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**Computer-integrated control system
for electrophysical methods of increasing plant productivity**

Abstract. Due to the growing demand for agricultural products, there is a need to intensify the process of growing plants and reduce their diseases. Therefore, the technical implementation of methods for controlling the functional activity of plants using electromagnetic radiation at different stages of organogenesis and their automation is an urgent task. The research aims to increase the efficiency of plant cultivation by studying electrophysical methods of controlling their productivity and implementing a computer-integrated system. To achieve this goal, a mathematical corrective model of the interaction of laser radiation with solid biological tissue, algorithms for measuring and generating control effects, methods of automatic control theory, and visual programming in LabView were used. The data were processed in MS Excel. The connections in the biotechnical plant-environment system were analysed, material flows and information channels were identified, a set of state parameters, and direct and cross relationships between them were singled out,

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and sources of disturbances were argued. The basic principles of the interaction of laser radiation with biological tissue are determined and the biophysical mechanism is substantiated. A set of software and hardware control and management tools for conducting experimental studies of electrophysical effects on plant biological objects has been developed. To obtain feedback from plants, new tools for diagnosing the physiological state of plant organisms were developed and a computer-integrated system for controlling the process of plant irradiation was created. The control system is based on the Arduino microcontroller software and is connected to a PC. An operator panel was created to provide automated process control and a subsystem for recording measured data. In practice, the results of this study can be applied in greenhouses in Ukraine and other countries, including in the cultivation of vegetable crops

Keywords: seed treatment; biotechnical system; laboratory setup; platform, algorithm; automation; integrated circuit board

INTRODUCTION

A decline in the profitability of greenhouses, their environmental friendliness, and the reduction of the area of covered ground is being observed in Ukraine. This problem is both food and environmental, so there is a need to develop high-yielding plant varieties. This requires many years of breeding and agronomic work on farms (Trachyova, 2006). To solve this problem, it is necessary to develop automated control systems for biotechnical objects, in which the plant will be the source of information. The information received from the plant will be transformed into a source for selecting optimal control actions. A biological object in the form of a plant is a complex cybernetic system. It is characterised by the ability to change both the tactics and the optimal management strategy to adapt it to the environment.

Adjustment of plant life processes is made possible by changing the spatial and spectral distribution of external electromagnetic radiation. Various methods, including optical ones, can provide this, as they allow to determine the quantitative and qualitative indicators of biological objects with a certain accuracy.

Many researchers in Ukraine and abroad have conducted experiments on microclimate control for growing plants in greenhouses and phytotrons. Experiments with maintaining the microclimate during plant cultivation are carried out using a phytotron, for example, as described by Taiwanese researchers Y.C. Chu & J.C. Chang (2020) and Algerian scientists H.E. Adjerid *et al.* A. Ouammi *et al.* (2020) presents an integrated energy management system for an intelligent greenhouse based on a microgrid, which allows to ensure optimal parameters of the internal environment during crop growth. The management of greenhouse parameters based on the Internet of Things (IoT) is presented in the article by Turkish researchers M.A. Akkas & R. Sokullu (2017). Scientists are creating a personal phytotron at an affordable price thanks to a wide range of equipment, cloud computing and new opportunities offered by the IoT (Internet of Things). R.A. Abdelouahid *et al.* (2020) investigated that temperature, relative humidity and lighting as environmental parameters represented the growing regimes of seedlings or plants in different developmental stages tested in phytotron chambers. To evaluate the impact of technological parameters on plants, phytotrons with various electronic control systems are also

created to develop new varieties. The article by A.A. Vetchinnikov *et al.* (2021) assesses the impact of different spectra of LED lights on the growth and development of vegetable crops in greenhouses. It is substantiated that LED lamps of different spectra affect the nutritional value of plants.

A. Cherenkov *et al.* (2018) used an electromagnetic pulse method to kill insect pests in gardens. L. Nykyforova (2019) presented the processes in plant production as a biotechnical system, as well as the electrical circuit of a device for measuring the bioelectrical potential of a plant.

The research aims to investigate electrophysical methods of plant productivity control as a biotechnical system, to develop and experimentally test a computer-integrated plant productivity control system.

The following goals were set: analyse the coupling in the biotechnical plant-environment system; create an algorithm for remote temperature measurement; perform the technical implementation of a plant productivity management system based on the Arduino board and the Lab-View software environment.

MATERIALS AND METHODS

The study used a mathematical correction model for the interaction of laser radiation with solid biological tissue (Cherenkov *et al.*, 2018; Nykyforova, 2019).

When it is necessary to describe the process of high-energy laser radiation affecting solid biological tissue, it is necessary to consider the processes of temperature distribution. The evaporation of biological tissue occurs at a temperature of more than 300°C. Therefore, the amount of heat that enters the area of biological tissue must heat it to a temperature greater than 300°C. To calculate this process, the general spatiotemporal characteristic of the temperature distribution was used (1):

$$\frac{dT}{dt} = \frac{q}{\rho \cdot c} + \frac{l \cdot \nabla^2 T_1}{\rho \cdot c}, \quad (1)$$

where q – heat amount; l – biological tissue heat conductivity; T_1 – initial biological tissue temperature; ρ – biological tissue density; c – thermal conductivity of biological tissue.

