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PROCESSING MODES SELECTION IN LOW-INTENSITY HYBRID MICROWAVE TECHNOLOGICAL COMPLEXES BASED ON "QUALITY-ENERGY CONSUMPTION" CRITERION

G.A. Morozov, Yu.E. Sedelnikov, V.I. Anfinogentov, N.E. Stakhova, O.G. Morozov

Kazan National Research Technical University
named after A.N. Tupolev-KAI
10, K. Marx st., Kazan, 420111, Russian Federation

Annotation. When creating a microwave technological complex (MWTC) of both unitary and hybrid types, the initial data for the designer are the data on the parameters of electromagnetic action. It is advisable to divide these parameters into two groups. The first of them refers to idealized processing conditions in a hypothetically homogeneous EMF (or, equivalently, EMF for an elementary volume of the processed material). The second group characterizes the processing parameters in real conditions, in particular, the heterogeneity of the EMF. The division into these groups is due to a number of reasons and also has the peculiarity that the first parameters are determined at the stage of pre-project studies, and the second parameters - at the stage of R&D. It should be emphasized that in most cases the stage of pre-project studies is carried out by specialists professionally oriented in the field of applications (biologists, chemists, etc.), while the R&D stage is carried out by radio engineers. This leads to the fact that the recommended processing conditions at best correspond to the conditions of optimal processing quality, i.e. they are determined without taking into account the specifics of subsequent implementation. The energy consumption factor and, especially, the reduced microwave energy costs often remain out of sight. We will call finding the specified parameters, optimal from the point of view of the “quality - energy consumption” ratio, determining the microwave processing mode. Examples and possibilities of effectively finding such modes corresponding to low-intensity MWTC for processing of seeds of agricultural and forest crops, inactivation of microorganisms and microflora, stimulating the development of bacteria and yeast are considered in this paper.

Key words: low-intensity hybrid microwave technological complex, microwave processing modes, idealized processing conditions, real conditions, optimal processing quality, “quality - energy consumption” ratio.

Introduction

The field of applications in which the effective use of SHF and EHF electromagnetic energy is possible is very wide. The intensity of the EMF, the duration of the treatment and its result – changes in the properties of the material being treated – also vary widely. The following characteristic groups can be distinguished among the described applications [1-4]:

1. The intensity of the EMF is very low and the treatment does not lead to any significant heating of the material. This group mainly includes various options for the effect of the EMF of the SHF range on biological objects with the purpose of their stimulation or suppression: pre-sowing treatment of seeds, stimulation of biochemical processes, therapy, etc.

2. The treatment is carried out by the EMF of the microwave range for a relatively short period. In these cases, the material is heated, however, due to the short duration of the process; the effects of heat transfer and, especially, heat exchange with the environment do not play a decisive role. As a result, the spatial distribution of EMF intensities and temperature fields are close to each other, which allows us to limit ourselves to EMF analysis, i.e. solving electrodynamic problems. An example is the stimulation of seeds by microwave EMF, some problems of material disinfection, etc.

3. The treatment is carried out by microwave EMF of relatively low intensity over a long period. A characteristic feature of this group of effects is that heat transfer processes play a significant role, because of which the spatial dependences of temperature fields and EMF intensities differ significantly. This requires solving both the corresponding electrodynamic and thermos-physical problems. The concept of "relatively low intensity" of EMF in this case means that as a result of heating there is no significant change in the electrical parameters of the material, nor, moreover, a change in its mass, composition and phase state. Examples of such processes include most cases of food disinfection.

4. The treatment is carried out by high-intensity EMF over a long period. Because of heating, the electro-physical parameters of the material change significantly, which leads to a significant change in the EMF pattern during the treatment. Typical examples of this group are various options for using EMF energy for polymerization of plastics, vulcanization of rubber, etc.

5. High-intensity and long-term EMF treatment, leading to a change in the phase state of the substance. The peculiarity of this group of applications is that when the phase state of most materials changes, a more significant and abrupt change in the electro-physical parameters occurs than in the previous case - both specific conductivity and permittivity, and thermal physical parameters. Examples - defrosting of products, melting of various materials, etc.

6. Long-term high-intensity EMF treatment, leading to a change in the mass and electro-physical parameters of the substance. A typical example is microwave drying of various materials. The most important feature of such processes is the fundamental need to take into account the above changes, both in the analysis of EMF and thermos-physical processes.

The classification of various options for implementing microwave technological processes (MWTP) based on the use of electromagnetic energy of the SHF and EHF ranges allows us to set the task of microwave processing modes selection in low-intensity hybrid microwave technological complexes (MWTC) based on the criterion of "quality-energy consumption".

1. Processing mode selection tasks

When creating a microwave processing complex of both unitary and combined types, the designer uses the data on the electromagnetic impact parameters - V_1 as the initial data. As shown in [1, 2], it is advisable to divide these parameters into two groups - V_{1hom} and V_{1inhom}. The first of them refers to idealized processing conditions in a hypothetically homogeneous EMF (or, equivalently, EMF for an elementary volume of the processed material). The second group characterizes the processing parameters under real conditions, in particular, the inhomogeneity of the EMF.

The division into these groups is due to a number of reasons and has the peculiarity that the parameters V_{1hom} are determined at the stage of pre-design studies and the parameters V_{1inhom} - at the stage of R&D to create a specific MWTP and MWTC implementing latter. It should be emphasized that in most cases the pre-project research stage is carried out by specialists professionally oriented in the field of applications (biologists, chemists, etc.), while the R&D stage is carried out by radio engineers. This leads to the fact that the recommended processing conditions (specified by the V_{1hom} parameters) at best correspond to the conditions of optimal processing quality, i.e. are determined without taking into account the specific features of subsequent implementation. The energy consumption factor and, especially, the reduced microwave energy consumption often remain out of sight. In accordance with the approach described in [1, 2], a somewhat different task should be solved at the pre-project research stage. Namely, such conditions of electromagnetic processing V_{1hom_opt} are determined, which correspond to the minimum of the reduced costs of electromagnetic energy

$$W_n \to \min \tag{1}$$

with acceptable quality of processing

$$Q\left(V_{1hom\_opt}\right) \geq \mathrm{Q_{acc}} \tag{2}$$

or under the condition

$$\left| Q\left(\overset{*}{V}_{1\text{hom}}\right) - Q\left(V_{1\text{hom\_opt}}\right) \right| \le \varepsilon \,, \tag{3}$$

where $Q\left(\overset{*}{V}_{1\text{hom}}\right)$ the best value of the quality indicator of processing, determined without taking into account the factor of energy costs.

Finding the specified parameters $V_{1\text{hom\_opt}}$, optimal from the point of view of the ratio "quality - energy costs", will be called determining the microwave processing mode. Examples and possibilities of effectively finding such modes corresponding to low-intensity MVTP are considered in the following sections of this paper.

2. Modes of processing seeds of agricultural and forest crops

2.1. Microwave seed treatment

For the first time, the effect of electromagnetic energy of the microwave range was tested for the purpose of scarification, i.e. for the destruction of the hard shell of the seeds of some crops [5]. The next step was heating the seeds with EMF, repeating in its objectives a long-known agricultural technique – heating the seeds at a temperature of about 40-45 °C [6-8]. It was soon discovered that the effect of stimulating the sowing properties when exposed to microwave EMF is more pronounced than when heated by traditional means to the same temperatures [9]. Numerous studies conducted in this direction have made it possible to reliably assert that as a result of exposure to decimeter wave range (SHF) EMF, at certain field intensities and durations of exposure, the sowing properties of seeds improve, sprouts develop faster, which ultimately leads to an increase in yield.

Thus, in particular, the increase in barley yield reaches 11.7%, spring wheat – 17%. Similar results have been achieved for a number of other crops - peas, lentils, onions, beetroot, etc. The degree of reliability of the scientific results is such that the Ministry of Agriculture of the Russian Federation has issued a document - "Methodological recommendations for the treatment of seeds with microwave EMF".

Moreover, pilot plants "Impulse-2" and "Impulse-3" have been created for pre-sowing treatment of seeds in accordance with these "Methodological recommendations..." [9]. We will note one circumstance that is important later: according to the aforementioned recommendations, the treatment should be carried out with continuous SHF EMF (915 or 2450 MHz). The recommended treatment mode is determined by the field intensity (about 0.1-1 W/cm2) and the duration of exposure (up to several minutes).

Since the 1970s, the effects of exposure to EMF in the short-wave millimeter wave range (MMW) (~ 40-60 GHz) have attracted the attention of specialists. It was found that under certain conditions, pronounced stimulating effects are observed [10-14], including an improvement in the sowing properties of seeds of various crops. It is important to note that these effects are the result of exposure to EMF of very low intensity (less than 10 $\mu W/cm^2$), have a frequency dependence of a resonant nature and with a "quality factor" of about 10^2.

Attempts have also been made to identify more subtle effects. Thus, for therapeutic applications, it is advisable to use frequency-modulated (FM) oscillations. According to [15-17], when treating seeds with SHF-range EMF, it is preferable to use circularly polarized fields, and with a certain direction of rotation. Studies of the biological effects of exposure to MMF are successfully continuing. The latest achievements in this area are devoted to special periodicals - "Millimeter Waves in Biology and Medicine" and "Biomedical Technologies and Radioelectronics".

2.2. Modes and effects of pre-sowing seed treatment

Let us briefly consider the main results of treating seeds of various crops with SHF and EHF-ranges of EMF.

The sowing properties of seeds are determined by two characteristics: germination energy and germination. Germination energy determines the vitality of seeds, their ability to germinate. Germination characterizes the ability of germinated seeds to further development (formation of a full-fledged plant). Of course, the yield depends on the sowing properties. In addition, for many crops, for example, cereals, seeds with a germination rate of (90-95)% make up only (40-45)% of the total volume. Thus, the seeding rate is constantly overestimated, which leads to high economic costs. Therefore, stimulation of seeds in order to improve their sowing properties seems very relevant. As noted above, seed treatment with SHF and EHF of EMF has a pronounced stimulating effect – sowing properties are improved (Fig. 1).

