

Проведено випробування мікрохвильового пристрою безперервної дії для термообробки рослинних матеріалів, яке розроблено та сконструйовано для реалізації мікрохвильових технологій в промисловості. Метою випробувань була оцінка ефективності мікрохвильового пристрою за показниками якості отриманого матеріалу і енергетичним витратам, обумовленими ефективністю перетворення мікрохвильової енергії у внутрішню енергію матеріалу. Проведено дослідження впливу мікрохвильової обробки солом'яного субстрату для дереворуйнівних грибів. Якість обробки визначалося по врожайності грибів Глива (*Pleurotus*), вирощених на отриманому субстраті. Мікрохвильова обробка проведена на різних режимах, які відрізнялися значенням питомої потужності. При аналізі ефективності мікрохвильової обробки проводилося зіставлення результатів з даними, що отримуються при традиційній технології стерилізації соломи. Показано, що урожай грибів гливи збільшився на 11%. Отримано, що в оптимальному режимі питома потужність становила $q_v=8,68 \cdot 10^5 \text{ Вт/м}^3$, кінцева температура $t=96^\circ\text{C}$, тривалість обробки 180 с. За тепловим розрахунками визначені значення ККД мікрохвильової камери η_c , в оптимальному режимі $\eta_c=62\%$. Досліджено вплив мікрохвильової обробки на посівні характеристики насіннєвого зерна пшениці. Ефективність мікрохвильової обробки визначалася за значеннями лабораторної схожості та енергії проростання насіння. В оптимальному режимі вихідна потужність магнетронів становила $\Sigma P_{\text{out}}=0,6 \text{ кВт}$, витрата зерна $G=2,1 \cdot 10^{-2} \text{ кг/с}$. Дослідження роботи мікрохвильової установки довело, що для даної конструкції для стабільного і рівномірного просування матеріалу по продуктопроводу слід підтримувати швидкість руху не вище 0,5 м/хв. Рекомендується застосовувати випробувану мікрохвильову установку безперервної дії в спеціалізованих фермерських господарствах

Ключові слова: мікрохвильовий пристрій, термообробка, соломистий матеріал, насіння, оптимальний режим, енергетична ефективність

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TESTING A MICROWAVE DEVICE FOR THE TREATMENT OF PLANT MATERIALS BY VARIOUS TECHNOLOGIES

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1. Introduction

Due to the specific features of the interaction of dielectric materials with a microwave (MW) field, the use

of microwave treatment in various technologies can lead to a significant improvement in the quality of the material. Detection of special thermal and non-thermal effects of the microwave interaction with materials explains a wide range

of studies that relate to studying the drying processes in the microwave field [1], the processes of organic synthesis [2, 3], processes of sintering of technical ceramics [4, 5] and metal powders [6].

The treatment of plant-based materials is important for the agro-industrial complex. In particular, pre-sowing treatment of seeds is applied to accelerate the appearance of shoots and reduce the plant disease incidence. As a result, the harvest is increased. In traditional technologies, seeds before sowing are warmed, calibrated, soaked in solutions of micronutrients, pelleted, etc. The pre-sowing treatment process is rather lengthy, requires huge material consumption and is not always effective. The pre-sowing seed treatment in the microwave field for biostimulation is simple, energy-efficient and lasts only a few minutes compared to traditional methods. Microwave biostimulation of seeds is associated with an increase in the transport properties of plant tissue due to the development of high-pressure gradients in closed micro volumes of microfibrils of cell walls and pores [7]. The influence on cell walls leads to an increase in the translocation of nutrients and improves seed sowing qualities. Effective use of the voluminous nature of microwave heating can be obtained by preparing a plant substrate for tree-destroying fungi. Plant material after the MW treatment is not only disinfected but also improves its nutritional properties due to the break of cellulose fibers [8]. Unlike traditional pasteurization and sterilization technologies, the energy consumption and duration of the process of the MW substrate preparation are significantly reduced.

It should be noted that the found efficiency and uniqueness of microwave heating of materials are mainly obtained on laboratory devices. Transition to the practical use with the application of industrial devices requires solving a series of interconnected tasks, which include the study of peculiarities of the microwave techniques, the device design, verification of its operational efficiency during the treatment of the plant material. It seems appropriate to move from laboratory research to industrial application with the development of low-capacity devices. The results of testing such devices make it possible to move towards the efficient industrial use of microwave technologies.

One of the most difficult tasks is to ensure that the transmission tract is aligned with the mass of the loaded material [9]. Incomplete absorption of microwave energy by the treated material and the reflection of electromagnetic waves back to the magnetron lead to reduced efficiency and deviation of frequency from the nominal one. It is necessary to conduct the tests under different modes of treatment of plant-based materials treatment to assess the completeness of the use of a microwave device energy use and its operational efficiency.