The amount of heat transferred to the biological tissue depends on the pulse power of the laser radiation, generation frequency, beam diameter, and absorption coefficient.

If the temperature of the biological tissue at the end of the previous pulse is not considered, it can be assumed that the time interval between pulses will be equal to the relaxation time of the biological tissue. The relaxation will be small due to the small diameter of the laser spot (2):

$$q = \frac{W_{im} \cdot (t_{im} + t_{rhl})}{t_{im}} - \frac{\pi \cdot d^2}{4} - \mu_a, \quad (2)$$

where t_{im} – impulse length; t_{rhl} – relax time; μ_a – weight absorption coefficient of biological tissue (3):

$$\mu_a = \frac{4 \cdot \rho \cdot R \cdot \mu_r}{\lambda \cdot d}. \quad (3)$$

Furthermore, refractive values, and transmittance μ_r are constants for these biological tissues.

The Lambert-Beer relationship is valid when the absorption of light is significantly greater than its scattering. The mechanism of light absorption depends on the concentration of the absorbing molecules, and the absorption values at the cellular and subcellular levels can vary significantly for different molecules. In addition, the absorption coefficient can vary for lasers operating in different spectral ranges since absorption is a wavelength-dependent function.

Light in the range of 600 to 1200 nm penetrates biological tissue more deeply with minimal effects on absorption and scattering. In this range, the radiation can reach deep molecular layers. Laser devices, such as argon, dye, and IAG (aluminium yttrium garnet): Nd-laser (both conventional and frequency-doubling) have a strong effect on haemoglobin, melanin, and other organic substances, and can have a coagulation effect. The parameters of biological tissue (thermal conductivity and specific thermal conductivity) are functions of water content, so (4):

$$l = \left(0,06 + 0,57 \cdot \frac{\omega}{\rho}\right), c = \left(1,55 + 0,28 \cdot \frac{\omega}{\rho}\right). \quad (4)$$

During the evaporation of biological tissue, a heat damage zone is formed. This fact confirms that the temperature distribution in biological tissues is gradient. The temperature distribution depends on the following parameters (5):

- distance of biological tissue (plant) to the radiation source (r^*),
- hole depth (h),
- Time (dynamic) characterisation of a biological tissue sample (N);
- impulse effect duration (t_{im}).

$$T = \frac{1}{r^*} \cdot \exp\left(-\left(\frac{N}{t_{im}}\right)^{\frac{1}{2}} - \frac{1}{h}\right), N = \frac{l}{\rho \cdot c}, \quad (5)$$

Considering the above parameters that affect the modelling of the process, the following equation for the dependence of the depth of the hole is derived (h) from the laser radiation duration (6):

$$h = \frac{\sqrt{\frac{l}{\rho \cdot c \cdot t_{im}}}}{\frac{W_{im} \left(t_{im} + \frac{d^2 \cdot \rho \cdot c}{4} \right) - \pi \cdot d^2 \cdot r^* - N}{\ln \frac{4 \cdot t_{im}}{\rho \cdot c \cdot t}} + l \cdot N^2 \cdot T_1 \cdot T^*}. \quad (6)$$

This mathematical model is best suited to describe the process of lithotripsy when biological tissue is ablated. It allows to find the depth of the hole created by the laser beam. The formula for determining the depth of the hole (the thickness of the removed biological layer) can be replaced by a simpler one that gives close values (7):

$$L = \frac{\ln\left(\alpha \cdot \frac{E}{E_v}\right)}{\mu_a}, \quad (7)$$

where E – impulse energy; E_v – volume density of absorbed energy; μ_a – absorption coefficient.

The mass of solid biological tissue material removed by ablation was determined by the average value of the volume of the cavity formed under the action of radiation pulses multiplied by the density of the biological tissue. The productivity of the destruction of solid biological tissue is the ratio of the removed mass of biological tissue to the pulse energy. Technical requirements were established and a prototype of a device for seed treatment using a low-intensity non-monochromatic field was used. To perform physiological measurements of seed treatment with a low-energy non-monochromatic field, the following technical equipment was used according to the developed methodology: a prototype of a device for seed treatment with a low-intensity non-monochromatic field (LIK-30A (laser research complex), manufactured in Russia) and a device for rapid diagnosis of biological objects (Prima-2005M, manufactured in Ukraine), which together form a unified optoelectronic technical system for research and rapid diagnosis of plant health.

Figure 1 shows a schematic diagram of a prototype of a laboratory setup for seed treatment using a low-energy non-monochromatic field.

The computer-integrated monitoring and control system is based on the Arduino Mega2560 hardware (Italy), which is based on the ATmega2560 microcontroller (Fig. 2).

The platform was configured to be powered with a voltage of 5-12 V. The chip receives a stabilising voltage for the microcontroller and sensors. This controller cannot communicate with a computer via the USB port. You can

also power the controller through the port. Arduino operates at a frequency of 16 MHz with 54 digital I/O channels, 16 analogue inputs, 14 of which can be used in PWM (pulse width modulation) mode, 4 hardware serial ports UART, which are designed to communicate with a personal computer and other devices connected to a computer-inte-

grated system. In case of an incorrect request, the “Reset” button can be used.

The software implementation of the described system was performed in the LabVIEW environment. The program is executed using a block diagram, and data processing and graphing are performed in MS Excel.