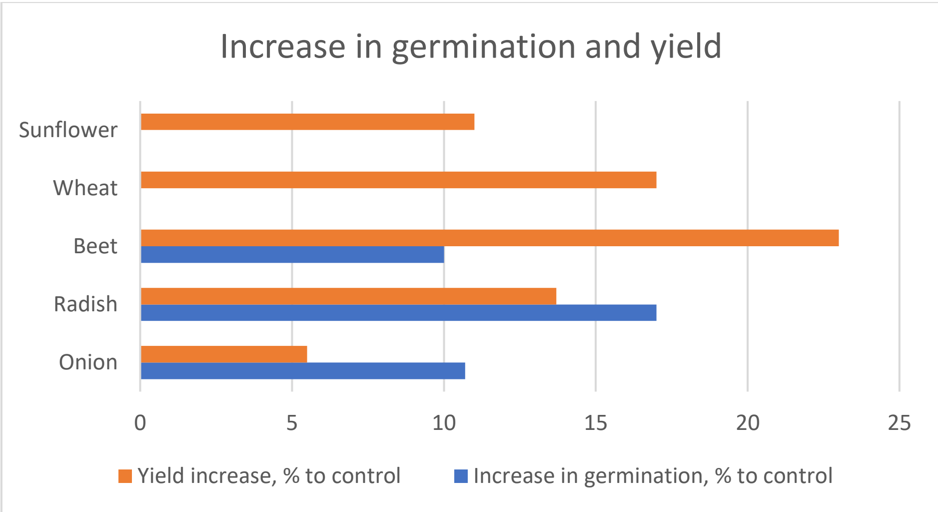


Fig. 1. Increase in germination and yield

The germination energy and germination are affected by the value of the EMF energy (per unit mass), exposure, heating temperature, and the time of seed storage after exposure before sowing. Fig. 3.2 shows the temperature values at which the sowing properties of seeds are stimulated or inhibited.

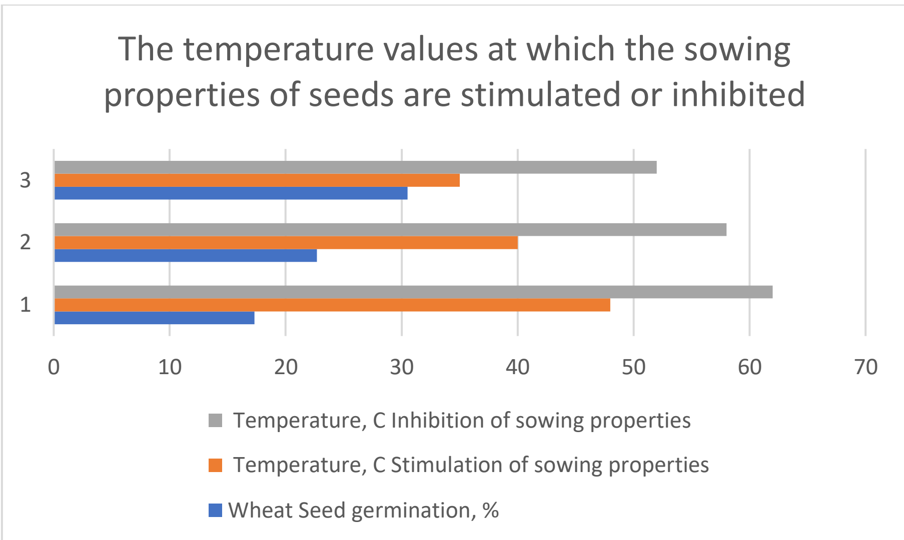


Fig. 2. The temperature values at which the sowing properties of seeds are stimulated or inhibited (conditioned seed germination (13-14)%)

The stimulating effect of microwave treatment in the microwave range is greatest for substandard, old or dry seeds.

Despite the difference in the required intensity and duration of treatment, there are general patterns for seeds of different crops [10-14]. The effect depends on the duration and intensity of treatment.

For seeds of any crops, the relationship between the quality of microwave treatment and the energy expended has the form of the dependence shown in Fig. 1.

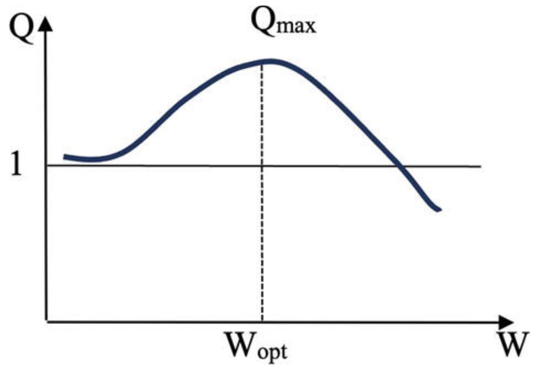


Fig. 3. Dependence of the quality of microwave processing on the energy expended in the SHF range

The effect of improving seed properties appears approximately six hours after treatment and increases with longer storage, reaching a maximum after 20-30 days. Then the effect stabilizes and lasts for up to two months. Treatment is carried out with parameters corresponding to heating of seeds to temperatures of about 45-50 °C, i.e. at a high intensity of SHF EMF (about 0.1-1 W/cm2).

When treating seeds with EHF EMF, the stimulation effect is manifested to at least no lesser extent. Germination and germination energy increase. In addition, with SHF treatment, the resistance of seedlings to diseases affecting plants at an early stage of development increases to a greater extent. A possible explanation for this fact is that, as a result of microwave treatment, seeds germinate faster than pathogens have time to develop.

As an illustration, Fig. 4 provides comparative data on microwave treatment of wheat seeds ("Moskovskaya-35") in laboratory conditions.

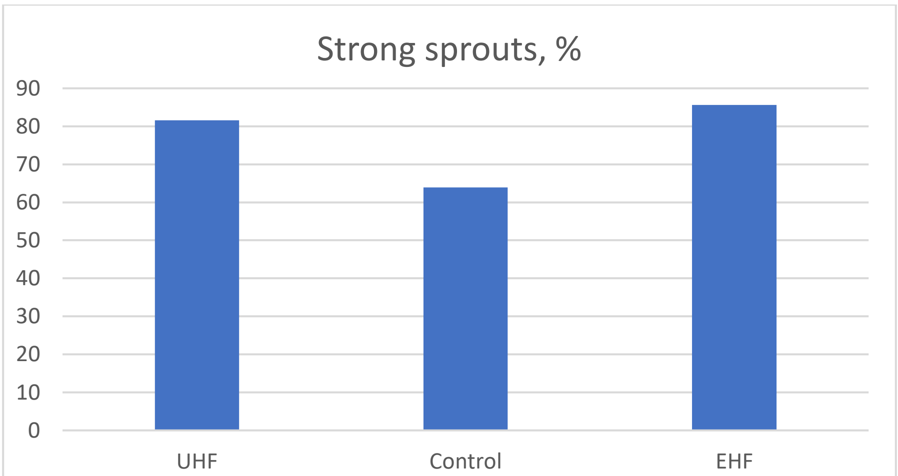
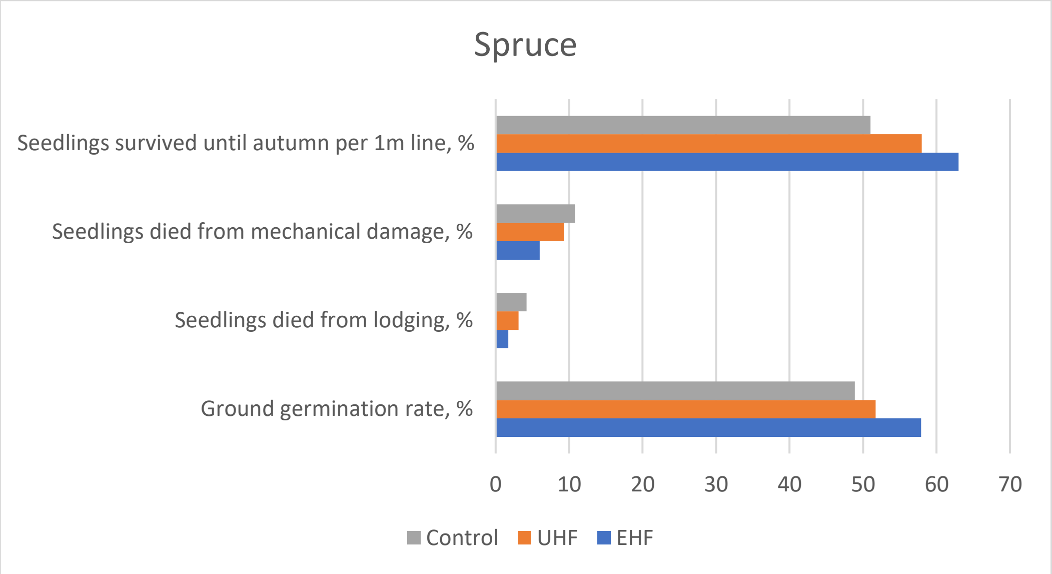


Fig. 4. Comparative data on microwave treatment of wheat seeds ("Moskovskaya-35") in laboratory conditions

Fig. 5, *a* and Fig. 5, *b* provides similar data for forest crops, spruce and pine respectively. The tests were conducted by the Tatar Experimental Forest Station (Kazan, Russia). The germination and development of spruce and pine crops during the first year were studied.