2. Literature review and problem statement

Paper [10] explored the conditions for improving the operational efficiency of devices for thermal treatment of raw material under the influence of electromagnetic radiation. The designs of microwave chambers, including the toroidal one, were studied. The authors note that when designing a toroidal resonator for continuous operation, it is necessary to reduce the equivalent capacity and increase the equivalent inductivity (toroidal surface). In this case, the losses of microwave energy decrease and its efficiency increases. However, this microwave device is difficult to manufacture. In

addition, in the process of designing, the geometric characteristics were consistent with the wavelength of microwave radiation in a vacuum. However, when the material is placed in a resonance chamber, the wavelength varies and the electromagnetic field will not correspond to the one formed in an empty chamber.

The authors of paper [11] claim that the microwave heating of food products is efficient and cost-effective. There is no loss of nutrients when cooking in a microwave oven. Microwave treatment of various foods was also studied by the authors of [12]. It is noted that microwave heating for pasteurization and sterilization contributes to the effective destruction of pathogenic microorganisms and significantly reduces the time of treatment compared to traditional methods. However, the authors note that in the preparation of foods microwave technologies are still inferior to the traditional in terms of organoleptic characteristics. Thus, the use of microwave devices is appropriate in the treatment of materials not intended for direct use in food. Such technologies are drying, disinfection, extermination, biostimulation of plant materials. In paper [13], there is a comparative assessment of the optimal mode parameters for the treatment of plant materials in the technologies of seed biostimulation, substrate sterilization, and grain drying. The results were obtained on the experimental device of the periodic operation, so the values of such characteristics as the heating rate and specific heat flow require adjustment for other structures.

Paper [14] shows the prospects of using microwave energy to dry grain crops. Based on the experimental data, it was established that microwave drying should be accompanied by blowing through a grain layer. Only microwave-convective drying ensures uniform heating and effective removal of moisture from the layer. The microwave device for grain drying should involve active ventilation.

Article [15] presents an overview of various aspects of modeling microwave devices from the mathematical formulation to the selection of necessary functional nodes.

The study of the relationship between the type of a microwave chamber, the volume of loaded products, and dielectric characteristics show the ways to enhance the efficiency of the conversion of microwave energy [16]. The type of a microwave chamber, that is a single-mode or a multimode one, as well as the design and chamber size have a direct impact on the effectiveness of microwave heating. Researchers emphasize the need to harmonize a microwave chamber and the load to improve energy concentration and, in turn, heating efficiency. The disadvantages of the research include the following. The authors note that the development of the treatment technology based on microwave radiation is significant because it minimizes the dependence on fossil fuels and other energy sources. In fact, the generation of microwave energy is based on the transformation of electric energy, which in turn is obtained from the use of fossil fuels, hydropower, nuclear energy, etc. Therefore, the issue of the energy feasibility of microwave heating is a determining factor in many technologies. To this end, the concept of general energy efficiency, which takes into consideration the microwave chamber efficiency, magnetron efficiency, and electric device efficiency, is introduced. The coordination of the magnetron with a microwave chamber, in which the material is placed, is very important. Poor coordination leads to a decrease in efficiency and a shift in generation frequency. Studies [17] have shown that the deviation of only 5 MHz

from nominal frequency (2.45 GHz) changes the water-absorbed microwave power by about 20 %.

Article [18] proposes a new multi-component structure of the turning table to improve the temperature uniformity in microwave ovens. Three rotating plates from polyethylene (PE) and alumina, as well as alumina and aluminum, respectively, are used in a microwave oven for modeling. Compared to turning tables consisting of one material, there is an increase in temperature uniformity by 26–47 %. However, for industrial devices, this method needs further study.

Analysis of sources [11, 15, 16] demonstrates the lack of actual industrial devices that implement the effects obtained on laboratory devices and the benefits of microwave treatment. There is a problem of switching to large capacities of microwave devices and large volumes of treated products. This problem is related to the issues of the conjunction of the main components of microwave devices, their rational choice for a specific application area and the changes in the conditions of the interaction of the microwave electromagnetic field with treated material. Due to the influence of a large number of factors on the completeness of the conversion of microwave energy into the internal energy of treated material, it is necessary to test the developed device under different treatment modes. Evaluation of the effectiveness of the application of the microwave device for the treatment of plant-based materials opens up the way to the rational use of microwave devices in the industry.

3. The aim and objectives of the study

The aim of this study is to assess the operational effectiveness of the microwave device of continuous action for the treatment of plant materials in the technologies of seed biostimulation and the preparation of a substrate for wood-destroying fungi.