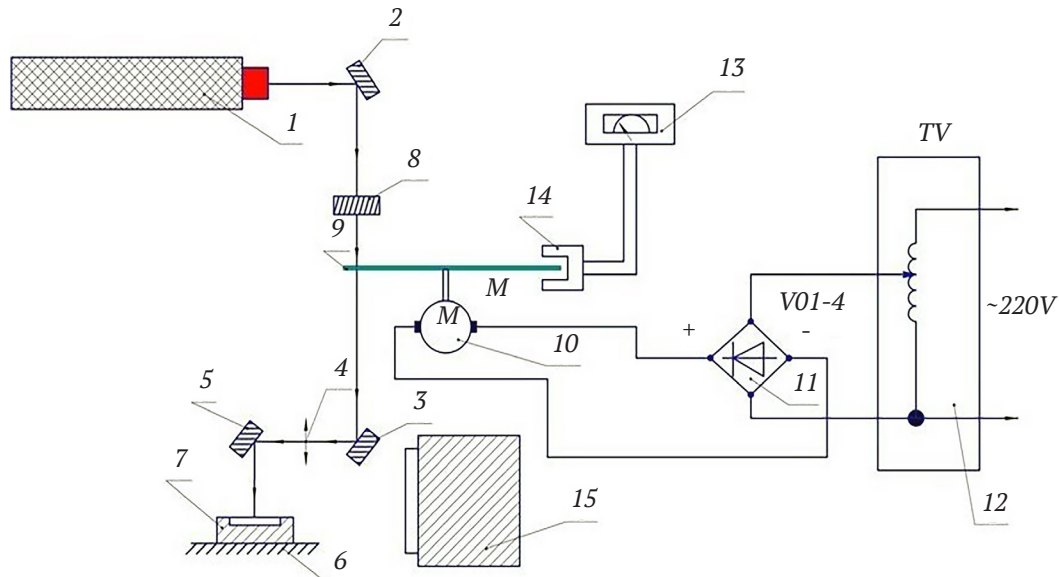


Figure 1. Diagram of a laboratory setup for seed treatment

Note: 1 – laser, 2, 3, 5 – mirror, 4 – lens, 6 – slide, 7 – petri dish with seeds, 8 – light filter, 9 – opaque disc with slots, 10 – electric motor, 11 – rectifier bridge, 12 – autotransformer, 13 – pulse counter/tachometer with sensor, 14, 15 – device for measuring energy density

Source: R.V. Vasilishin (2005)

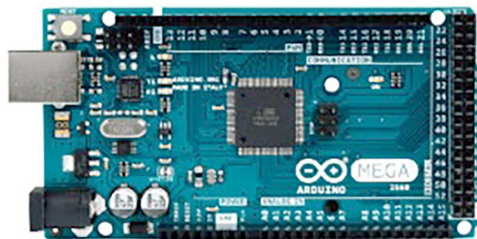


Figure 2. Arduino Mega2560

RESULTS AND DISCUSSION

When analysing the plant-environment biotechnical system, material and information channels were identified, a set of input and output state parameters, as well as the nature of direct and cross-correlation, were determined, and sources of external disturbances were identified. Figure 3 shows a parametric model of a plant biosystem. The most important material and information flows that need to be monitored and analysed are highlighted

(Cherenkov *et al.*, 2018, Nykyforova, 2019). These are the solar radiation inflow E , heat inflow Q , water inflow W , carbon dioxide inflow, and mineral elements C .

The following factors also affect the plant in Figure 3: T_n , T_b , Ψ_n , Ψ_b – temperature and humidity, respectively, of the outside air and the plant, C – nitrogen concentration (NO_3), methane (NH_4), calcium K , calcium Ca , phosphate (PO_4), $f(t)$ – the impact of external disturbances.

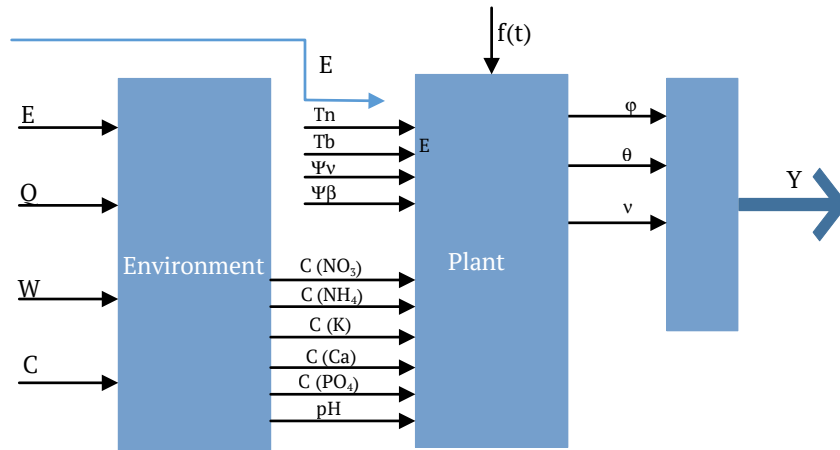


Figure 3. Structural and functional model of a plant biosystem

Note: T_n , T_b , Ψ_n , Ψ_b – temperature and humidity, respectively, of the outside air and the plant, C – nitrogen concentration (NO_3), methane (NH_4), calcium K, calcium Ca, phosphate (PO_4), $f(t)$ – the impact of external disturbances

Source: A. Cherenkov *et al.* (2018), L. Nykyforova (2019)

These technical requirements make it possible to identify a set of plant condition parameters that will include:

- turgor (i.e. water) potential v , %;
- bioelectric field potential ϕ , MW;
- thermodynamic potential θ , °C.

