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Research Article

Probabilistic and Statistical Assessment of Lethal Effect on Seeds during Microwave Treatment

Sergey V. Vendin, Yury V. Saenko, Sergey F. Volvak,
Sergey V. Solovev and Konstantin V. Kazakov
FGBOU VO Belgorod State University

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ABSTRACT

The article presents a mathematical model of the probabilistic assessment of the effectiveness of microwave heat treatment of seeds expressed as the mortality integral which takes into account the specifics of the microwave exposure. The presented form of assessing the lethal effect considersthe impact of the seeds heating rate and final temperature on their sowing qualities within the developed integral approach for assessing the lethal effect during thermal exposure of biological objects. A distinctive feature of the proposed assessment method is estimating the function of the intensity of the biological object "failure" as a sum of functions depending on the rates of heating and cooling of the object, the exposure time and final temperatures at the heating and cooling stages. To accurately reflect the specifics of microwave impact on the function of theintensity of biological object's"failures", the authors introduced the asymmetric impulse function, whosephysical significance implies the potential resistance of seeds to microwave exposure, if the seedpossesses one at a given time.

The findings show that the mortality integral can be represented as the probability of a "failure" of a biological object, and this can be used to estimate the lethal effect during microwave heat treatment of seeds. The proposed form of the mortality integral allows us to predict the outcome of microwave heat treatment of seeds, taking into account such technological processing parameters as the rate of microwave heating, the initial temperature of the seeds (ambient temperature); the final temperature of the microwave seeds heating, the duration of heating and cooling of the seeds. This makes it possible to improve the reliability of microwave treatment of seeds. The assessment of the effectiveness of microwave heat treatment of seeds by means of integrals requires only the knowledge of the process kinetics at the heating and cooling stages and the values of bio-resistance coefficients, which are determined at the stage of preliminary experiments.

Presenting the mortality integral of temperature and time effects during microwave treatment of seeds as the probability of a "failure" of a biological object also makes it possible to effectively use the theoretical results of the microwave heating kinetics to predict the outcome and increase the reliability of the technological processes of microwave heat treatment of seeds. This is a crucial point, as microwave treatment of seeds can be carried out on any microwave equipment that allows microwave treatment (heating) of bulk materials.

Keywords:electromagnetic field, ultra-high frequency, seeds, microwave heating, mortalityintegral, probability of object failure, failure rate.

Novelty

The article proposes acriterion for estimatingthe lethal effect of an electromagnetic field energy during microwave heat treatment of seeds which is considered as the probability of the "failure" of a biological object. Along with this, the function of failure rate takes into account changes in technological parameters (microwave heating rate, microwave final temperature of heating and cooling conditions of seeds after microwave treatment) in the course of seed treatment.

Scientific value

The scientific value includes the development of a criterion for probabilistic and statistical assessment of the lethal effect of an electromagnetic field energy during microwave heat treatment of seeds.

Relevance

The energy of the microwave electromagnetic field can be effectively used in various technological processes of post-harvest and pre-sowing treatment of seeds (grain). However, to improve treatment efficiency, to predict the result and improve the reliability of technological processes of seeds microwave heat treatment, it is necessary to have criteria that take into account the technological parameters of the process and their influence on the quality of treatment.

INTRODUCTION.

Electromagnetic field of ultra-high frequency can be successfully applied in various technological processes for pre-sowing and post-harvest seed treatment [1-13, etc.]. At the same time, according to many researchers, the quality of seeds exposed to heating is linked with the concept of the mortalityintegral which represents an integral functiondependent on the change in seeds temperature over time and their bio-resistance coefficients [13].

The research aims to improve the efficiency of using the microwave electromagnetic field energy (MW EMF) in the technological processes of pre-sowing and post-harvest treatment of seeds.

The subject matter of the study istechnological processes of microwave heat treatment of the seeds.

Scope of the research includes patterns of change in qualitative and quantitative indicators in the technological processes of pre-sowing and post-harvest microwave treatment of seeds.