To accomplish the aim, the following tasks have been set:

- to study the energy efficiency of a working chamber during the treatment of plant material by the value of efficiency and to determine the conditions for the steady movement of the material by product line;
- to conduct the research into the impact of the microwave treatment of straw substrate for tree-destroying fungi; the substrate quality is determined by the yield of the Oyster mushrooms;
- to study the effect of microwave treatment on sowing characteristics of seed grain.

4. Materials and methods of research

4.1. Description of the microwave device for the treatment of bulk material

Periodic and continuous microwave devices are currently manufactured by specialized companies, such as Linn High Therm GmbH (Germany). However, the devices are not designed to treat plant materials. Their misuse can lead to local overheating and ignition of material. The Ferrite Microwave Technologies (FMT) company also produces tunnel- and chamber-type microwave ovens. Such devices can be successfully used to warm up portions of food on cruise ships or planes, but their use is not feasible for the agro-industrial complex. In addition, the proposed

devices have two drawbacks. To transfer energy from the generator to the material, they have a waveguide, the manufacture of which requires large material costs. Microwave heating of material occurs in a resonance chamber, which does not ensure the uniform treatment that is necessary for the problems considered in this paper. Microwave devices of friable type for biostimulation of seeds are offered by the Generator device (Kyiv, Ukraine). Despite the pronounced biostimulating effect, the device design does not make it possible to treat seeds evenly enough.

The optimization of the cost of a microwave device is relevant to the agro-industrial complex. That is why it is rational to use horn-type antennas to transfer energy from a magnetron to device material. In addition to the low cost of manufacturing, horn-type antennas make it possible to irradiate material evenly. The microwave device developed in the paper is intended for the treatment of plant materials in various technologies and implies the use of horn-type antennas. The working chamber provides a product pipeline, which reduces the risk of ignition of material.

The scheme of the microwave device, developed and manufactured to treat bulk materials in various technologies, is shown in Fig. 1.

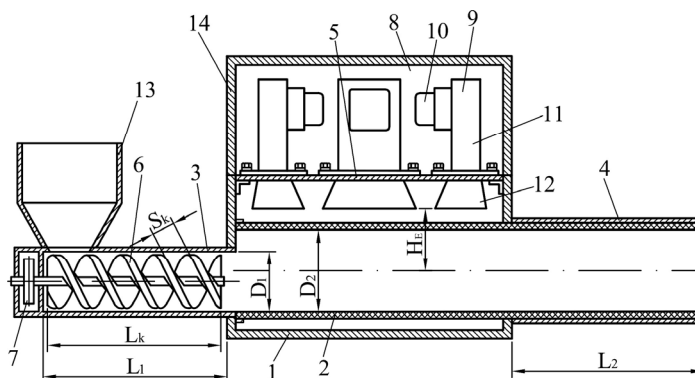


Fig. 1. Scheme of microwave device of continuous action for the treatment of bulk materials: 1 – working chamber, 2 – product pipeline, 3 – load pipeline, 4 – outlet pipeline, 5 – partitions, 6 – screw, 7 – driving node, 8 – technological compartment, 9 – microwave modules, 10 – magnetron, 11 – waveguide, 12 – antenna emitter, 13 – load tank, 14 – lid

The specifications of the device are the following.

Consumed power: 5 kW; power: single-phase current network, frequency of 50 Hz, voltage of 220 volts; energy power in the microwave work chamber: 3 kW; frequency of the microwave field in the working chamber: 2,450 MHz; recommended operation cycle: 50 minutes of work, followed by a 19-minute pause; type of cooling system: forced air ventilation.

The microwave device contains a working chamber, in the middle of which there is a product pipeline. The product pipeline is connected to the load and outlet pipelines for the passage of the treated product. The walls of the chamber, partitions, and pipelines are made of the material that does not let microwaves pass through. The internal space of the working chamber is waterproof relative to the external space and from the treated product. The product pipeline is made in the form of a waterproof pipeline and is made of radio-transparent material. There is a screw (screw conveyor) in the inlet pipeline. The screw is mounted on the console

shaft and is connected to the driving node. In the technology compartment, there are MW modules, which consist of an MW energy source (magnetron), a waveguide and an antenna emitter. The technological compartment is separated from the outer space by a lid that prevents the leakage of MW radiation from the plant. Excess heat, formed as a result of the work of magnetrons and auxiliary equipment, is removed from the technological compartment through the auxiliary windows or lid blinds (are not shown conditionally in the figure). Length L_1 of the input and length L_2 of the outlet pipelines are designed to ensure the maximum attenuation of electromagnetic irradiation to the level that is safe for service personnel.

4. 2. Specific features of the microwave device for the thermal treatment of bulk materials

The principle of device operation is based on the absorption by the material of microwave energy supplied into the working chamber. The material moves as a continuous stream in a radio-transparent channel passing through the work chamber. The operation of a microwave device can be presented as follows. The original material, which can be the plant material, such as seeds, grain, wood chips and sawdust, straw, sunflower husk, etc., is loaded into a load tank, located on the outer end of the inlet pipeline. The driving node rotates the shaft of the screw conveyor (screw), which moves the product from the load tank to the product pipeline and then pushes it through the product pipeline and the outlet pipeline to the outside of the device.