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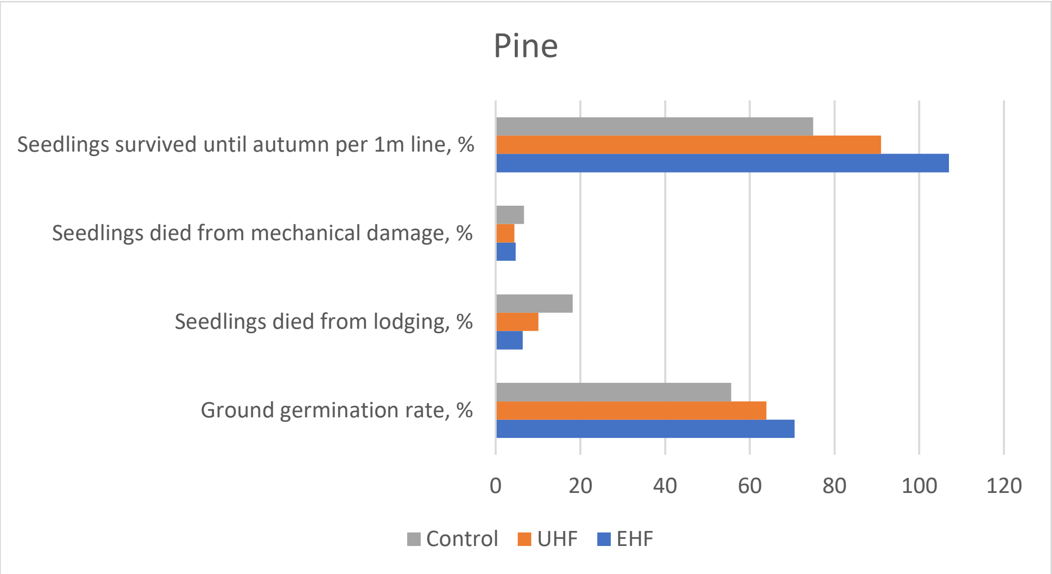


b

Fig. 5. Comparative data on microwave treatment of spruce (*a*) and pine (*b*) seeds (were conducted by the Tatar Experimental Forest Station, Kazan, Russia)

Regardless of the type of crop, EHF seed treatment has a number of common patterns:

- the effect is manifested when treated with EMF with a frequency of about 42 and 53 GHz;

- there is a threshold level of field intensity, above which the stimulation effect is observed. The value of this threshold is no more than 10 μW/cm2;

- there is a minimum exposure time required to achieve a useful result. This time is practically independent of the field intensity exceeding the threshold level. Further increase in the processing time in some cases can lead to the opposite effect - deterioration of seed properties;

- the effect of exposure to EHF EMF is manifested almost immediately (i.e. long-term storage of seeds is not required) and persists for a fairly long time (at least a month).

2.3. Ways to reduce energy costs during microwave treatment of seeds

According to the literature [1, 2], including recommendations, when processing with SHF, it is necessary to ensure that the seeds are heated to temperatures of about 45-55 °C. This means that the required energy costs are about 60 J/cm^3. When processing with EHF, the energy costs are significantly lower and are about 6×10^{-3} J/cm^3 (i.e. about 4 orders of magnitude less) with a processing time of 20 minutes. The purpose of choosing the most effective mode is to reduction of energy consumption compared to the specified values. The studies conducted by the authors show the presence of significant reserves for savings.

Processing of seeds in the microwave range (SHF).

The studies conducted by the authors revealed the following reserves. Firstly, it was established that a noticeable stimulation effect occurs at significantly lower field intensities and duration of exposure, compared to the recommended values [10-14].

For example, when studying the effects of stimulation of wheat seeds "Moskovskaya-55" it was found that at a field intensity of (1-10) W/cm^3, the duration of treatment is (10-30) seconds. This means that the specific costs of electromagnetic energy may not exceed a value of about 10-20 J/cm^3. Secondly, it has been established that with equal specific absorbed energy, the time mode plays a significant role, in particular, the presence of low-frequency modulation (with frequencies of no more than 0.1 Hz). As an illustration, Fig. 6 provides data from laboratory studies of stimulation of Moskovskaya-35 wheat seeds in the microwave range. In both cases, the absorbed energy values are the same. Mode RD 01/2 - seed treatment in a quasi-pulse mode with a duty cycle of 10 for 2 minutes, RD 02/1 - with a duty cycle of 5 for 1 minute.

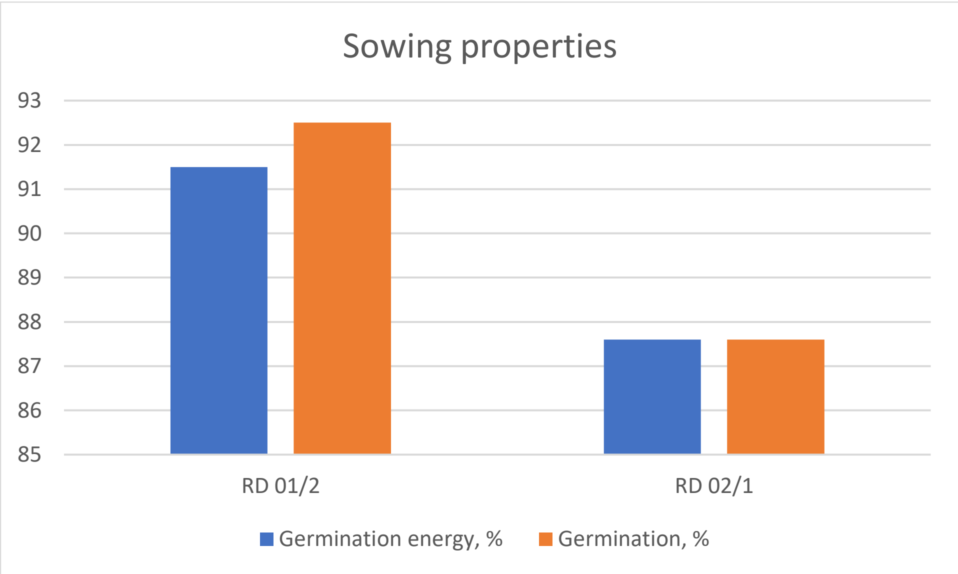


Fig. 6. Data from laboratory studies of stimulation of Moskovskaya-35 wheat seeds in the microwave range (SHF)

Seed treatment in the microwave range (EHF).

According to the accepted concept [10-14], EHF EMF affect biological objects, influencing their vital functions (presumably information exchange) at the cellular level and thus influencing regulatory functions at this level. The effects of exposure appear at certain frequency values, have a resonant nature and are characterized by threshold intensity values, at which the effect begins to manifest itself in an abrupt manner. In addition, the quantitatively useful effect depends on the duration of exposure, which is usually tens of minutes. The possibilities of reducing the energy costs during processing in the EHF range are determined by the choice of:

- exposure frequency (from the point of view of reduced energy costs, it is desirable that with equal manifestations of the useful effect this frequency has the lowest value);
- clarification of the threshold level of exposure (assessment of its real value, and not a deliberately overestimated one) for a given variety of seeds, class, etc.;
- specifying the minimum required processing time based on the relationship between the effect achieved and energy consumption;
- selecting the type, modulation parameters and, possibly, the polarization characteristics of the EMF.

Due to the current lack of a constructive understanding of the essence of EMF seed stimulation, the only way to find an effective and economical mode is a very labor-intensive experiment. Work on this plan is at the beginning of the path, it is premature to draw final conclusions. However, the results obtained to date indicate the presence of significant reserves for reducing the energy costs. Let us briefly present some of these results.

Exposure duration. Fig. 7 presents the data of laboratory studies on the stimulation of sowing properties of Moskovskaya-35 wheat seeds by EMF with a frequency of 42.25 GHz. It is clearly seen that an increase in the processing time has virtually no effect on the stimulation effect. Further studies have shown that the processing time of 30 minutes is also too high and can be reduced without significant damage.

Fig. 7. Data of laboratory studies on the stimulation of sowing properties of Moskovskaya-35 wheat seeds by EMF with a frequency of 42.25 GHz

Intensity of EMF. According to preliminary data [15-17], the threshold level is ~ 50 μW/cm2. In reality, this level may be significantly lower than 10 μW/cm2. As an illustration of this fact, Table 1 provides data from one of the series of laboratory studies of pine and spruce seed stimulation in the EHF range at different EMF intensities (frequency of about 42 GHz).

Table 1. Data from one of the series of laboratory studies of pine and spruce seed stimulation (EMF)

Culture	Intensity, μW/cm^2	Germination energy, %	Germination rate, %
Spruce	20	85	94,2
	5	89,2	96,7
	Control	90	97,5
Pine	20	81,7	86,7
	5	80	82,5
	Control	78,3	80

Frequency of electromagnetic oscillations. The problem of choosing the best frequency value (taking into account the resonant nature of the effects and the presence of a number of resonant frequencies) has not yet been studied to a sufficient degree. Only the existence of useful effects for two frequency bands, respectively, about 42.25 and 53.57 GHz, has been reliably established. A comparison of the processing effects at the specified frequencies showed that the stimulation effect occurs for both frequencies, and the results correspond somewhat better to the oscillation frequency of 42.25 GHz (Table 1). This circumstance is important, both due to the value of due the achieved effect, and also due to the fact that the value of the reduced energy consumption for processing EMF in the 42 GHz range is 10-20% less than for fields in the 53 GHz range (at least due to the use of waveguides with a larger cross-section).

Processing EMF in the centimeter wave range (CMW).

Most of the studies [5-17] studied the effects of either decimeter wave range (DMW, SHF) (915 or 2450 MHz) or milimeter wave range (MMW, EHF) (42 or 53 GHz) EMF. The effects of CMW EMF (10-29 GHz) are almost not covered in the literature. Nevertheless, the available data indicate the presence of stimulating effects when using CMW EMF. Table 2 presents comparative data on the sowing properties of spruce seeds when processing them with fields of different ranges, including CMW.