Research methods. The authorsapplied the basic principles of the theory of probability, integral calculus, mathematical statistics, methods for experiment planning and processing of experimental data.

Results and discussion. It is known that not every change in seed temperature leads to a toxic effect, but only those temperature fluctuations that are above certain critical temperature T_{cr}, which leads to a moment when significant biochemical changes in the cells of the seeds begin.

In the simplest case of “heating-cooling”, shown in Figure 1, the mortality integral represents the sum of the integrals at the heating stage and at the cooling stage.

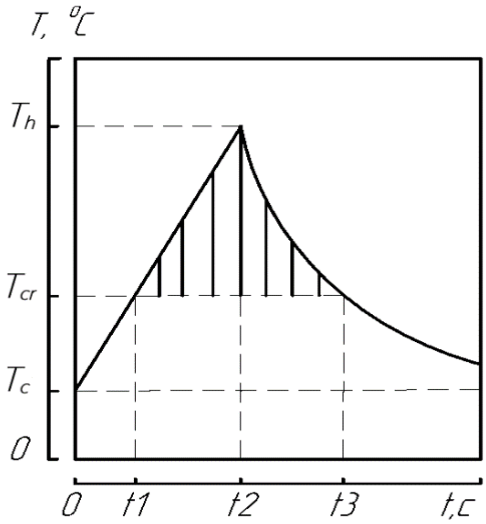

Figure 1. The calculation of the mortality integral during heating

In general form, according to [9], the mortality integral for the case under consideration can be defined as follows:

$$= \int_{1}^{2} \quad (+0) \mid \int_{2}^{3} \quad (+0), \qquad (1)$$

whereT(t) isthe temperature change over time, ^{o}C; AandBare the coefficients of thermal bio-resistance of seeds.

In this form, the mortality integral can take values from 0 (complete preservation of sowing properties) to 1 (total loss of viability).

The main difficulty in using the integral expression (1) is finding the coefficients of thermal bio-resistance. However, one can calculate the approximate values of these coefficients under strictly defined conditions, having conducted a series of experiments.

One of the possible combinations of these conditions is defined as follows:

1. A relatively linear change in the temperature of the seeds at the heating stage;
2. Maintaining the same cooling conditions for all heated seed samples.

It should be noted that the first condition is approximately metduring microwave heating, whileit is not difficult to fulfill the second when conducting an experiment.

In this case, the expression (1) takes the form:

$$= \int_{1}^{2} \quad (\ (\ ) \ ) + \int_{2}^{3} \quad (\ ( ), \qquad (2)$$

where$T_0$is the initial temperature of seeds, ^{o}C; *k*is the average heating rate, ^{o}C/s.

After integrating the first term we get:

$$= [\ - \ ] + \int_{2}^{3} \quad (+ ( ). \quad (3)$$

It should be noted that in the case of heating of two samples of seeds with the same mass and the same thermal characteristics to temperature T_{h1} under the same cooling conditions, the second integral for both samples, according to the expression (2), will have the same value. Then the difference between the mortality integrals of the first and second seed samples will take the following form:

$$_{1} - _{2} = \frac{+}{-}\left[(_{1}-) - 1 \right] + \left[\frac{1}{_{1}} - \frac{1}{_{2}} \right], \qquad (4)$$

wherek_1, $k_2$are the heating rates of the first and second samples,respectively, ^{o}C/s.

If we heat two seed samples to temperature T_{h1} and two samples to temperature T_{h2}, then taking into account the expression (4), we have a system of transcendental equations for determining coefficients A and B:

$$_{1} - _{2} = \frac{+}{-}\left[(_{1}-) - 1 \right] + \left[\frac{1}{_{1}} - \frac{1}{_{2}} \right],$$

$$_{3} \quad _{4} = \frac{+}{}\left[(_{1}-) \quad 1 \right] \ \left[\frac{1}{_{3}} \quad \frac{1}{_{4}} \right], \qquad (5)$$

which can be solved by numerical methods using experimental values $_{1}, _{2}, _{3}, _{4}$.