These physical quantities need to be measured in real-time to ensure that the plant's condition is monitored.

Y – is an integrated indicator of the specified output parameters, which is calculated by the formula (8) (Nykyforova, 2019):

$$Y = C \int_t^{t+T_H} y(t) dt, \quad (8)$$

where $y(t)$ – dynamic values of a set of technical parameters.

Thus, to create automated plant productivity management systems, it is necessary to develop a software and hardware complex for measuring bioelectric potential, which will allow for rapid diagnostics while simultaneously monitoring the dynamic state of plants online.

The absorption of laser radiation leads to the appearance of biochemical, bioelectrical and bioenergetic effects in biological tissue. The flowchart in Figure 4 demonstrates the biophysical effects that occur after the absorption of laser radiation, both low and medium power. These effects occur at low power densities and relatively long exposure times.

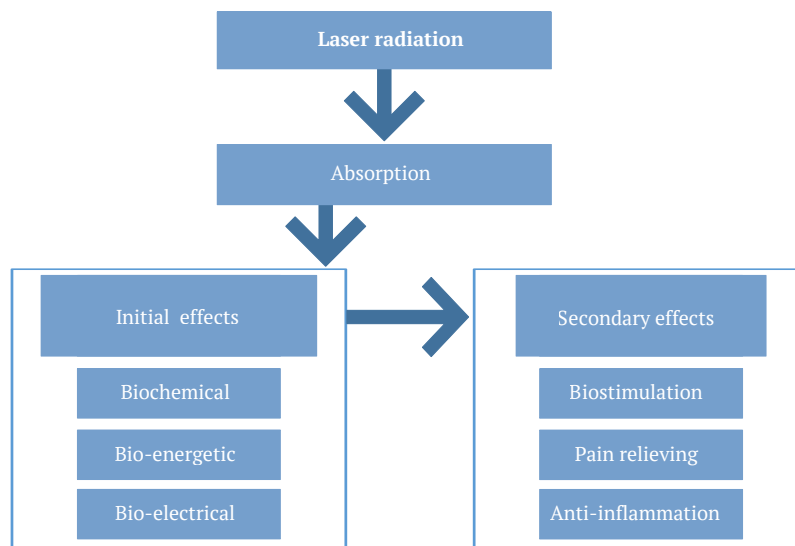


Figure 4. Simplified diagram of the reaction of biological tissue to low or medium-power laser light

Source: compiled by the authors

The photons of the laser source capture a selection in the biological tissue, regardless of the time of illumination

of the selected point. In Figure 5, the arrows indicate the amount of energy incident on the biological tissue.