When the material passes through the working chamber, it is irradiated by MW energy. Magnetron creates an EMF oscillation and they are transmitted by a waveguide to the antenna emitter, which directs the EMF to the material that moves in the radio-transparent product pipeline. The horn-type emitter is used. The horn-type emitter creates a diagram of the electromagnetic field direction, which ensures uniform coverage of the product pipeline surface without the formation of shadow zones. In order to prevent unwanted heating of the screw, its length L_K is made so that the end of the metal parts facing the work chamber should be located outside the emitter's irradiation area.

Fig. 2 shows the photograph of the device, Fig. 3, 4 show the separate parts of the device.



Fig. 2. Microwave device for thermal treatment of bulk materials

The system of feeding the treated material to the device includes a screw (Fig. 3, *b*) powered by a chain transmission (Fig. 3, *a*) from an electric motor.



Fig. 3. The system of feeding treated material to the device: *a* – driving mechanism; *b* – view of the screw in the load tank of the device

The product pipeline is removable for effective cleaning after the completion of the operation cycle. The technology compartment of the device with microwave modules (Fig. 4) is isolated from the working chamber with the product pipeline.

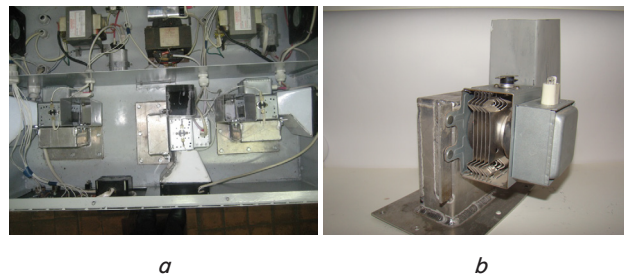


Fig. 4. Technological compartment of the device with microwave modules: *a* – general view from above; *b* – view of magnetron with air ducts of cooling system

The device is equipped with three mass-produced magnetrons with a maximum output capacity of 1 kW. An air-cooling system is intended to ensure the thermal mode. To this end, air ducts compatible with the technology compartment of the device (Fig. 4, *b*) were manufactured.

Feeding the material using a screw increases the compactness and improves the mass and dimension characteristics of the device. The device for thermal treatment of bulk materials was tested for biostimulation of wheat seeds and in the heat treatment of the straw substrate.

4. 3. Procedure for the microwave treatment of straw substrate for tree-destroying fungi

Shredded straw was soaked for 48 hours, and then pressed to the moisture content of $W=73\%$. The wet material is fed to the device and passes along the product pipeline, absorbing microwave energy. As a result, the temperature of the material increased. The temperature of the material at the end of the treatment was measured by copper-constant thermocouples. Thermocouples were located on the surface of the straw layer, in its center and at the distance of 3 cm from the surface. The results of the measurements were averaged. The effect of the microwave field can destroy the harmful microflora in the treated fungi substrate. In addition, the influence of microwave energy causes partial destruction

of the outer shell of straw, which as a result accelerates the process of overgrowth of the substrate by fungal mycelium.

After the treatment in the microwave device, the straw was cooled and inoculated with mycelium. The inoculated straw was then placed into plastic bags with slits for the fruit bodies to come out. In the study of different treatment modes, the substrate consumption varied in the range of $5.5 \cdot 10^{-3}$ – $9.0 \cdot 10^{-3}$ kg/s.

4. 4. Methods for assessing the impact of the microwave field on sowing qualities of wheat seeds

The effect of wheat biostimulation was studied. Grain with the consumption of $0.83 \cdot 10^{-2}$ – $2.1 \cdot 10^{-2}$ kg/s was delivered through the loading tank to the working compartment, where it was irradiated by microwave energy with the given power. Two analytical samples by 500 whole grains each were selected from the grain treated in the MW field. Each sample was placed in a glass funnel, the end of which was covered with a rubber tube with a clamp. A glass ball was placed in the hole of the funnel. The funnel was fixed in the holder of the tripod.

The grain in the funnel was poured with water at the temperature of 20 °C so that the water level should be 1.5–2.0 cm above the surface of the grain. Every 4 hours, the water from the funnel was let out and the grain remained in the funnel with an open clamp for 18 hours. At the same time, to avoid grain drying, the funnel was covered with a glass lid with damp filtering paper on the inside. Then the clamp was closed again and the grain was poured with fresh water. Repeating this procedure, after 72 hours the grain was placed on the filtering paper and the number of grains that did not germinate was counted.