Table 2. Comparative data on the sowing properties of spruce seeds in different ranges

Frequency range	Germination energy, %	Laboratory germination, %
DMW	94,2	94,2
SMW	95,8	96,7
MMW	96,7	97,5
Control	93,3	85

The data given in Table 2 for SHF and EHF correspond to the intensities and durations of processing described above. When processing SMW EMF ($f \sim 20$ GHz), the duration of processing also corresponded in order of magnitude to the case of EHF range stimulation, the field intensity was somewhat higher, but of the same order. The data provided are preliminary and do not yet allow us to give substantiated recommendations. However, they are of considerable interest from the point of view of the concept of minimum reduced energy costs. Indeed, even if we allow for the required increase in energy costs compared to MMW processing by 2...3 times, the cost of processing with MMW fields looks promising, since the cost of 1 J of SMW energy is at least 4 times less compared to the value for frequencies of the order of 40-50 GHz. However, a final conclusion can only be made after completion of detailed experimental studies.

Combined multi-frequency processing.

There is a (though limited) number of studies that demonstrate the effectiveness of using multi-frequency treatment for seed stimulation. The combined use of SMW and DMW EMFs was studied at [18-20], and DMW and MMW fields were studied at KNRTU-KAI. According to these studies, combined multi-frequency seed treatment can lead to additional improvement of seed properties. As an illustration, Table 3 shows the results of spruce seed stimulation using fields of only the EHF range and with the combined use of SHF and EHF radiation.

Table 3. The results of spruce seed stimulation using fields of only the EHF range and with the combined use of SHF and EHF radiation

Mode	Germination energy, %	Laboratory germination, %
SHF	73,3	75,8
ЕНФ→SHF	76,7	81,7
Control	71,7	74,2

These results, despite their preliminary nature, are also of some interest from the point of view of reducing the reduced energy costs. Firstly, since the best of the achieved results exceeds the value obtained with separate action, dual-frequency seed treatment may be more effective in terms of the ratio between the reduced energy costs and quality. Secondly, the possibility of achieving a better result gives grounds to expect that a result similar to the case of single-frequency treatment may be achieved with lower total reduced energy costs.

3. Microwave Treatment Mode for Microflora Inactivation

3.1. Tasks of Inactivation of Biological Objects

Historically, the use of electromagnetic energy for the purpose of destroying microflora was one of the first directions in the development of microwave technologies MWT [2]. Later, a significant number of studies were carried out that led to the development of methods (and in some cases equipment) for pasteurization of food products, sterilization of instruments and materials, disinfection of greenhouse soils, destruction of seeds and sprouts of weeds, and a number of others [3]. There is a vast literature devoted to the solution of the above problems, the presentation of which goes far beyond the scope of this section. The goals and objectives in this case are to show the presence of significant reserves for reducing the costs of electromagnetic energy in a number of tasks of inactivation of microorganisms, disinfestation, etc.

At first glance, the mechanism of inactivation seems quite clear: under the influence of EMF the product is heated. Microorganisms and (or) their spores, insects and (or) their eggs, seeds, etc. contained in it die at a sufficiently high ambient temperature and duration of heating. Typical values of the above temperatures are within 80-120 °C, the duration of heating, depending on the specific type of objects, can be from several seconds to several tens of minutes. The reader can find more detailed data on the values of the above quantities in specialized literature, including the one already cited [21, 22]. The possibilities of reducing electromagnetic energy consumption in inactivation tasks are determined by a number of circumstances. Some of them seem clear enough, at least from a fundamental point of view, while others require careful study, and the main tool for them can only be an experiment. Thus, according to the concept of a given heating, with a known range of values of the electrophysical parameters of the material, the required temperature and duration of heating and at this temperature, the task of optimally selecting the frequency range, EMF intensity and duration of exposure, ensuring minimum energy expenditure, can be set. This path, in principle, is no different from that used in other problems of heating SHF EMF; directions for solving such problems are discussed in a number of works, for example, [15-22].

There are also a number of less studied possibilities based on more subtle effects of a physical and biological nature. We will note the most interesting of them, in our opinion:

- the fact of selective heating. Biological objects and the product in which they are located have different electrophysical parameters, and in many cases biological objects have the property of greater specific absorption. As a result, when exposed to EMF, they heat up faster than the product surrounding them, and inactivation occurs with less heating of the product itself;

- the question of the optimal relationship between the heating temperature and the duration of exposure is not obvious. The latter becomes especially important, since the rate of change of temperature of the environment around them affects the disruption of vital functions of a fairly wide range of biological objects;

- from known works, for example, [21], it follows that in a number of cases the inactivation of microorganisms occurs more effectively (and what is important, with less heating of the product itself) when using pulsed EMFs;

- finally, there are preliminary data indicating the presence of resonance effects of inhibition under low-intensity effects of EMFs in the EHF range.

The listed circumstances give grounds to expect the possibility of a significant reduction in the reduced energy costs in problems of inactivation of biological objects of various natures. In the following sections, some of these possibilities are considered in relation to a number of specific problems.

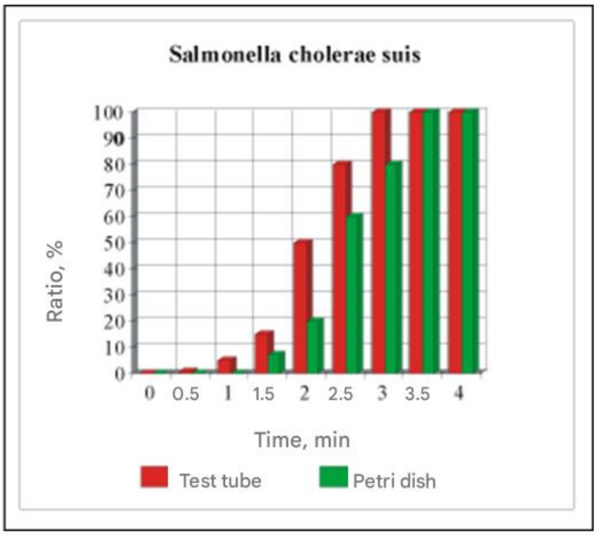
3.2. Microwave processing modes for inactivation of microorganisms and microflora

One of the hygienic factors determining the suitability of food products is their safety in terms of epidemics, which is assessed by such indicators as: quantity, viability, ability to further develop and reproduce microflora and microorganisms that cause diseases. For the experiments, *E. coli* and saprophytic organisms of drinking water and *Salmonella* cultures were selected.

The tasks of destroying harmful microflora are also of great importance for agriculture. In particular, disinfection of greenhouse soils is a serious problem. A common practice is thermal treatment of natural soils before sowing (with superheated steam, for several hours). The artificial soils that are becoming widespread are practically not amenable to disinfection and are subject to complete replacement after a certain service life. Finally, helminthiasis, which causes serious losses, mainly in young animals, and significantly reduces the productivity of the herd, is a serious problem for poultry farming and livestock farming. Finally, there is another area of management where microflora inactivation is of primary importance - the tasks of disinfecting drinking water, equipment and filters for drinking water supply systems. In particular, when using filters to purify water, it stagnates and becomes contaminated with organisms. Traditional methods of influencing these biological objects are energy-intensive and not always effective. In crop production, agrochemical methods using chemicals lead to soil depletion and a decrease in the efficiency of their use, including due to the loss of the ecological purity of the products. Thermal heating for the purpose of inactivating microorganisms and microflora is either energy-consuming (water, preserving poultry and meat products) or is very difficult due to the low humidity and thermal conductivity of the processed media. Therefore, the development of highly effective microwave methods for inactivating microflora and microorganisms, disinfecting water and soil is very important [23-26]. Approaches to selecting effective microwave processing modes for the above purposes are described below.

Microwave processing of Salmonella cultures.

To study the modes, samples of two cultures were selected: *Salmonella gallinarium* (SG), *Salmonella cholerae suis* (SCS). Their choice was due to their good resistance to life in the external environment, the ability to survive for a long time in soil, manure, water and food products. It is believed that boiling kills Salmonella instantly, at a temperature of 80 °C they are preserved for up to 15 minutes. Samples placed in test tubes or Petri dishes were exposed to EMF at different values of the average radiated power (continuous and intermittent generation modes, frequency - 2450 MHz, maximum). The results of processing *Salmonella cultures* in epidemic terms were assessed as a percentage of suppressed samples to processed ones depending on the duration of processing. Typical results are shown in Fig. 8.



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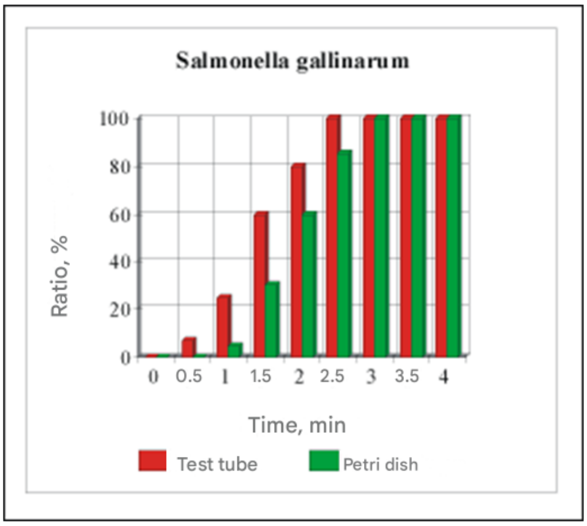

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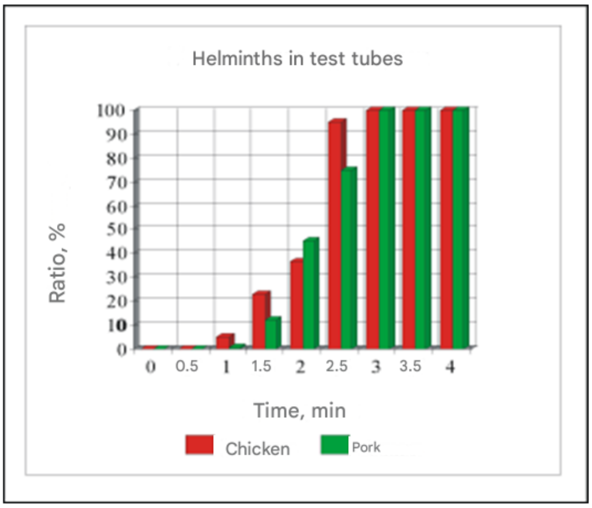
Fig. 8. The results of SCS (*a*) and SG (*b*) processing

It is clearly seen that o at a power flux density of P0 ~ 0.5 W/cm^2 there is a minimum treatment time at which 100% suppression of microflora occurs. Comparison of the specified data for different values of EMF intensity allows choosing the option that corresponds to both complete inactivation and the minimum level of energy consumption.