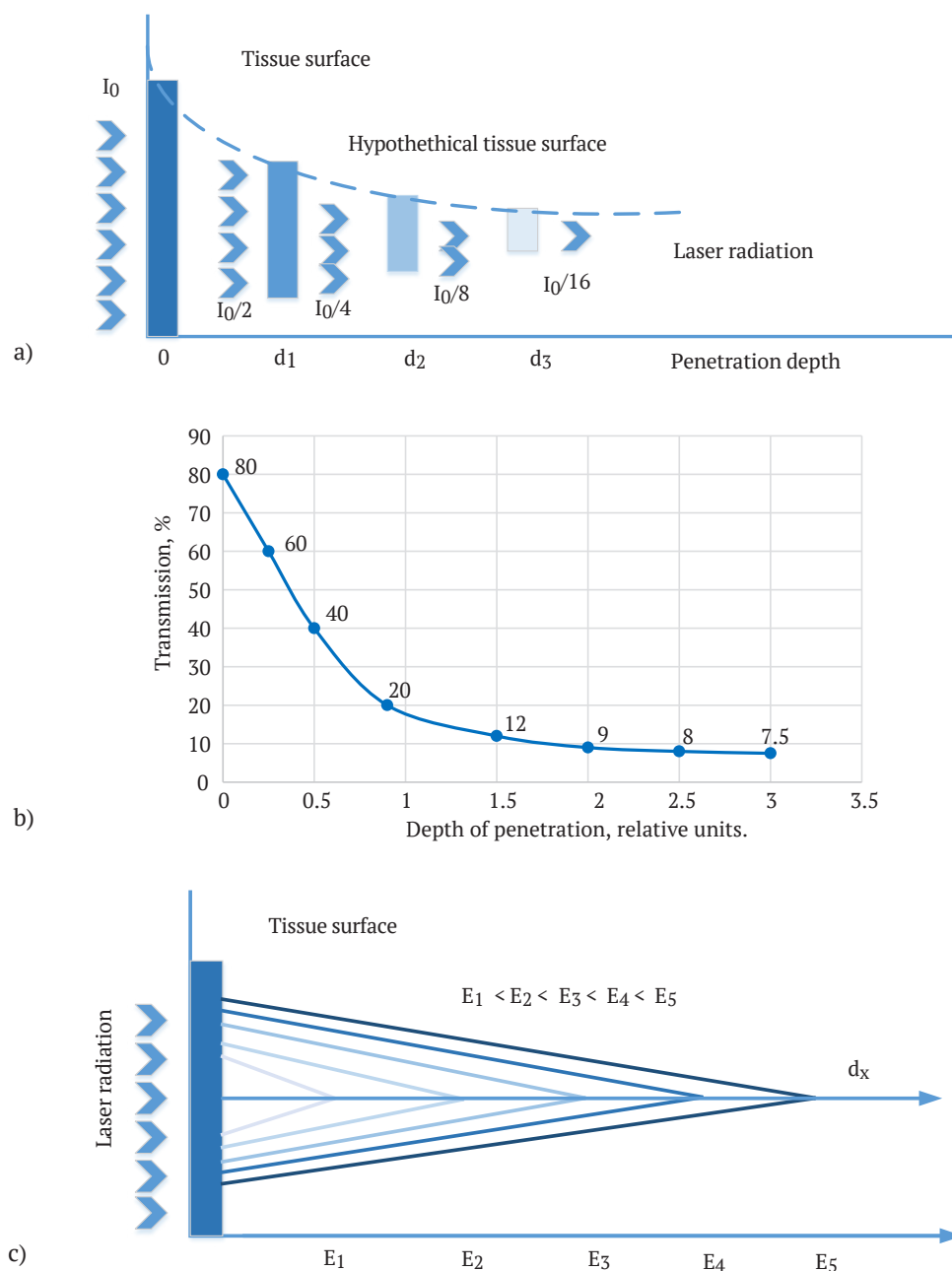


Figure 5. Illustration of the processes of laser radiation penetration into biological tissue

Note: $d_1, d_2, d_3 \dots$ – penetration depth, I_0 – laser radiation index, which decreases multiply upon penetration into the plant, E_1-E_5 – types of laser wave energy, d_x – energy value

Source: compiled by the authors

Penetration into such layers of biological tissue is associated with a decrease in energy. The half penetration depth is the depth of the biological tissue layer that accounts for 50% of the initial energy (Fig. 5a). At the same time, the skin transmits about 80% of the incoming light energy of the tissue (Fig. 5b) when the rays are transversely incident on the tissue. The dependence on the intensity of laser wave penetration with different types of

energy is shown in a schematic graph in Figure 5c. In general, Figure 5 is a “single photon” instruction. According to this theory, a single photon located in biological tissue is sufficient to achieve a bioenergy process.

Figure 6 shows a comparison of the depth of penetration of laser radiation in experiments related to biology and medicine. The algorithm of the control system is shown in Figure 7.

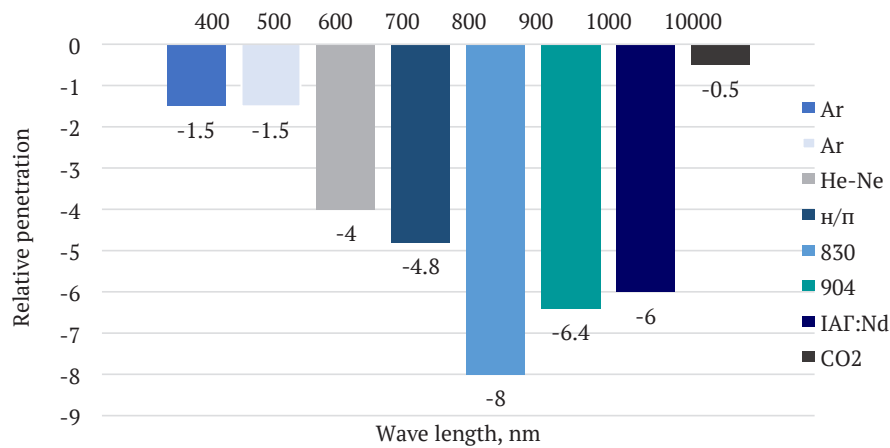


Figure 6. Dependence of the depth of relative penetration of lasers on the wavelength of radiation