In the simplest case, when $k_1 = k_3$, $k_2 = k_4$, the equations for determining the coefficients are:

$$\frac{_{1}-_{2}}{_{3}-_{4}} - \frac{(_{1}-)-_{1}}{(_{2}-)-_{1}}, \qquad (6)$$

$$- \left\{ \frac{(_{1}-_{2})}{\left[\frac{1}{_{1}} - \frac{1}{_{2}} \right] \left[(_{1}-) \right]} \right\}. \qquad (7)$$

Thus, to conduct experimental studies of the integral effect of temperature and time on the sowing qualities of seeds and determine the coefficients of thermal bio-resistance of seeds during microwave heating one should take the following steps:

1. Selecting four seed samples with identical weight and moisture;
2. Microwave treatment of the samples is carried out at two heating rates until two final temperatures are reached, with fixation of the final temperature (according to the thermometer) and heating rate (measuring the time);
3. The same cooling conditions are maintained for all seed samples;
4. The analysis of seed germination is carried out and the experimental values of the mortality integral are determined by the formula:

$$- (-)/, \qquad (8)$$

where and

areseed germination at the control point and seed germination at the experimental point after processing, respectively, %.

5. One estimates the seed bio-resistance coefficients according to the expressions (6) - (7). The critical temperature can be defined as the temperature of possible protein denaturation, for example 35-42 ^{o}C.

The conducted research and statistical processing of experimental data for the studied crops (wheat, barley, oats, peas, beans) showed that the experimentally obtained tendency of mortality effects of heating rate and temperature during microwave treatment of seeds does not allow determining the values of thermal bio-resistance coefficients, i.e. given the available experimental data, the system of equations (6) - (7) cannot be solved for A and B. This indicates that, due to the specific nature of the microwave treatment of seeds, these biological objects, along with the thermal impact, are influenced by the strengthof the electromagnetic field. Therefore, the effectiveness of the influence is determined by the set of processes occurring in the seeds due to thermal and electrodynamic phenomena; thus, the expressions of the form (1) are not suitable for evaluating the effect of the thermal action during microwave treatment of seeds, and the integral temperature and time effects should be represented in a different form.

If we assume that the mortality integral in its essence is not a strict analytical dependence, but represents a probabilistic characteristic of a mortality outcome, then it can be defined as the probability of death (failure) of a biological object (seed) by the end of the cooling stage to the critical temperature T_{cr}. Then, in accordance with the basic ratiosof the theory of probability and reliability of systems [14], the mortality integral can be defined as a function of the form:

$$= () = 1 - [- \int_0 \quad ()], \quad (9)$$

where () is the probability of failure (death of a seed or an insect); () is the failure rate per unit time (lethal effect for a single biological object), a function depending on the temperature change over time and the coefficients of biological objects resistance to thermal microwave exposure.

Experimental studies have shown that factors such as the rate of temperature rise at the heating stage and the final heating temperature determining the duration of the seeds cooling are the most significant during microwave heat treatment of seeds. However, one should also consider the specific effect of microwave exposure. In this case, in the first approximation, the function ()for seeds can be represented as follows:

$$() = {}_{+}() + \{\frac{1()}{-}\}, \text{ with } \leq \ \leq ,$$

$$() = {}_{+}() + \{()\}, \text{ with } \leq \ \leq , \quad (10)$$

where

, $\delta_{+}()$is,respectively,some constant and asymmetric impulse function [15] the physical significance of which is the potential resistance of the seeds to the microwave effect, if the seed possesses one at a given time.