Microwave inactivation of helminths of chickens and pigs.

To determine the modes of treatment of helminths of chickens and pigs, samples of their roundworms were taken. The samples were exposed to microwave EMF at different power and duration of treatment. The safety of helminths in terms of epidemics was assessed by their viability after placement in a thermostat at a temperature of 37.8 °C. The presence of movement of roundworms, the state of their cuticles and nematodes, the presence of elements of their decomposition in the solution were assessed. Typical results of treatment (f = 2450 MHz, П0 ~ 1 W/cm2) are shown in Fig. 9.



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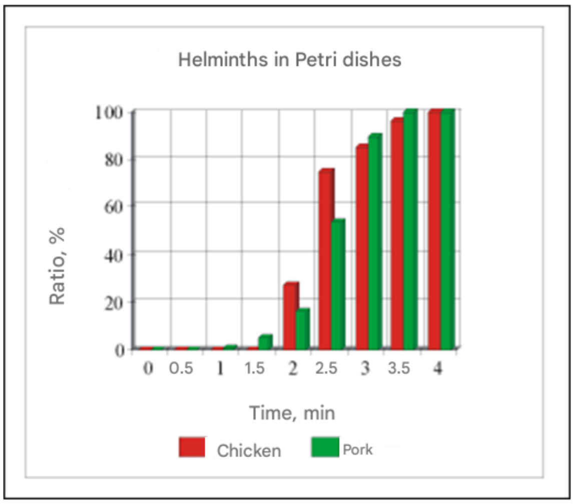


b

Fig. 9. The results of chickens and pigs helminths processing in test tubes (*a*) and Petri dishes (*b*)

Further studies were conducted for helminths in wastewater. Faeces were taken from pigs spontaneously infected with ascariasis and other intestinal nematodes. A series of experiments were conducted for natural, semi-dry and liquid feces, for which samples were prepared according to the method used earlier. The viability of pig ascarid larvae was determined after treatment with microwave EMF at different exposure and power flux density. Typical results of the experiments are shown in Fig. 10.

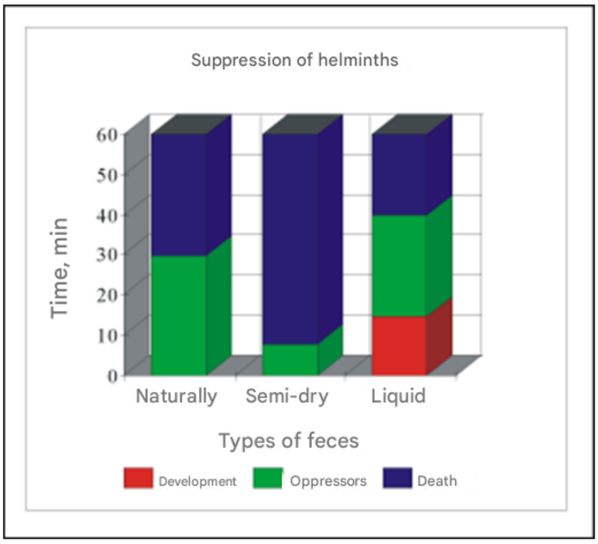


Fig. 10. Helminth survival results after treatment of various types of feces

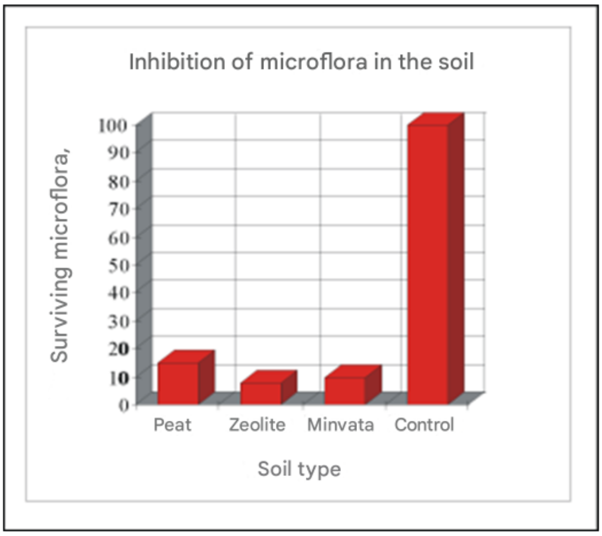


Fig. 11. The results of SHF treatment compared to the control group for the specified soils

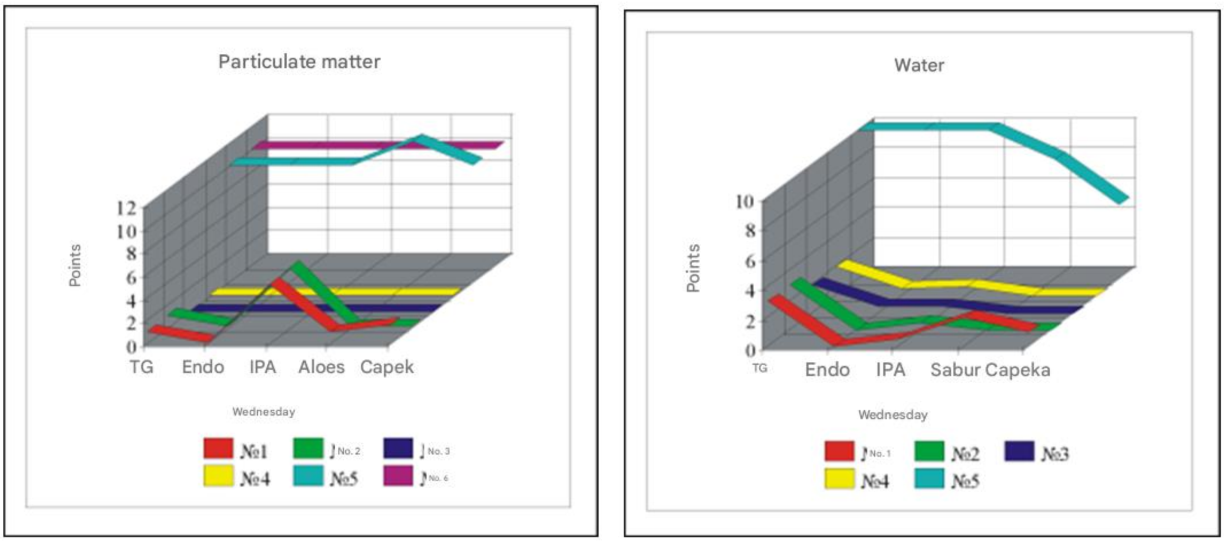
As in the case of *Salmonella* inactivation, the possibility of choosing a treatment mode with minimal energy consumption is clearly visible from the data provided, for example, Fig. 8.

Microwave treatment of secondary soils.

To study the modes of processing secondary soils, peat-humus mixture, zeolite soil and mineral wool were selected as the most widely used in greenhouses. The samples were exposed to microwave EMF at different power flux densities and treatment durations. Microflora inactivation was assessed by its viability, determined by standard methods. Fig. 11 shows the results of microwave EMF treatment compared to the control group for the specified soils. The results of microbiological examination of soil samples before and after microwave treatment show a pronounced effect of microwave radiation on bacterial and fungal microflora. It follows from the experimental data that when exposed to 2450 MHz EMF, soil treatment for a duration of 2-2.5 minutes at P_0 ~ 1 W/cm^2 should be considered minimally sufficient. Note that this irradiation frequency is determined based on the condition that microflora and microorganisms are located at a depth of 5-10 cm from the surface.

Study of drinking water treatment modes.

To study the microwave treatment modes of drinking water, samples of water itself (No. 1-5) and solid particles of its sediments (No. 1-6) were selected. Samples (No. 1-4) of both sample sets were exposed to the microwave range under various treatment modes (frequency 2450 MHz), samples No. 5 of water and No. 5-6 of solid particles control without irradiation. Safety in terms of epidemics was assessed in bacterial cultures of the lactose-positive Escherichia coli group and the total number of saprophytic microorganisms. The results of the bacteriological and mycological examination are shown in Fig. 12.



a *b*

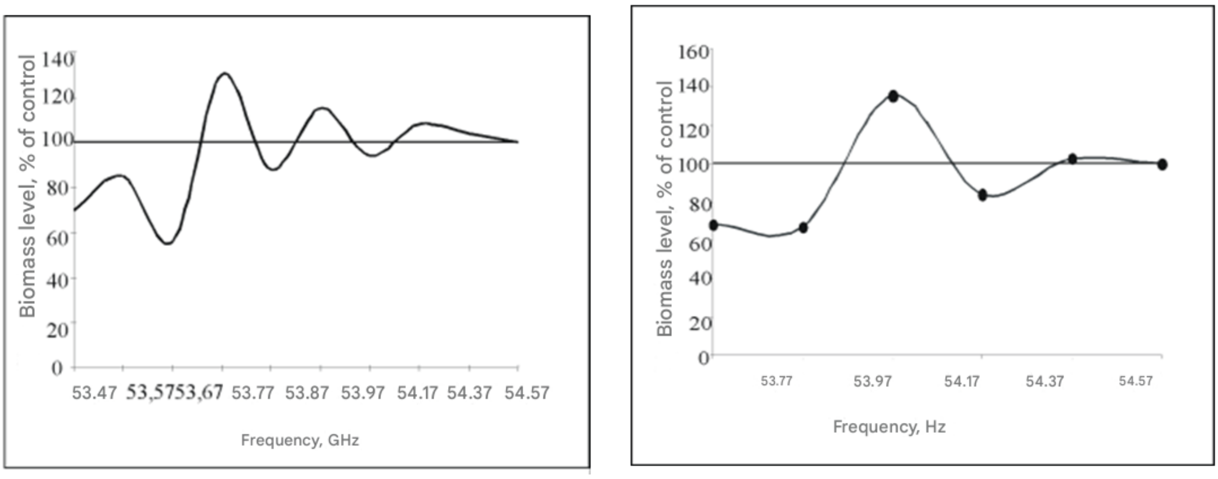
Fig. 12. Results of the bacteriological and mycological examination of particle matters (*a*) and water (*b*)