Source: compiled by the authors

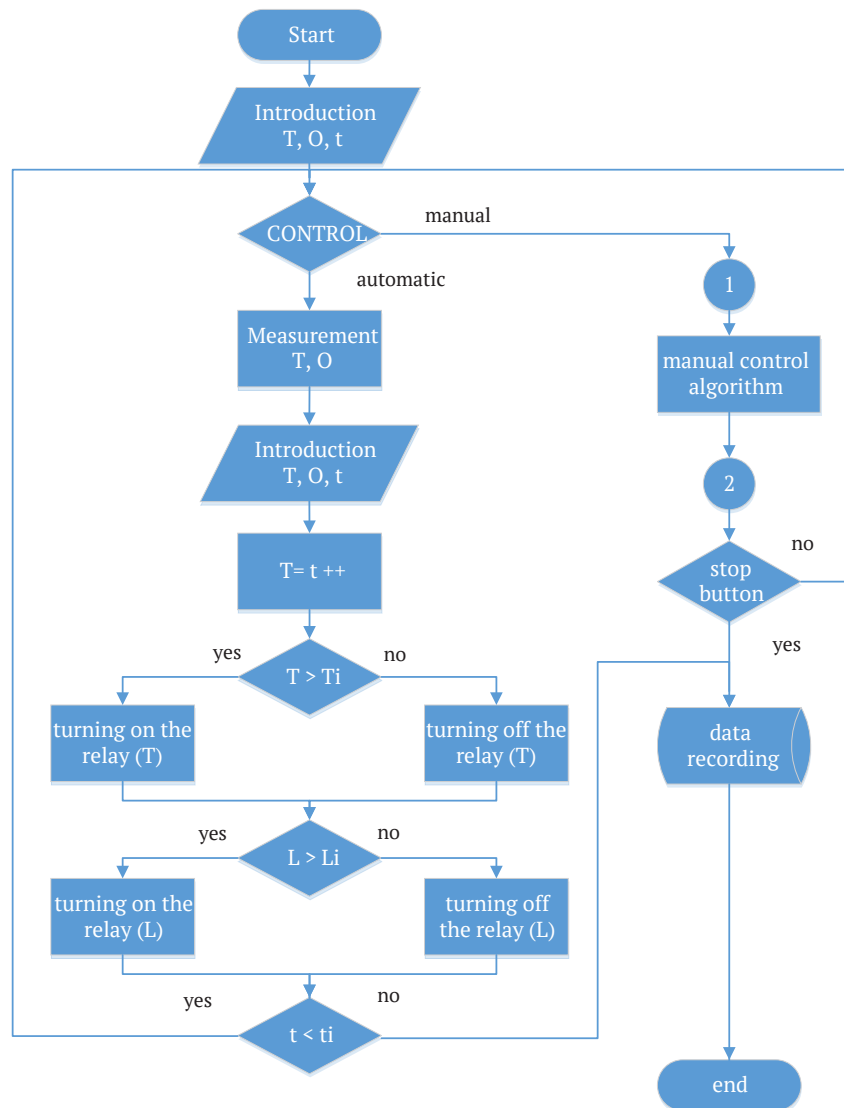


Figure 7. Algorithm for remote temperature measurement (T)

Source: compiled by the authors

The system works as follows:

1) after the power supply is presented, the entire system is initialised, and the critical time value t_k is entered; 2) the effective time value t is compared with the critical time value t_k (the time during which the entire technological process takes place); 3) measurement of process parameters; 4) check the wireless connection, assign an IP address; 5) when connected wirelessly, the measured value is displayed; 6) expectations of the team; go to point 2; 7) in the absence of wireless communication, the system switches to automatic mode; 8) after the control action is transmitted to the actuators, the data is transmitted to

the personal computer of the general control system; go to paragraph 2; 9) when the critical time is reached, the programme is terminated.

One of the most important features of the ESP8266 (Espressif Systems, China) is that it cannot only connect to an existing Wi-Fi network and act as a web server, but it can also set up its network, allowing other devices to directly connect to it and access web pages. This is possible because the ESP8266 can operate in three different modes: station mode, access point mode, and both of the first two modes simultaneously. Figure 8 details the formation of control actions – switching on the relay.

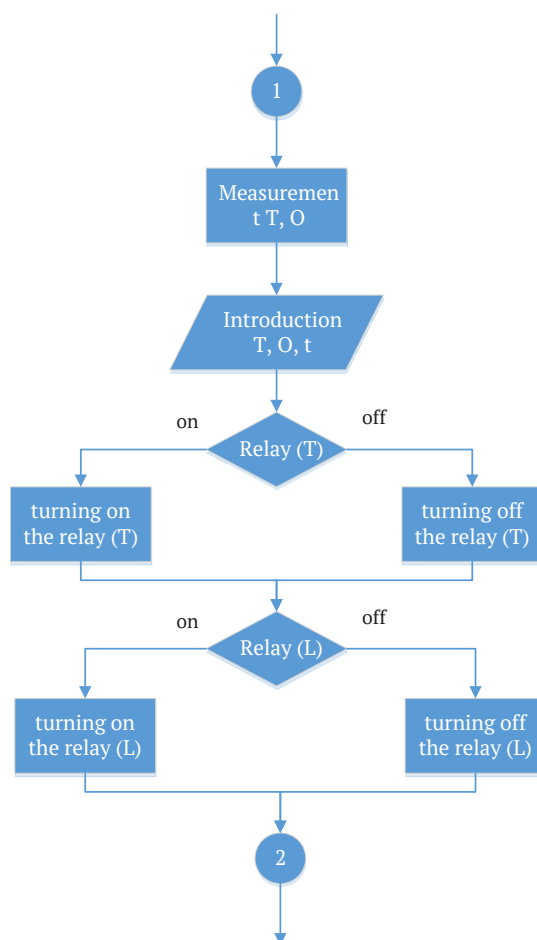


Figure 8. Subroutine for generating control influences

Source: compiled by the authors

Algorithm description.

After the system is initialised, the initial values are entered. Next, select the control mode: automatic or manual. When selecting automatic control, the operation timer (t) is first activated. The control system then measures the process parameters and compares the measured value with the setpoint. After each comparison, the drive relay is switched on or off (relay T, relay L). In the automatic mode, the system timer time

is increased by one step after each operation. The automatic mode is executed until the set control time ($t > t_k$) is reached.