Empirical coefficient A is a cumulative characteristic that takes into account thermal and electrodynamic action; $\tilde{T}$(t), (), $\frac{()}{}$ are, respectively, the dependence of temperature and its change rate over time, $() = () - {}_0$, °C; ${}_0$is the initial temperature of the seeds (ambient temperature), °C; , are, respectively, the initial and final heating time, which characterize the cycle of the temperature increase stage, s; , are, respectively, the initial and final heating time, characterizing the cycles of heating and cooling to a certain critical temperature T_{cr} (for example, the generally accepted temperature limit for denaturation of the protein molecule is 42°C). The zone of the seed temperature constant in time, if it is higher than T_{cr} can be referred to the stage of temperature reduction; B and C, respectively, are empirical coefficients characterizing a decrease in the seed resistance to thermal effects at the heating and cooling stages.

It should be noted that microwave exposure includes both thermal and electrodynamic factors, function () must be estimated over the entire time interval from the moment of exposure t=0 to t=t_{cr}, where t_{cr} corresponds to T_{cr} in the last cycle of the microwave exposure.

In the simplest and most common case of microwave heat treatment of seeds, presented in Figure 1, function () is defined as follows:

$$() = {}_{+}() + \{\frac{1()}{2}\}, \text{ with } 0 \leq \ \leq {}_2,$$

$$() = {}_{+}() + \{()\}, \text{ with } {}_1 \leq \ \leq {}_3, \quad (11)$$

and the expression of mortality integral takes the form:

$$= ({}_3) = 1 - [- \int_0^3 \quad ()]. \quad (12)$$

$$= 1 - [-\{ + \frac{}{2} \int_0^2 \frac{()}{} + \int_1^3 \ ()]. \quad (13)$$

Then, using experimental values and the data on the kinetics of the process,empirical coefficients A, B and C can be estimated by solving the system of equations:

$$-(1 -) = + \frac{}{2} \int_0^2 \frac{()}{} + \int_1^3 \ (), i=1,2,3, \quad (14)$$

whereisthe average values of the integral expression in a series of experiments, estimated in accordance with (8)

$$= \frac{1}{} \sum_{=1} \quad . \quad (15)$$

Thus, using the values of A, B, and C to assess the effectiveness of the lethal effect, it is enough to know only the kinetics of the process – the analytical dependences of the temperature change over time.

A relatively linear change in the temperature at the heating stage and an exponential change at the cooling stage are very important practical cases of microwave seeds processing:

$$() - {}_0 - , \quad 0 \leq \ \leq {}_2,$$

$$() - {}_0 = ({}_{\text{н}} - {}_0)^{-(-2)}, \quad {}_2 \leq \ < \infty, \quad (16)$$

Where *k* is the microwave heating rate; α is the value characterizing the cooling rate which can be determined using the experimental data according to the expression:

$$\alpha = \frac{1}{_3 \quad _2}\left[\frac{-_0}{_0}\right]. \qquad (17)$$

Then for the expression (11) we have:

$$\int_0^{3} \quad 0 - + + \left[\frac{-}{} + \frac{_3 - _2}{2}\right]. \qquad (18)$$

To determine coefficients A, B, and C, it is enough to conduct a series of experiments recording the parameters $_0$, , , $_2$, $_3$ and estimating the value of the impact efficiency

Coefficients A, B, and C can be calculated similarly to the coefficients of the regression equation:

$$Y = a_0 + a_1x_1 + a_2x_2 \qquad (19)$$

within the methods of the experiment planning, i.e. if we assume that

$Y= - \ln(1-)$, $a_0 = A$, $a_1 = B$, $a_2 = C$,

$$_1 = , _2 = \frac{-}{} + \frac{_2 - _3}{2}.$$

The above method for estimating the mortality integral as the probability of a “failure” of a biological object due to electrodynamic and thermal effects at the stage of microwave heating and at the cooling stage enabled to use the available experimental data to calculate the bio-resistance coefficients for seeds of different crops. Data on seed germination were used as the initial data for calculations. The seeds were cooled in a calm environment (without fanning), the calculated value of α estimated (1.9 ... 2.1) $x10^{-3}s^{-1}$ [16].