The growth of rods and fungal microflora was assessed in points based on their quantity in a milliliter of the medium. For water treatment, the duration of EMF treatment varied within 1-5 minutes (groups No. 1-4, respectively). For solid sediment treatment, it varied within 1-2.5 minutes (groups No. 1-4). Control group No. 5 consisted of solid sediment, control group No. 6 consisted of sludge from water purification filter settling tanks. The results of microbiological examination of water samples and solid particles before and after irradiation revealed a pronounced bactericidal effect of microwave radiation on bacterial and fungal microflora. The minimum sufficient treatment of water and its sediment with microwave EMF for 2-2.5 minutes at a radiation power flux density of 5 W/cm^2 should be considered.

The data presented, firstly, show the possibility of effective suppression of microflora and other harmful organisms, including in areas unconventional for MWT. Secondly, they suggest the possibility of consciously choosing economical processing modes, including ways of determining the processing mode. The possibilities for reducing the given energy costs, however, cannot be considered exhausted. Undoubtedly, the already mentioned methods are promising in these tasks – the use of pulsed EMF with an optimal choice of the average power flux density and duty cycle, as well as, possibly, specific effects of exposure to low-intensity EMF of the SHF range of certain frequencies.

4. Modes for stimulating the development of bacteria and yeast processing

One of the promising areas of application of microwave processing methods is the stimulation of various microorganisms. The possibility of implementing such processes was first described in the monograph by N. D. Devyatkov [10]. The indicated work and subsequent publications present the results of studies conducted on microbes belonging to various taxonomic groups. This section presents data on the stimulation of the SHF range for two different classes: prokaryotes *Bacillus subtilis* (*B. sub.*) and yeast *Saccharomyces cerevisiae* (*S. cer.*), which are of great practical importance [27-28]. Bacteria *B. sub.* are the basis of a biological preparation for plant protection. Yeast *S. cer.* are used in the baking industry. Therefore, stimulation of growth and an increase in the biological activity of the studied microorganism cultures is an urgent task. The studies conducted confirm the presence of a stimulating effect of SHF range treatment on these microorganisms, as well as the resonance nature of the effects. Fig. 13,*a* shows the dependence of the biomass concentration on the irradiation frequency for *B. sub* bacteria.



a *b*

Fig. 13. The dependence of the biomass concentration on the irradiation frequency for *B. sub bacteria* (*a*) and of *S. cer yeast* (b)

As can be seen from the data provided, the change in biomass concentration depending on the irradiation frequency with all other constant parameters remaining constant also has a resonant nature. There is a processing frequency value (53.77 GHz) at which the biomass concentration value (130% of the control) is maximum. With an increase in the exposure frequency relative to the optimal value, the value of the extremes decreases and at values above 54.57 GHz the stimulation effect is practically not observed, approaching the control value. A decrease in the exposure frequency relative to the optimal value even leads to a decrease in the biomass concentration compared to the control.

Fig. 13,*b* shows a similar dependence – a graph of the change in the biomass concentration of S. cer yeast depending on the irradiation frequency with all other parameters remaining constant. This dependence also has a resonant nature, although less pronounced, compared to B. Sub. In this case, the maximum biomass increase, amounting to 36% in relation to the control, corresponds to a frequency of 54.17 GHz.

When the frequency increases above 54.57 GHz, there is practically no increase, and at frequency values from 53.77 to 53.07 GHz, a negative effect is observed - a decrease in biomass (Fig. 3.11).

Possible changes in the main technological parameters of the cultures of the studied microorganisms under the influence of EMR were also analyzed. One of the most important physiological characteristics of microorganism growth is the biomass yield from the consumed substrate. Sugars contained in the nutrient medium are used as a substrate for the growth of B. subtilis. Changes in the composition of the culture liquid during cultivation are presented in Table 4.

Table 4. Changes in the composition of the culture liquid during cultivation

Frequency	Number of reducing substances, %	Protein content, mg/ml
Nutrient medium	0.504±0,001	13.7±0.05
53.67 GHz	0.256±0,0012	22.4±0,012
53.77 GHz	0.247±0,001	39.9±0.04
Control	0.288±0,001	23.4±0.03

Samples irradiated with fields of stimulating (53.77 GHz) and inhibiting (53.67 GHz) frequencies were analyzed. During cultivation, the amount of reducing substances in the nutrient medium decreased for all the samples studied. This is due to the consumption of sugars during culture growth. However, the efficiency of using sugars for growth, defined as the yield on the substrate, is higher for the culture irradiated with the stimulating frequency. The culture of B. subtilis bacteria is used in agriculture to protect plants. One of the mechanisms of the biocidal action of these bacteria is associated with the release of substances of a polypeptide nature. Analysis of changes in the protein content in the composition of the culture liquid (Table 4) shows that during growth its content increases in all the samples studied.

However, when exposed to the stimulating frequency (53.77 GHz), protein excretion significantly exceeds the control value, and when exposed to the inhibitory frequency (53.67 GHz), the protein concentration is below the control. The yeast culture we studied is of great industrial importance, so it is of interest to consider the effect of SHF EMF on the main technological indicators. The ability of yeast to ferment glucose and fructose is determined by the magnitude of the lifting force and zymase activity. Experiments to determine these indicators were conducted using a culture irradiated with an EMF with an optimal frequency (54.17 GHz), and on a control sample, that is, on yeast not exposed to EMF. The lifting force of the experimental yeast increased almost twice as much as the control. It should be noted that the lifting force determines the activity of the enzymatic systems of not only yeast, but also the flour used in these analyses. Therefore, there was an objective need to conduct experiments to determine the enzymatic activity of the yeast itself. For this purpose, experiments were conducted to determine the zymase and maltase activities of yeast. These indicators characterize the level of consumption of sugars - glucose and maltose from the nutrient medium and characterize the overall activity of the enzymatic systems responsible for the utilization of glucose and maltose. The results showed (Table 5) that there is an increase in zymase activity by 37%, and maltase by 35% in relation to the corresponding indicators of the control yeast.

Table 5. Results of yeast processing

Technological indicators	Frequency 54.17 GHz	Control
Lifting force, min.	10,5	21
	7	12
Osmosensitivity, min	7	7
Winter activity, min	60	45
Maltase activity, ml per 1 hour	6	4
	5	3,75

The ability of yeast to ferment sugars in a medium with an increased salt content is determined by the osmosensitivity index. The results of determining the experimental and control samples do not differ. Thus, the influence of the EMF of the SHF range on this indicator is not observed.

To summarize, it should be noted that the effect of the EMF of the SHF range on different types of microorganisms is in many ways similar. In particular, the resonant nature of the effect is preserved for both cultures. The choice of the optimal processing mode includes, first of all, determining the frequency values at which the stimulation effect is manifested to the greatest extent. Secondly, the choice of the most effective processing mode should include determining the minimum required EMF intensity and the duration of the treatment.

Conclusion

This article is published on the eve of the 85th anniversary of the founder of the Kazan Scientific School of Microwave Technologies, Professor G.A. Morozov.

The works of the school, created in the 80s, can be traced today by the works of 2000-2025 years listed in the references. \

In conclusion, the authors would like to present a number of MWTCs created using approaches based on optimizing the “quality - energy consumption” ratio, which are most obviously implemented in hybrid variants based on the use of decimeter and millimeter range waves for seed treatment.

Dual-range microwave unit for pre-sowing seed treatment «SHYTYM»

Dual-range MWTC (Fig. 14) for pre-sowing seed treatment «SHYTYM» operates in two ranges: SHF and EHF.

The microwave installation provides:

- irradiation of seeds with electromagnetic SHF and EHF fields with regulation of the irradiation intensity;
- time sampling of the effect of microwave energy in accordance with the processing program;
- a sufficiently high uniformity of seed processing for all parameters of the intensity, time sampling and spectrum.