According to the obtained data, the germination energy was calculated:

$$X_1 = \frac{500 - n_1}{500} \cdot 100\%, \quad (1)$$

where n_1 is the number of seeds that did not germinate.

To determine the germination capacity, all seeds, including those that did not germinate, were placed back in the funnel, poured with water at an open clamp and withstood for another 48 hours under the glass lid.

The grain germination capacity of each analytical sample in percent is calculated from formula:

$$X_2 = \frac{500 - n_2}{500} \cdot 100\%, \quad (2)$$

where n_2 is the number of grains that did not germinate within 120 h, pieces.

The arithmetic means of the results from determining two analytical samples were adopted as the final result of energy and germination capacity.

5. Results of studying the effectiveness of the microwave treatment of plant material

5. 1. Thermal treatment of straw substrate for tree-destroring fungi

Testing of the microwave device in the technology of thermal treatment of the substrate at the initial stage led to the establishment of the boundary value of the consump-

tion and maximum permissible motion rate of the material. When the substrate was fed into the load tank with the consumption above $9.2 \cdot 10^{-2}$ – $9.5 \cdot 10^{-2}$ kg/s, the product pipeline was clogged, the material motion slowed down. The rate of the material movement in the product pipeline at the consumption of $G_{\max} = 9.2 \cdot 10^{-2}$ kg/s was equal to 0.5 m/s. This value was accepted as the maximum permissible. The effect of thermal treatment in the microwave field of the straw substrate was studied on the tree-destroying fungus Oyster (Lat. *Pleurotus*). Oyster mushroom grows rapidly, which makes it possible to assess in a short time the effectiveness of the microwave method for substrate preparation. To grow them, substrate units, inoculated with mycelium, were formed. Each unit weighed 10 kg. Fig. 5 shows the photograph of oyster mushroom growing on a substrate unit.



Fig. 5. Substrate unit with Oyster mushrooms

The density of wet straw was 400 kg/m³. The speed of the material motion in the product pipeline in all experiments was the same and amounted to $w = 0.5$ m/min. The exposition was $\tau = 180$ s. The specific energy costs were determined as the amount of heat Q_m , J, related to the weight of the obtained products after three waves of fruiting. Specific microwave power q_v was determined as the ratio of the output power of three magnetrons to the volume of the treated material in the product pipeline.

In order to assess the energy effectiveness of microwave treatment, the efficiency of the device is very important. The expression of general efficiency is presented in the following form: $\eta = \eta_m \cdot \eta_c$, where η_m is the efficiency of magnetron, η_c is the efficiency of the microwave chamber. The value η_m shows the efficiency at which the magnetron converts the energy of the electric field of industrial frequency (50 Hz) into the energy with the frequency of the microwave field. This is the passport magnitude and it does not depend on the treatment conditions. Value η_c depends on the type of loaded material and its weight and is determined by thermal calculations of chamber efficiency, it shows what part of microwave energy is converted into the internal energy of the treated material. Table 1 gives the data obtained after three waves of fruiting.

The CT mode is the treatment of straw in the chamber-sterilizer using the traditional technology according to the modes set for this treatment (the temperature at sterilization reaches 120 °C, the pressure is 1.5 atmospheres). The duration of sterilization takes about 3 hours, which is much longer than the time of microwave treatment.

Table 1

The number of mushrooms grown on the substrate after the treatment in the MW field Initial humidity $W=73\%$

No.	$q_v, W/m^3$	Final temperature, °C	Result (yield per unit, kg)	$Q_m, MJ/kg$	$\eta_c, \%$
1	$7.24 \cdot 10^5$	72	2.35	0.38	48
2	$7.64 \cdot 10^5$	77	2.86	0.31	52
3	$8.12 \cdot 10^5$	92	3.64	0.25	60
4	$8.36 \cdot 10^5$	96	3.88	0.23	62
5	$8.68 \cdot 10^5$	96.5	3.90	0.23	59
6	$12.2 \cdot 10^5$	123	3.61	0.25	57
CT	–	120	3.50	1.15	–
K	–	20	0.350	–	–

Control K is the mode, in which heat treatment was not carried out, straw was soaked in hot water and after pressing was inoculated with mycelium.

Mode 4 can be considered optimal because it gives almost the maximum possible yield of mushrooms, and specific energy consumption was minimal, in addition, the maximum efficiency of the chamber was reached.

The efficiency of the microwave chamber was calculated by the heat balance equation. The heat flow consumed to heat the substrate is:

$$Q = G \cdot c \cdot \Delta t, \tag{3}$$

where G is the material consumption, kg/s; c is the thermal capacity of a material, J/(kg·K), Δt is the change in temperature, °C.

The chamber efficiency was determined as the ratio of the absorbed thermal flow Q to the output power of the magnetron. The losses to the environment were not taken into consideration. The specific heat intensity of the wet straw was determined in accordance with an additive dependence [19].