In the manual control mode, the process parameters are measured, and when the operator presses the control buttons, the actuator relays (relay T, relay L) are switched on or off. Measurements are recorded in both modes.

A graphical representation of the application system interface is shown in Figure 9.

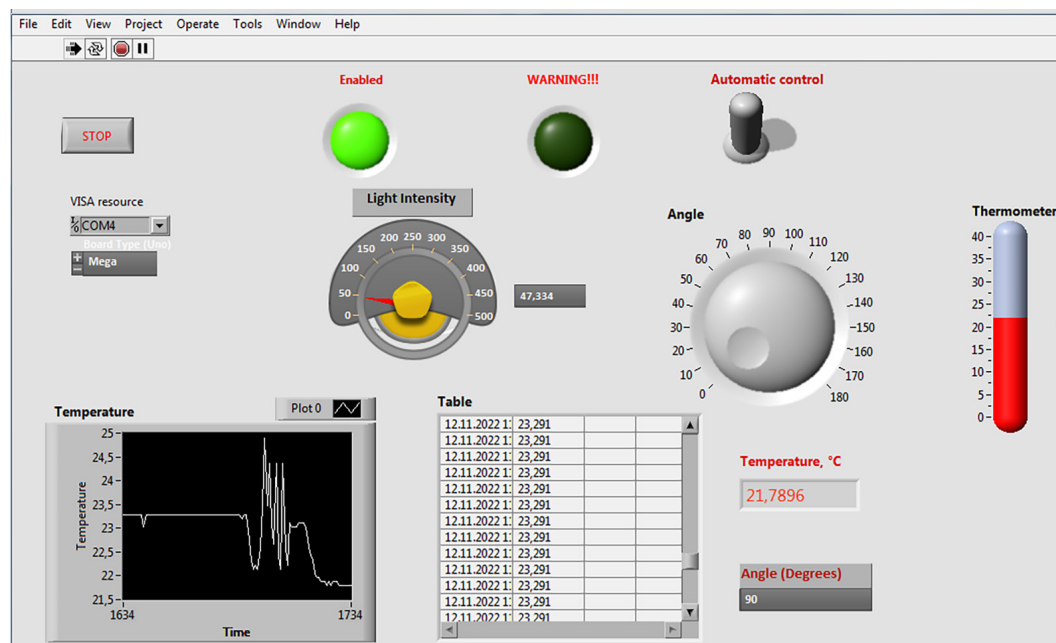


Figure 9. Operator's window

Source: compiled by the authors

The software for this system is implemented in the LabVIEW environment, and the reading of information from the sensors is also decomposed in the operator interface. In addition, the recorded values were transferred to the database for further statistical analysis – building correlation relationships, forecasting, clustering, etc. The data is stored in memory in the form of a table that is unified with data processing programs, the main part of which is Microsoft Office Excel.

Many scientists have also studied the problems of increasing the efficiency of growing seeds and plants by influencing them. A.Y. Cherenkov *et al.* (2018), and I.G. Smirnov *et al.* (2019) considered the treatment of seeds with a magnetic pulse field. The authors conducted experiments to study the effect of a low frequency pulsed magnetic field on seed germination and growth of garden strawberry seedlings. For this purpose, an installation for magnetic pulse treatment of plants in the form of a low frequency pulsed magnetic field emitter was developed. The use of this device made it possible to stimulate the processes of vital activity and growth of garden plants, vegetables, and crops. During the experiment, different treatment conditions were established with a periodic sequence of magnetic induction pulses in the low-frequency range with simultaneous irradiation with light pulses of certain wavelengths of the optical range. It was found that the germination energy of seeds treated with a pulsed magnetic field ranged from 29 to 47%, and the germination rate from 34 to 48%. The analysis of the data from the factorial experiments showed that the most effective irradiation parameter for increasing germination and germination energy of seeds is irradiation with a frequency of 15.325 Hz, a band gap of 16.145 and magnetic induction in the irradiation zone of 5.05 mT.

The control of plant functional activity by coherent light was described by J. Chávez *et al.* (2018). In particular, the methodology, analytical equipment, and technical means for studying the interaction of coherent light with biological systems and structures were developed, and a block-modular principle for designing laser installations and diagnostic devices for crop production was proposed and developed. The study presents experiments on the irradiation of both seeds and ripened fruits. Multifunctional installations of the LIC series (laser research complex) and production installations of the LOS series (agricultural laser irradiator) were used in the studies.

The LIK-30A complex (laser research complex) can be used as an irradiation device, which allows for solving a wide range of research tasks, including irradiation of biological objects according to a given programme. The LIK-30A control system (Russia) provides automatic irradiation of one or two biological objects in the mode of single or multiple periodic exposures to optical radiation with specified parameters. The control block diagram is given by J. Chávez *et al.* (2018) and includes three blocks connected by electrical signals: BUCF (control and operation unit), BOS (object feedback unit) and BFPI (radiation flux formation unit).

The most modern device for laser irradiation is Li-ka-Led (PE "Photonika-plus", Cherkasy, Ukraine). Development and implementation of a system for phytomonitoring of technological parameters of cultivation in a phytotron and the possibility of remote switching of connected devices of the electrical complex.