Table 1 presents the data for calculating the mortality integral during microwave treatment of wheat seeds. The numerical values of coefficients A, B, and C are given in Table 2. The temperature T_{cr} = 35 ° C was taken as the critical temperature.

In general, the calculation of the seed germination index according to analytical expressions (12), (16) with the bio-resistance coefficients (Table 2) shows that the discrepancy between the calculated and experimentally obtained values does not exceed 10%.

Table 1. Calculation of the mortality integral during microwave treatment of wheat seeds

No.	Seed moisture, %	Average microwave heating rate, °C	Final heating temperature, °C	Average seed germination, %	Mortality integral value
1	8	0.67	55±1	88	0
2	8	0.81	55±1	86	0.023
3	8	0.67	77±1	79	0.102
4	8	0.81	77±1	69	0.215
5	20	0.70	64±1	76	0.136
6	20	0.92	64±1	78	0.114
7	20	0.70	77±1	36	0.591
8	20	0.92	77±1	34	0.614
Control	-	-	-	88	-

Table 2. Calculated values of seed bio-resistance coefficients

Crop	Moisture, %	A	B	C
Wheat	8±0.5	$-5.51x10^{-1}$	$5.69x10^{-1}$	$1.29x10^{-5}$
	20±0.5	-1.62	$2.21x10^{-1}$	$9.87x10^{-5}$

Table 3 shows the individual results of comparing the calculated and experimental values of seeds germination for different crops.

Table 3. The comparison results of experimental and calculated values of seed germination

Crop	Microwave heating rate, °C/s	Final temperature, °C	Seed germination, %			Relative calculation error, %
			before treatment	during the experiment	calculated	
Wheat	0.81	55±1	88	86	83.0	3.4
	0.70	64±1	88	76	74.5	2.0

It should be noted that the integral expression (12) can take values from 1 to . However, there is no contradiction, since, in fact, expressions of the form (12) are proposed for describing the lethal integral microwave treatment. In other words, if takes the value> 0, then this denotes the presence of a negative (inhibitory) effect, and if ≤ 0, then it should be understood that negative impact is not observed under these conditions: there may be cases or no lethal effects or stimulation of physiological processes (increased germination, etc.). But one should keep in mind that the proposed relationships (12) cannot be used for quantitative estimation of the stimulation effect (increased germination or yield).

We should mention that since it is necessary to fulfill certain technological requirements during microwave heat treatment of seeds (reduction in germination is unacceptable, disinsection should be highly efficient), the integral expressions of the form (12) allow determining thermal conditions and exposure parameters.

CONCLUSION

The research paper presents a mathematical model of the probabilistic evaluation of the effectiveness of microwave heat treatment of seeds in the form of a mortality integral which takes into account the specifics of microwave exposure.

The findings show that the presentation of the mortality integral as the probability of a “failure” of a biological object can enable to estimate the lethal effect during microwave heat treatment of seeds. The proposed form of the mortality integral allowed us to predict the result of microwave heat treatment of seeds, taking into account such technological processing parameters as the rate of microwave heating, the initial temperature of the seeds (ambient temperature); the final temperature of the microwave heating of seeds, the time of seeds heating and cooling. This makes it possible to increase the reliability of the technological process.

To evaluate the effectiveness of microwave heat treatment of seeds using integral expressions, it is enough to know the kinetics of the process at the heating and cooling stages and to have the values of bio-resistance coefficients, which are determined at the stage of preliminary experiments.

The presentation of the mortality integral of temperature and time effects during microwave treatment of seeds as the probability of a “failure” of a biological object also makes it possible to effectively use the theoretical results of the microwave heating kinetics [17–25] to predict the result and increase the reliability of technological processes of microwave heat treatment of seeds. This is very important since microwave processing of seeds can be carried out on any microwave equipment that allows microwave treatment (heating) of bulk materials.

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