The data of Table 1 show that the increase in temperature up to 96–96.5 °C leads to an increase in the weight of mushrooms, which is supposedly associated with the scattering of pulp and an increase in nutritional qualities for oyster mushroom. This assumption is supported by research [8]. The authors of the paper presented the view of the surface of the original straw samples and those treated in the microwave field (Fig. 6).

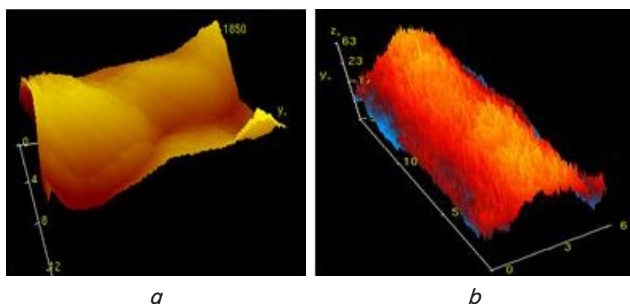


Fig. 6. The surface of straw material of dimensions 23×23 microns: a – original; b – treated [8]

The cross-section of untreated straw is characterized by a smooth surface (Fig. 6, a), and there is a needle structure after the microwave treatment (Fig. 6, b). This phenomenon is due to the voluminous nature of heating. As a result of micro-explosions within closed volumes, the fibers are de-

stroyed and non-homogeneity occurs in the structure of the material. This material acquires the best nutritional properties for growing mushrooms.

5. 2. Studying the effect of the microwave field on the sowing qualities of wheat seeds

The research was carried out on the wheat seeds of the Odessa-162 variety. The results of determining the laboratory germination and germination energy are shown in Table 2. The speed of the screw motion did not change, the output power of magnetrons was regulated. Due to the features of the device and the principle of the magnetron operation, smooth power adjustment is impossible. The control system turns on and off the magnetron as it works. In this case, the magnetron works at full capacity every time it is turned on. When the device works, the value of average power, which is determined by the duration of pauses and the duration of the magnetron, is set. The total output power of the magnetron ΣP takes into consideration the output power of all working magnetrons. The final temperature t_f of the grain was determined by the readings of three thermocouples placed at different distances in its thickness. The initial temperature in all experiments was 19 °C. Specific energy consumption q_m was determined as the ratio of consumed energy to the weight of grain, which is in the device at the same time.

Table 2

Influence of microwave treatment on sowing qualities of wheat seeds

No.	$\Sigma P_{out}, kW$	Grain consumption $G, kg/s$	$t_f, °C$	$q_m, W/kg$	Germination energy	Germination capacity
1	0.3	$0.83 \cdot 10^{-5}$	27.0	201	82	86
2	0.6	$1.62 \cdot 10^{-5}$	27.3	205	84	88
3	0.6	$2.1 \cdot 10^{-5}$	25.3	158	84	89
4	0.9	$2.1 \cdot 10^{-5}$	28.5	238	83	87
5	1.8	$2.1 \cdot 10^{-5}$	38.0	476	72	78
K	–	–	–	–	78	83

The data from Table 2 indicate that an increase in temperature has its limit, beyond which the effect of biostimulation begins to decrease. This is due to the overheating of seed germs, the moisture content of which is higher than average for the volume of grain weight. Fig. 7 shows the photographs of the root system and wheat sprouts, the seeds of which were treated in the microwave field.



Fig. 7. Results of wheat seed germination after treatment: a – the view of the root system, b – the view of germinated wheat

The results show that after the treatment, all plants show a biostimulating effect of the microwave field. There were no special differences in growth intensity in this range of specific energy consumption q_m . The control sample (seeds without treatment) germinated less intensely, in Fig. 7, b the sprouts are extreme on the right.

6. Discussion of results of the treatment of plant materials in the developed microwave device

Microwave technologies show their relevance, but treatment modes must be tested on every design of the microwave device. Testing of the microwave device during the thermal treatment of the substrate showed that the excess of consumption above the maximum permissible value $G_{\max}=9.2 \cdot 10^{-2}$ kg/s leads to clogging of the product pipeline and slowing down of the motion of the material. The rate of the material moving along the product pipeline at the consumption of $9.2 \cdot 10^{-2}$ kg/s amounted to 0.5 m/min and was determined as the maximum admissible. Increased rate and consumption of the treated material can be ensured by applying a screw running along the entire length of the product pipeline. At the same time, the screw should be made in the shape of a composite structure. The screw in the product pipeline should be made of radio-transparent polymer, and it is desirable to make the screw in the load tank from metal to ensure the strength and durability of the supplying mechanisms. Conducted thermal calculations to estimate the efficiency of the microwave chamber demonstrate a significant dependence of efficiency on specific microwave power. At the change in specific power within 15 % in the range from $7.24 \cdot 10^5$ W/m³ to $8.36 \cdot 10^5$ W/m³, efficiency increased by 29 %. After passing the maximum value, efficiency slightly decreases. It is necessary to look for the cause of this phenomenon in a decrease in the area of irradiation of material while consumption decreases. Under the optimal mode, the value of efficiency was 62 % (No. 4, Table 1). In the future, the ways of increasing efficiency should be considered.

