal values of the factor (in the optimum zone) are the best indicators of plant vital activity observed: they actively grow, feed, and multiply. The greater the deviation of the factor from these indicators, the less favourable it is for plants. As a result of the study, the authors came to the conclusion that:

a) under optimal environmental conditions, the process of normal, balanced growth and development of the plant is observed;

b) with non-optimum, that is, with a lack of certain factors (heat, air, light, water), a slowdown of plant growth and development is observed.

In the course of the study, the following was performed: a biological experiment was carried out; the dependence of growth on the conditions of microclimate parameters were determined.

The following conclusions were also made:

1. Vegetable plants react very sharply to changes in environmental factors, these factors are not interrelated, none can be replaced by another. The lack of illumination cannot be replaced by an increase in temperature or an improvement in root nutrition.

2. The full development of plants, and, consequently, a high yield is achieved while maintaining a complex of environmental factors within the optimum range.

When receiving a crop yield of 20 kg/m^2, at a price of 500 tenge/kg, the economic effect has amounted to 10,000 tenge.

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