For loading and unloading the drum on its side surface there is a hatch with a throttle valve. On the inner side surface of the drum at an angle to the generators, dielectric ribs are installed. To ensure uniform processing in a non-uniform field, the mass of seeds randomly moves in the working chamber. The rotation speed of the drum is selected from the condition of ensuring a suspended state of the seed cloud. This is achieved at rotation speed at which centrifugal forces and gravity are balanced. After receiving a suspended cloud of seeds [after 3-4 turns] the processing program begins to be executed. In the MWTC «SHYTYM» two different sources of electromagnetic field are used:

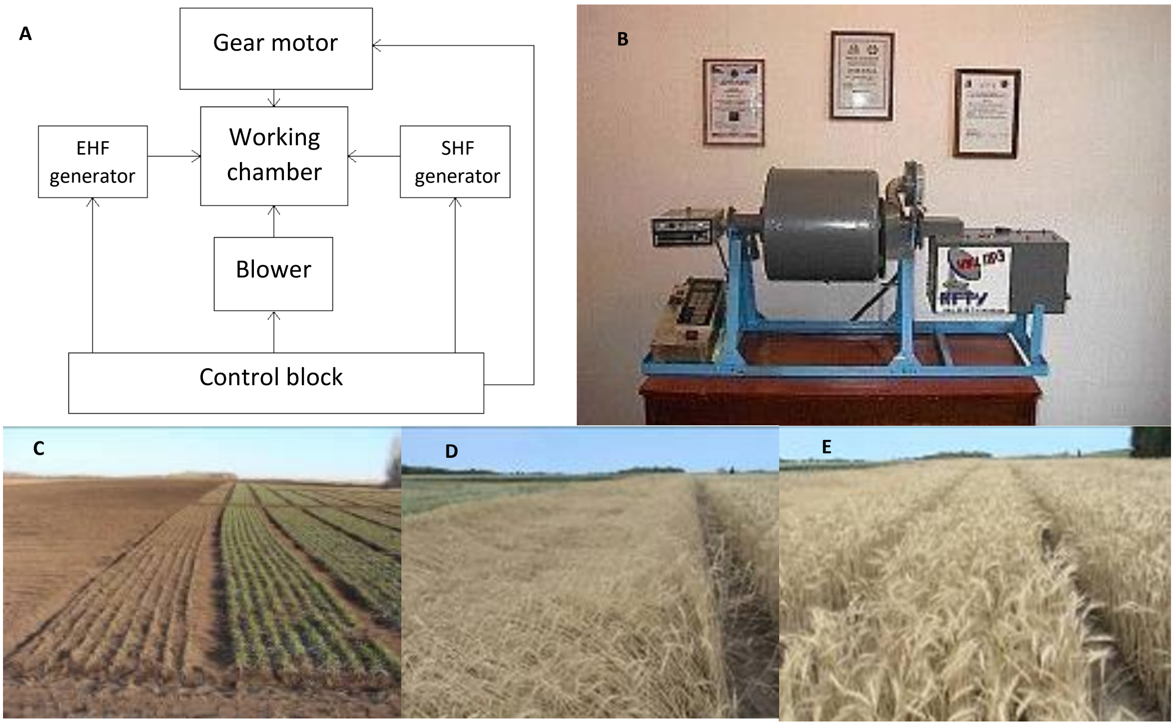


Fig. 14. Dual-range MWTC for pre-sowing seed treatment «SHYTYM»:
a generalized scheme (A); microwave unit photo (B); sprouted seedlings of winter wheat Kazan-560 – weak in the control band without treatment on the left and strong in the band with treatment on the right (C); ears of winter wheat Kazan-560 – empty, lodging in the control band without treatment (D) and filled, stable in the band with treatment (E)

SHF range: frequency 2450 MHz, productivity 24 kg/hour; power consumption no more than 0.3 kW/hour;

EHF range: frequencies (30…80) GHz, productivity 10 kg/hour, power consumption no more than 0.05 kW/hour.

Pre-sowing treatment of agricultural crop seeds with electromagnetic fields of the SHF and EHF ranges improves their sowing qualities, germination energy, stability to lodging, resistance to infectious diseases, which leads to increased yields.

MWTC MSP «Microwave Seed Processor» is the analogue of MWTC «SHYTYM» with a maximally integral body made of composite material, protecting the operator from microwave leaks (Fig. 15).

Fig. 15. Dual-range MWTC for pre-sowing seed treatment «MSP»

Small-sized Dual-range for pre-sowing seed treatment MWTC «ROSTOK»

A prototype of a small-sized MWTC «ROSTOK» for final drying and pre-sowing treatment of seeds of agricultural crops was developed. The MWTC is intended for laboratory testing of seed sowing properties (in the field) and for individuals.

The MWTC «ROSTOK» microwave installation is based on the household microwave oven «Elektronika» (manufactured by POZIS, Zelenodolsk) and the medical serial installation «Yav-7», (optionally «Yav-5»). Accordingly, two generators are used: a SHF magnetron M-136 (2450 MHz) and a generator on an LPD (1-42 or 53 GHz), and allows for software control of seed processing taking into account their initial state (temperature, humidity).

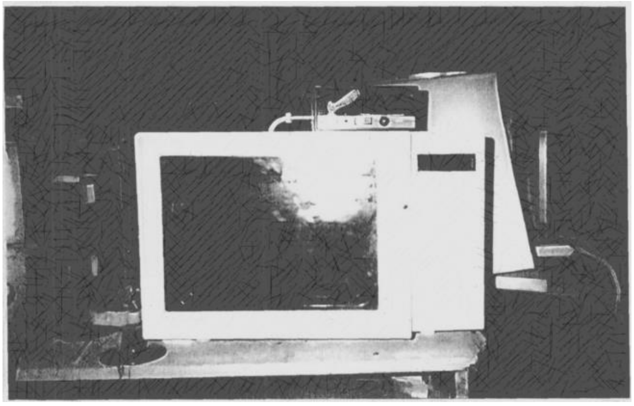


Fig. 16. Small-sized dual-range MWTC for pre-sowing seed treatment «ROSTOK»

For this type of MWTC total power consumption is no more than 4 kW, load of dry seeds is no less than, 2 kg, productivity in the «drying» mode – no less than 20 kg-hour, productivity in the «stimulation» - not less than 18 kg-hour in SHF range and 6 kg-hour in EHF ones.

The frequencies and processing modes for the MWTC «ROSTOK» were selected based on the results of studies conducted by the authors. The efficiency of the thermal and information impact of electromagnetic fields was tested in laboratory tests at KNRTU-KAI for seeds of agricultural crops (rye, wheat, carrots, corn), as well as for pine and spruce seeds. Field tests were carried out in the forestry enterprise «PRIGORODNY».

Single-range MWTC "ROSTOK-3"

Single-range MWTC "ROSTOK-3" is intended for farms and individual households (Fig. 17) and operates in EHF range.

Fig. 17. Single-range microwave installation "ROSTOK-3"

Technical specifications:

- EHF range, frequencies (30...70) GHz
- productivity 8 kg/hour
- power consumption, no more than 0.03 kW/hour.

References

1. Morozov G. Perspective Chapter: Microwave Technological Processes, Electromagnetic Field - From Atomic Level to Engineering Applications [Working Title]/ G. Morozov, Y. Sedelnikov, V. Anfinogentov et al. // IntechOpen, May 05, 2025. doi: 10.5772/intechopen.1009869.
2. Morozov G.A. Low-Intensity Microwave Technology: Methods and Apparatus / G.A. Morozov, O.G. Morozov, N.E. Stahova et al. // Moscow: Radioelectronics and Communications Systems. - 2003. - 128 p. (in Russian)
3. Osepchuk J.M. A history of microwave heating applications / J.M. Osepchuk // IEEE Transcription On Microwave Theory and Techniques. – 1984. - Vol. 32, Iss: 9. – P.1200-1224.
4. Thuery J's. In: Grant EM, editor. Microwave Industrial. Scientific and Medical Applications. Boston, London: Larstin Arteda House; 1992
5. Jolly J. A. and Tate R. L. Douglas Fir tree Seeds Germination Enchacement Using Microwave Energy / J. A. Jolly, R. L.Tate // Journal Of Microwave Power. – 1971. - 6(2). - P. 125-130.
6. Nelson S. O. Long Term effects of RF dielectric heating on germination of alfa alfa seeds / S. O. Nelson et all. // Transaction of the ASAE. - 1984. - P. 255-258.
7. Nelson S. O. Germination responses of selected plants species to RF electrical seeds treatment / S.O. Nelson, L.E. Stretson // Transaction of the ASAE/ - 1985. - P.2051-2058.
8. Tran V.N. Optimising of the microwave treatment of Acacia Seeds / V.N. Tran // Journal of microwave Power. – 1981. -16. - P. 277.
9. Brodie G. Applications of Microwave Heating in Agricultural and Forestry Related Industries: in book The Development and Application of Microwave Heating. - InTech, Nov. 07, 2012. doi: 10.5772/45919.
10. Devyatkov N.D. Non-thermal effects of millimeter radiation. - M.: Rotaprint IRE, 1981. (in Russian)
11. Betsky O.V. Low-intensity millimeter waves in medicine and biology / O.V. Betsky, N.D.Devyatkov, V.V. Kislov // Biomedical radio electronics. – 1988. - No.4. - P. 13-29. (in Russian)
12. Michaelson S.M. Biological Effects and Health Hazards of RF and MW Energy: Fundamentals and Overall Phenomenology. In: Grandolfo, M., Michaelson, S.M., Rindi, A. (eds) Biological Effects and Dosimetry of Nonionizing Radiation. NATO Advanced Study Institutes Series. – 1983. - V. 49. - Springer, Boston, MA. https://doi.org/10.1007/978-1-4684-4253-3_15
13. Lin J.C. Biological Effects of Microwave Radiation. In: Bersani, F. (eds) Electricity and Magnetism in Biology and Medicine. – 1999. - Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-4867-6_35.
14. Analysis of Biological Effects of Microwave Energy and Safe Distance Calculations. Journal of Al-Rafidain University College For Sciences (Print ISSN: 1681-6870 ,Online ISSN: 2790-2293). - 2021. - 25(2). – P. 1-14. https://doi.org/10.55562/jrucs.v25i2.435.
15. Morozov G.A. Development and practical use of microwave for agricultural applications / G.A. Morozov, Ju.E. Sedelnikov // Jnf.Symp. JINA-96, Nice, France.

16. Kipriyanov F.A. Prospects for the use of microwave energy in grain crop seeding / F.A. Kipriyanov, P.A.Savinykh, A.Yu. Isupov et al. // Journal of Water and Land Development. - 2021. - No. 49 (IV–VI) - P. 74–78. DOI 10.24425/jwld.2021.137098.