The results of microwave testing show that microwave treatment is more effective than traditional sterilization (Table 1). Energy consumption under the optimal mode of microwave treatment is five times lower, in addition, the treatment duration for small volumes is significantly lower, as sterilization involves keeping within three hours. Analysis of the data of Table 1 shows that an increase in the temperature of the material at the output up to 96–96.5 °C leads to an improvement in the nutritional qualities of the substrate, as evidenced by the resulting yield of oyster mushrooms. The process of the thermal treatment of the substrate in a microwave device is more energy effective than traditional sterilization and makes it possible to obtain a higher yield of mushrooms. Sterilization takes about 3 hours, which is much longer than the time of microwave treatment. In addition, the microwave technology of substrate preparation does not require the maintenance of more pressure than is provided in the sterilizer. The absence of mold fungi on the substrate indicates the uniformity of the treatment (Fig. 5).

The presented microwave device can be successfully used for pre-sowing seed treatment. Microwave treatment of winter wheat seeds Odessa-162 for 180 s at changing microwave power within 0.3–0.9 kW led to an increase in germination energy and laboratory germination (Table 2). The type of sprouts from the treated seeds did not practically depend on the treatment mode in the given range (Fig. 7, b). Therefore, some deviations from the optimal mode will not lead to significant changes in the effects of biostimulation. More research is needed to obtain the modes of treatment of other kinds of seeds.

The limitations of the study are that only two types of plant materials were selected. At the same time, farms

may have an interest in biostimulation of different types of seeds, which also requires setting optimal modes. The thermal treatment of the straw substrate does not make it possible to transfer the results to substrates from other plant fillers. Pauses are needed to prevent transformers from overheating, which decreases their performance. The disadvantages of the microwave treatment of bulk materials on the tested device include the fact that the volume of material is small. Thus, when preparing a substrate, it is possible to obtain 200 kg per day, that is, one device can supply 20 units. 460 kg can be treated during pre-planting preparation of wheat seeds. This productivity will be of interest to small farms.

Testing the developed device under different treatment modes solves the problem of switching to the practical application of microwave technologies. Developed microwave device of continuous operation can be used in the established optimal modes for thermal treatment of bulk materials in the technologies of biostimulation and preparation of substrate for tree-destroying fungi. In the future, it is advisable to test the microwave device for the sterilization of combined feed. In this case, the developed device can get wider use.

7. Conclusions

1. The study of the operation of the microwave device for the treatment of bulk materials showed that for this design, there is a limit speed of feeding material to the work chamber. For the material to move steadily and evenly, it is necessary to maintain the motion speed not higher than 0.5 m/min. By aligning the microwave wavelengths with the geometric characteristics of the product pipeline, the efficiency of a microwave chamber reaches 62 %. The developed microwave device of continuous operation can be recommended for use at specialized farms.

2. The study of the effect of the microwave treatment on the quality of the straw substrate showed that the resulting substrate is of high quality and contributes to the intensive growth of the tree-destroying oyster mushroom. Microwave preparation of the substrate requires much less energy consumption than traditional technologies. For example, if for traditional sterilization, the specific energy consumption is $Q_m=1.15$ MJ/kg, under the optimal mode of microwave treatment the specific consumption was $Q_m=0.23$ MJ/kg. At the same time, the yield of mushrooms increased by 11 %, which is due to the improvement of the nutritional properties of the straw substrate.

3. The study of the effect of biostimulation of seeds in the microwave device showed that microwave treatment leads to an increase in germination energy and germination capacity in the range of connecting power of 0.3–0.9 kW at the treatment duration of 180 s. Compared to the control (untreated seeds), germination energy increased by 8 %, germination capacity increased by 7.4 %. In order to use the presented device for the purpose of biostimulation, it is necessary to regulate the output power of each magnetron. When the final temperature rises to 38 °C, the effect of biostimulation decreases and there is a deterioration of planting qualities. Under the optimal mode, specific energy consumption is 158 W/kg, the treatment duration is 180 s, and the average final temperature of seeds is 28.5 °C.