Optimisation of energy costs for growing vegetables in greenhouses is presented by Canadian researchers M.C. Bozchalui *et al.* (2015). The developed monitoring

system based on a wireless sensor network for a greenhouse using solar energy is described in the article by Chinese researchers J. Hou & Y. Gao (2010). An energy-efficient greenhouse based on renewable energy sources is presented in the article by Romanian researchers R. Grigoriu *et al.* (2015).

Similar computer-integrated systems have been implemented by the authors for a phytotron (Lendiel *et al.*, 2021), a feed store and a livestock building (Kiktev *et al.*, 2021). In recent years, there have been publications on studies of laser effects on plants and seeds. Scientists from Saudi Arabia, Egypt, and Belgium, M.K. Okla *et al.* (2021) described the effect of laser-irradiation on lemongrass seedlings, namely on improving biomass photosynthesis, chemical composition, and biological activity. The authors found that laser light improved photosynthetic activity, respiration and, consequently, the seedlings' fresh weight. Polish researchers A. Klimek-Kopyra *et al.* (2020), J. Dłużniewska *et al.* (2021) evaluated the productivity and health of soybean plants as a result of coherent seed irradiation together with irradiation of a fungal inoculum, which showed a decrease in the incidence of diseases in this crop. The authors determined the best wavelength for laser irradiation, which was 514 and 632.8 nm.

A system for controlling plant germination performance based on a plant for laser irradiation of corn seeds using a time relay is presented by Malaysian and Iraqi authors M. Hasan *et al.* (2020). The authors have established the best wavelengths and optimal time for irradiating the seeds of a given crop.

Compared to the studies conducted by scientists around the world on increasing plant productivity, it can be noted that this study combines biophysical research with modern algorithms and technical means of automation, i.e., an automated process of plant productivity management.

CONCLUSIONS

Based on the results described above, a model for studying plant development was developed and implemented,

which links the inflows of solar radiation, heat, water, carbon dioxide and mineral elements with an integral indicator that combines bioelectric, water and thermodynamic potential. A plant productivity management system based on electrophysical methods was designed and investigated. Diagrams of the amount of energy incident on biological tissue, the transmittance of incoming light energy to the tissue when the rays are transversely incident on the tissue, and a graph of the dependence on the intensity of laser wave penetration with different types of energy were constructed. The structure of the laboratory setup and control system was developed, an algorithmic control flowchart was built, and a phytomonitoring system for plant growth parameters was implemented using computer-integrated technologies, namely the Arduino Mega2560 integrated circuit board and the LabView software package. An interface for the graphical display of measured data from temperature, pressure, and humidity sensors and the ability to switch relays to which the devices of the electrical complex are connected was built. The data received from the sensors is transferred to the database in MS Excel for further processing.

In the future, it is planned to develop the project, namely, to use a modern device for laser radiation of different frequencies, LIKA-LED, and to include it in the circuit of the developed computer-integrated system. Studies are also planned to measure the bioelectrical potential of plants, radiation by CWH signals (short high-frequency waves) with a frequency of 39-56 GHz and the effect of radiation on the plant life cycle at different stages of vegetation. Future studies are also planned to analyse the effect of different laser wavelengths on the growth of seeds and seedlings of vegetable crops.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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**Комп'ютерно-інтегрована система керування електрофізичними методами
підвищення продуктивності рослин**

Анотація. У зв'язку зі зростанням попиту на аграрну продукцію, виникає потреба інтенсифікації процесу вирощування рослин, зменшення їх захворювань. Тому технічна реалізація методів управління функціональною активністю рослин за допомогою електромагнітного випромінювання на різних етапах органогенезу та їх автоматизація є актуальною задачею. Метою статті було підвищення ефективності вирощування росли шляхом дослідження електрофізичних методів управління їх продуктивністю та реалізації комп'ютерно-інтегрованої системи. Для реалізації поставленої мети була використана математична коригуюча модель взаємодії лазерного випромінювання із твердою біологічною тканиною, алгоритми вимірювання і формування управляючих впливів, методи теорії автоматичного управління, а також візуальне програмування в пакеті LabView. Дані оброблялися в пакеті MS Excel. Проаналізовано зв'язки в біотехнічній системі рослина-середовище, виділені матеріальні потоки та інформаційні канали, виокремлена множина параметрів стану, прямі та перехресні взаємозв'язки між ними, аргументовані джерела збурень. Визначено основні положення взаємодії лазерного випромінювання з біологічною тканиною та обґрунтовано біофізичний механізм. Розроблено комплекс програмно-апаратних засобів контролю та керування для проведення експериментальних досліджень режимів електрофізичного впливу на рослинні біологічні об'єкти. З метою отримання зворотного зв'язку від рослин розроблено новий інструментарій діагностики фізіологічного стану рослинних організмів та створено комп'ютерно-інтегровану систему керування процесом опромінення рослин. На базі програмного забезпечення мікроконтролера Arduino реалізована система управління, яка підключається до ПК. Створено панель оператора, де забезпечено автоматизоване керування процесом та розроблена підсистема реєстрації вимірюваних даних. На практиці результати цього дослідження можуть бути застосовані у тепличних господарствах України та інших країн, в тому числі при вирощуванні овочевих культур

Ключові слова: обробка насіння; біотехнічна система; лабораторна установка; платформа; алгоритм; автоматизація; інтегрована плата