17. Cepolina F. Energizing Sustainable Agriculture: Advances in Greenhouse Heating through Microwave-Based Technologies / F. Cepolina, F. Silenzi, L.Cirillo et al. // Energies. – 2023. – 16. - 7843. https://doi.org/10.3390/en16237843

18. Xinyue Lu. Effects of microwave treatment on the microstructure, germination characteristics, morphological characteristics and nutrient composition of maize / Xinyue Lu, Shunmin Wang, Yulu Dong et al. // South African Journal of Botany. – 2024. - V.165. –P. 144-152, https://doi.org/10.1016/j.sajb.2023.12.034.

19. Rogov I. A. Electrophysical methods of food processing. - Moscow: Agropromizdat, 1988. (in Russian)

20. Steven L.H. Microwave and millimeter wave method and apparatus for controlling insects in stored-products, US6192598B1 / L. H. Steven, S. B. Timothy // Micro Grain Inc., 2001-02-27

21. Sohail Mumtaz. Pulsed high power microwave seeds priming modulates germination, growth, redox homeostasis, and hormonal shifts in barley for improved seedling growth: Unleashing the molecular dynamics / Sohail Mumtaz, Rida Javed, Juie Nahushkumar Rana, Madeeha Iqbal, Eun Ha Choi // Free Radical Biology and Medicine. – 2024. - V. 222. - P.371-385, https://doi.org/10.1016/j.freeradbiomed.2024.06.013.

22. Arkhangelsky Yu. S. Microwave electrothermy. – Saratov: Saratov State University, 1998. - 408 p. (in Russian)

23. Yavchunovsky V.Ya. Microwave and combined drying. Physical principles of technology and equipment. - Saratov: Saratov State University Publishing House, 1992. - 233 p. (in Russian)

24. Zhang Z. Microwaves, a potential treatment for bacteria: A review / Z. Zhang, J. Wang, Y. Hu et al. // Front Microbiol. - 2022 Jul 25;13:888266. doi: 10.3389/fmicb.2022.888266. PMID: 35958124; PMCID: PMC9358438.

25. Chang S. An Innovative Food Processing Technology: Microwave Electrodeless Ultraviolet, Luminescence Mechanism, Microbial Inactivation, and Food Application / S. Chang, Z. Zhang, Q. Liu et al. // Foods, 2024. – 13. - 4110. https://doi.org/10.3390/foods13244110

27. Ignatov V. D. Effect of microwave EM fields on microorganisms/ V.D. Ignatov, V.I. Panasenko et al. // Saratov: Saratov State University Press. – 1978. - 78 p. (in Russian)

28. Krinitskaya A. Yu. Effect of coherent microwave radiation of non-thermal intensity on the growth of Bac.subt. / A.Yu.Krinitskaya, M.N. Astrakhantseva, V.S.Gamayurova et al.// Biomedical Radioelectronics. - No. 2. - 2001. - P. 49-53. (in Russian)

29. Anfinogentov V.I. Optimization of microwave heating of dielectrics taking into account errors in amplitudes of the excitation electromagnetic field emitters / V.I. Anfinogentov, G.A. Morozov, N.E. Stakhova et al. // Proceedings of IEEE 11th International Conference on Antenna Theory and Techniques. - IEEE. - 2017. - P. 433-436.

30. Morozov G. Modeling and optimization of microwave heating in cylindrical volumes / G. Morozov, V. Anfinogentov et al. // Proceedings of IEEE 11th International Conference on Antenna Theory and Techniques. – IEEE. - 2017. -P. 68-73.

31. Smirnov S.V. Mathematical model for technological process of organic livestock waste microwave treatment in conveyor installation / S.V. Smirnov, A.R. Nasybullin, G.A. Morozov et al. // Proceedings of IEEE Wave Electronics and its Application in Information and Telecommunication Systems. – IEEE. - 2021. - P. 9470652

32. Morozov G.A Microwave heating. The design, modeling and monitoring of thermal processes and complexes / G.A. Morozov, Y.N. Shangaraeva // Proceedings of IEEE 9th International Conference on Antenna Theory and Techniques. – IEEE. - 2013. - P. 526-528.

33. Chetverikov A.P. The modeling of electrodynamics and thermodynamics processes while electromagnetic field and dielectric interaction / A.P. Chetverikov, V.V. Yavchunovsky, G.A. Morozov et al. // Proceedings of IEEE 5th International Conference on Antenna Theory and Techniques. – IEEE. - 2005. - P. 491-493.

32. Anfinogentov V.I. The review of methods of physical and mathematical modelling of the microwave heating / V.I. Anfinogentov, G.A. Morozov // Proceedings of IEEE 13th International Crimean Conference “Microwave and Telecommunication Technology”. – IEEE. - 2003. - P. 710-711.

34. Morozov G.A. Development of microwave processes and complexes today / G.A. Morozov, O.G. Morozov // IEEE 2015 International Conference on Antenna Theory and Techniques (ICATT). - 2015. - P. 1-6.

35. Anfinogentov V.I. Increase of uniformity of temperature fields at the microwave heating in open chambers / V.I. Anfinogentov, T.K. Garaev, G.A. Morozov // Proceedings of IEEE 13th International Crimean Conference “Microwave and Telecommunication Technology”. IEEE. - 2003. - P. 714-715.

36. Anfinogentov V.I., Garayev T.K., Morozov G.A. Optimization of dielectric microwave heating by moving radiator / Anfinogentov V.I., Garayev T.K., Morozov G.A. // Proceedings of IEEE 12th International Conference “Microwave and Telecommunication Technology”. - IEEE. - 2002. - P. 605-606.

37. Morozov G.A. Microwave technological complexes design in view of power consumption factor / G.A. Morozov // Proceedings of IEEE 10th International Crimean Microwave Conference “Microwave and Telecommunication Technology”. – IEEE. - 2000. -P. 61-62.

38. Nasybullin A.R. Multi-sensor temperature and humidity measuring system for technological process of organic livestock waste microwave treatment monitoring / A.R. Nasybullin, G.A. Morozov, V.I. Anfinogentov et al. // Proceedings of IEEE Wave Electronics and its Application in Information and Telecommunication Systems. – IEEE. - 2021. - P. 9470606

39. Patent RU 2744079 C2, 02.03.2021. Device for Disinfecting Bulk Products Application No. 2019127997 dated 14.03.2019 / P.P. Krynitsky, G.A.Morozov, A.Yu. Krynitskaya, P.P. Sukhanov, E.G. Vokhmyanina, S.V. Smirnov, A.R. Nasybullin.

40. Krynitsky P.P. Use of NMR Relaxometry Parameters to Assess the impact of UHF EMF on Biological Environments / P.P. Krynitsky, G.A. Morozov, P.P. Sukhanov et al. // Physics of wave processes and radio engineering systems. - 2017. - Vol. 20. - No. 3-2. - P. 52-59. (in Russian)

41. Krynitskiy P.P. Effect of Low-Intensity Electromagnetic Field of Extremely high Frequencies on Baker's yeast / P.P. Krynitskiy, G.A. Morozov, A.Yu. Krynitskaya et al. // Butlerov communications. - 2016. - Vol. 45. - No. 2. - Pp. 119-122. (in Russian)

42. Morozov G.A. Microwave Field Energy as Bsker's Yeast Metabolism Regulator / G.A. Morozov, P.P. Krynitskiy // 2015 International Conference on Antenna Theory and Techniques: Dedicated to 95 Year Jubilee of Prof. Yakov S. Shifrin, ICATT 2015 - Proceedings. - 10. - 2015. - P. 7136888.

ВЫБОР РЕЖИМОВ ОБРАБОТКИ В НИЗКОИНТЕНСИВНЫХ ГИБРИДНЫХ СВЧ-ТЕХНОЛОГИЧЕСКИХ КОМПЛЕКСАХ ПО КРИТЕРИЮ «КАЧЕСТВО-ЭНЕРГОПОТРЕБЛЕНИЕ»

Г.А. Морозов, Ю.Е. Седельников, В.И. Анфиногентов, Н.Е. Стахова, О.Г. Морозов

Казанский национальный исследовательский технический университет им. А.Н. Туполева-КАИ
420111, г. Казань, ул. К. Маркса, 10

Аннотация. При создании СВЧ-технологического комплекса (СВЧТК) как унитарного, так и гибридного типов, исходными данными для проектировщика являются данные о параметрах электромагнитного воздействия. Целесообразно разделить эти параметры на две группы. Первая из них относится к идеализированным условиям обработки в гипотетически однородном ЭМП (или, что то же самое ЭМП элементарного объема обрабатываемого материала). Вторая группа характеризует параметры обработки в реальных условиях, в частности, неоднородность ЭМП. Разделение на эти группы обусловлено рядом причин, а также имеет ту особенность, что первые параметры определяются на этапе предпроектных исследований, а вторые – на этапе НИОКР. Следует подчеркнуть, что в большинстве случаев этап предпроектных исследований выполняют специалисты, профессионально ориентированные в области приложений (биологи, химики и т.д.), тогда как этап НИОКР – радиоинженеры. Это приводит к тому, что рекомендуемые условия обработки в лучшем случае соответствуют условиям оптимального качества обработки, т.е. определяются без учета специфики последующей реализации. Коэффициент энергопотребления и, особенно, приведенные затраты СВЧ-энергии часто остаются вне поля зрения. Нахождение указанных параметров, оптимальных с точки зрения соотношения «качество-энергопотребление», будет заложено в основу определения режима СВЧ-обработки. В данной работе рассмотрены примеры и возможности эффективного поиска режимов, соответствующих низко-интенсивному СВЧ-воздействию для обработки семян сельскохозяйственных и лесных культур, инактивации микроорганизмов и микрофлоры, стимуляции развития бактерий и дрожжей.

Ключевые слова: низкоинтенсивный гибридный СВЧ-технологический комплекс, режимы СВЧ-обработки, идеализированные условия обработки, реальные условия, оптимальное качество обработки, соотношение «качество – энергозатраты».

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