References

1. Feng, H., Yin, Y., Tang, J. (2012). Microwave Drying of Food and Agricultural Materials: Basics and Heat and Mass Transfer Modeling. *Food Engineering Reviews*, 4 (2), 89–106. doi: <https://doi.org/10.1007/s12393-012-9048-x>
2. Kappe, C. O. (2004). Controlled Microwave Heating in Modern Organic Synthesis. *Angewandte Chemie International Edition*, 43 (46), 6250–6284. doi: <https://doi.org/10.1002/anie.200400655>
3. Leonelli, C., Veronesi, P. (2014). Microwave Reactors for Chemical Synthesis and Biofuels Preparation. *Biofuels and Biorefineries*, 17–40. doi: https://doi.org/10.1007/978-94-017-9612-5_2
4. Burlutskiy, D. S., Kaleeva, Zh. G. (2011). Izmenenie fizicheskikh svoystv materialov v rezul'tate eksperimental'nogo vozdeystviya sharovogo elektricheskogo razryada, poluchennogo s pomoshch'yu sverhvysochastotnogo izlucheniya. *Sovremennye naukoemkie tehnologii*, 5, 22–32.
5. Agrawal, D. (2010). Microwave sintering of ceramics, composites and metal powders. *Sintering of Advanced Materials*, 222–248. doi: <https://doi.org/10.1533/9781845699949.2.222>
6. Srinath, M. S., Sharma, A. K., Kumar, P. (2011). A new approach to joining of bulk copper using microwave energy. *Materials & Design*, 32 (5), 2685–2694. doi: <https://doi.org/10.1016/j.matdes.2011.01.023>
7. Kalinin, L. G., Boshkova, I. L. (2003). Physical model of the plant tissue response to exposure to the microwave electromagnetic field. *Biophysics*, 48 (1), 111–113.
8. Moskovskiy, M. N., Fridrikh, R. A., Gulyayev, A. A. (2010). Structural analysis of culmiferous material surface under microwave radiation treatment. *Vestnik Donskogo gosudarstvennogo tehničeskogo universiteta*, 10 (5 (48)), 648–654.
9. Sapunov, G. S. (1998). Remont mikrovolnovykh pechey. Moscow: Solon, 268.
10. Lukina, D., Belov, V., Lukina, O., Volkov, A., Mayorov, A., Smirnova, I. (2018). Increasing the Efficiency of the Operation of the Facilities for the Thermal Processing of Raw Materials by Exposure to Electromagnetic Radiation. *Key Engineering Materials*, 781, 185–189. doi: <https://doi.org/10.4028/www.scientific.net/kem.781.185>
11. Okeke, C. Abioye, A. E., Omosun, Y. (2014). Microwave Heating Applications in Food Processing. *IOSR Journal of Electrical and Electronics Engineering*, 9 (4), 29–34.
12. Puligundla, P. (2013). Potentials of Microwave Heating Technology for Select Food Processing Applications - a Brief Overview and Update. *Journal of Food Processing & Technology*, 04 (11). doi: <https://doi.org/10.4172/2157-7110.1000278>
13. Volgusheva, N., Altman, E., Boshkova, I., Titlov, A., Boshkov, L. (2017). Study into effects of a microwave field on the plant tissue. *Eastern-European Journal of Enterprise Technologies*, 6 (8 (90)), 47–54. doi: <https://doi.org/10.15587/1729-4061.2017.115118>
14. Boshkova, I., Volgusheva, N., Titlov, A., Titar, S., Boshkov, L. (2019). Assessment of efficiency of drying grain materials using microwave heating. *Eastern-European Journal of Enterprise Technologies*, 1 (8 (97)), 78–85. doi: <https://doi.org/10.15587/1729-4061.2019.154527>
15. Pedro, J. C., Cunha, T. R. (2014). Behavioral Models for Microwave Circuit Design. *Microwave De-Embedding*, 255–315. doi: <https://doi.org/10.1016/b978-0-12-401700-9.00007-0>
16. Loharkar, P. K., Ingle, A., Jhavar, S. (2019). Parametric review of microwave-based materials processing and its applications. *Journal of Materials Research and Technology*, 8 (3), 3306–3326. doi: <https://doi.org/10.1016/j.jmrt.2019.04.004>
17. Cherbański, R., Rudniak, L. (2013). Modelling of microwave heating of water in a monomode applicator – Influence of operating conditions. *International Journal of Thermal Sciences*, 74, 214–229. doi: <https://doi.org/10.1016/j.ijthermalsci.2013.07.001>
18. Ye, J., Hong, T., Wu, Y., Wu, L., Liao, Y., Zhu, H. et. al. (2017). Model Stirrer Based on a Multi-Material Turntable for Microwave Processing Materials. *Materials*, 10 (2), 95. doi: <https://doi.org/10.3390/ma10020095>
19. Efremova, E. N., Karpacheva, E. A. (2015). Hranenie i pererabotka produktsii rastenievodstva. Volgograd: GAU, 148.