



Factor analysis of irradiation of the strawberries (*Fragaria × ananassa*) seeds pulsed low-frequency magnetic field

I G SMIRNOV¹, D. O KHORT², R A FILIPPOV³ and A I KUTYREV⁴

Federal Scientific Agroengineering Center VIM, 1-st Institutskiyproezd, 5, Moscow, Russian Federation 109 428

Received: 13 July 2018; Accepted: 30 November 2018

ABSTRACT

The present study explored the effect of the irradiation of strawberry (*Fragaria × ananassa*) seeds by a low-frequency magnetic field with the help of a developed device for magnetic-pulse processing of plants. The experiment was repeated three times; 24 batches of 30 seeds per batch were involved and one batch of 100 seeds was taken as a control. The induction of the pulsed magnetic field in the processing zone was 4, 5, 6 mT, regulated by moving the working body of the inductor (magnetic coil). The experiment showed that low-frequency pulsed magnetic had a positive effect on the germination energy and the germination of strawberry seeds. Statistical processing of the obtained experimental results was carried out by means of mathematical modeling by orthogonal planning of experiments. On the 18th day of registration, the germination energy of strawberry seeds treated with a low-frequency pulsed magnetic field exceeded the control indicators by 21%. Based on the calculated coefficients of the mathematical model, the response function and equation of the mathematical model were found. The graphical interpretation of the function of three variables and the chart of lines of equal level (contours) were constructed. The values of the extremum of the response function and the corresponding values of the factors in the coded and natural form were obtained. The analysis of these factorial experiments showed that the most effective parameter of irradiation for increasing germination and seed germination energy is irradiation with a frequency of 15.325 Hz, a duty ratio of 16.145 and magnetic induction in the irradiation zone of 5.05 MT.

Key words: Electrophysical method, Irradiation, Low-frequency field, Magnetic-pulse processing, Plant irradiation

Besides the well-known ways of increasing the yield of agricultural crops, alternative methods such as, low-frequency pulsed electromagnetic fields (LFPEF) are also used. It is known that the electromagnetic field (EMF) is one of the important environmental factors affecting the biological activity of plants, it has an impact on the physiological, biochemical and biophysical characteristics of plants [1, 2, 3].

The positive effect of EMF in the processing of seeds is more studied and used in the preparation of seeds of crops. At the same time, the effect of pulsed EMF of low frequency (LF) on the sowing qualities of seeds of garden plants has been little studied so far and is an urgent task of scientific and practical importance.

One of the factors restraining the development of magnetic impulse actions is the absence of specialized technical means and technological methods that are able to implement EMF LF in the field plants.

To create units and instruments, it is necessary to carry out research to identify the most effective parameters of irradiation and to specify the parameters of the working bodies, through the functions of responsiveness of plants and organisms to the action of a pulsed magnetic field (PMF) [3].

Numerous studies show the promise of using pulsed magnetic fields in bioregulatory technologies. The analysis of literature sources shows that a safe and highly effective method of increasing the physiological potential of seeds is their exposure to EMF LF.

This method allows to significantly increase the germination energy, seed germination, increase the growth of shoots and seedlings, and their survival during planting [4, 5, 6].

The influence of the magnetic field on a living organism is determined by parameters such as intensity (field strength, magnetic induction), gradient (rate of increase or decrease of the field), vector (direction of field lines), exposure (duration of action), frequency (number of magnetic field oscillations per second), pulse form (the characteristic of increase and decrease of the intensity) and localization (spatial characteristic).

In this regard, there was a practical need to expand the scope of low-frequency magnetic fields, the establishment

^{1,2,3,4}(rashn-smirnov@yandex.ru, dmitriyhort@mail.ru, rostislav-filippov@yandex.ru, alexeykutyrev@gmail.com), Federal State Budgetary Scientific Institution.

of parameters and development of special technical means for magnetic-impulse processing of plants that reduce the use of pesticides, increase production and quality of products.

The purpose of the research is to identify the most effective parameters of the apparatus for magnetic pulse irradiation (MPI) of plants (frequency, duty cycle and exposure time), to establish the effect of pulsed low-frequency magnetic field on the germination of strawberry seeds.

MATERIALS AND METHODS

As an object of research, seeds of strawberry (*Fragaria × ananassa*) "Zenga Zengana" were used. The experiment was carried out with a triple repetition, 24 batches of 30 seeds per batch were used and one lot of 100 seeds was taken as a control (not irradiated). The exposure time of the samples was 360 sec. Prior to irradiation, the seed moisture content was 7.42% and the mass of 1,000 seeds was 0.32 g. Determination of humidity was carried out according to GOST 12041-82, mass of 1,000 seeds according to GOST 10842-89, germination and shoot energy according to GOST 12038-84 [7, 8, 9]. Seeds were germinated in the dark in Petri dishes with filter paper, at a constant temperature of 20°C. The energy of shoot was determined on day 16. Germination of seeds was determined on day 18.

A series of experiments was carried out using a magnetic-pulse treatment apparatus for plants developed in FSAC VIM (Moscow) (Fig 1).

The developed device allows generating a pulsed magnetic field, changing the frequency, duty cycle and the

exposure time [10]. The induction of the pulsed magnetic field in the processing zone was 4, 5, 6 mT, regulated by moving the working body of the inductor (magnetic coil).

To create a magnetic field corresponding to the selected parameters in the CAE Elcut 6.3 Professional program, we modeled and analyzed the distribution of the pulsed magnetic field values of a flat spiral coil with various parameters: cable cross-sectional area 1-3 mm, number of turns 30-60 pcs, winding pitch 0, 5-3 mm, internal diameter 20-90 mm and external diameter 300-500 mm.

In the axisymmetric delivery (cylindrical symmetry) of the magnetostatic module, geometric 2D models of the upper part of the coil section are shown and a finite element grid is constructed. The boundary conditions of the calculation area and their physical properties are specified. (Air and copper coils with magnetic permeability $\mu = 1$, field source $i = 1$ A and boundary with magnetic potential $A = A_0$).

Analysis of the distribution of MP different inductors showed that the most suitable is the use of a flat coil of 48 cable turns 1×2.5 mm with an outer diameter of 400 mm, an inner diameter of 30 mm, an inductance of 373 mH. This coil is simple on the device and allows you to get a fairly uniform field, using less winding (Fig 2).

Statistical processing of the obtained experimental results was carried out with the help of mathematical modeling by the method of orthogonal experiment planning (Table 1). The algorithm for constructing experimental plans is applicable to most optimization problems, both calculated and experimental. This method has a significant advantage compared to other existing methods in solving research problems. It has a high reliability of the results [11].

In the factor plan calculation, input factor levels are assumed to be encoded, with each factor's primary level (center of the plan) designated as «0», and the lower and upper levels as «-1» and «+1», respectively (Table 2).

To generate codes factorial experiment design (Fig 3) was used. The factor space is limited to 4-6 mT. The value 4 mT will correspond to the number encoded as -1, and the value 6 mT value +1. The range of variation of the factors is equal to $\Delta C = (6 \text{ mT} - 4 \text{ mT}) = 2 \text{ mT}$.

The recalculation of the given natural values of factors is carried out by linear interpolation of the values:

$$x_i = X_i = \frac{X0_i}{\Delta X_i}$$

Table 1 Factorial plan of the experiment with irradiation parameters

	Lower level (-1)	Basic level (0)	Top level (+1)	Variation-interval	Factor-name
x1:	14	16	18	2	Frequency, (Hz)
x2:	12	16	20	4	Dutycycle
x3:	4	5	6	1	Induction, (mT)



Fig 1 The MIO plants device

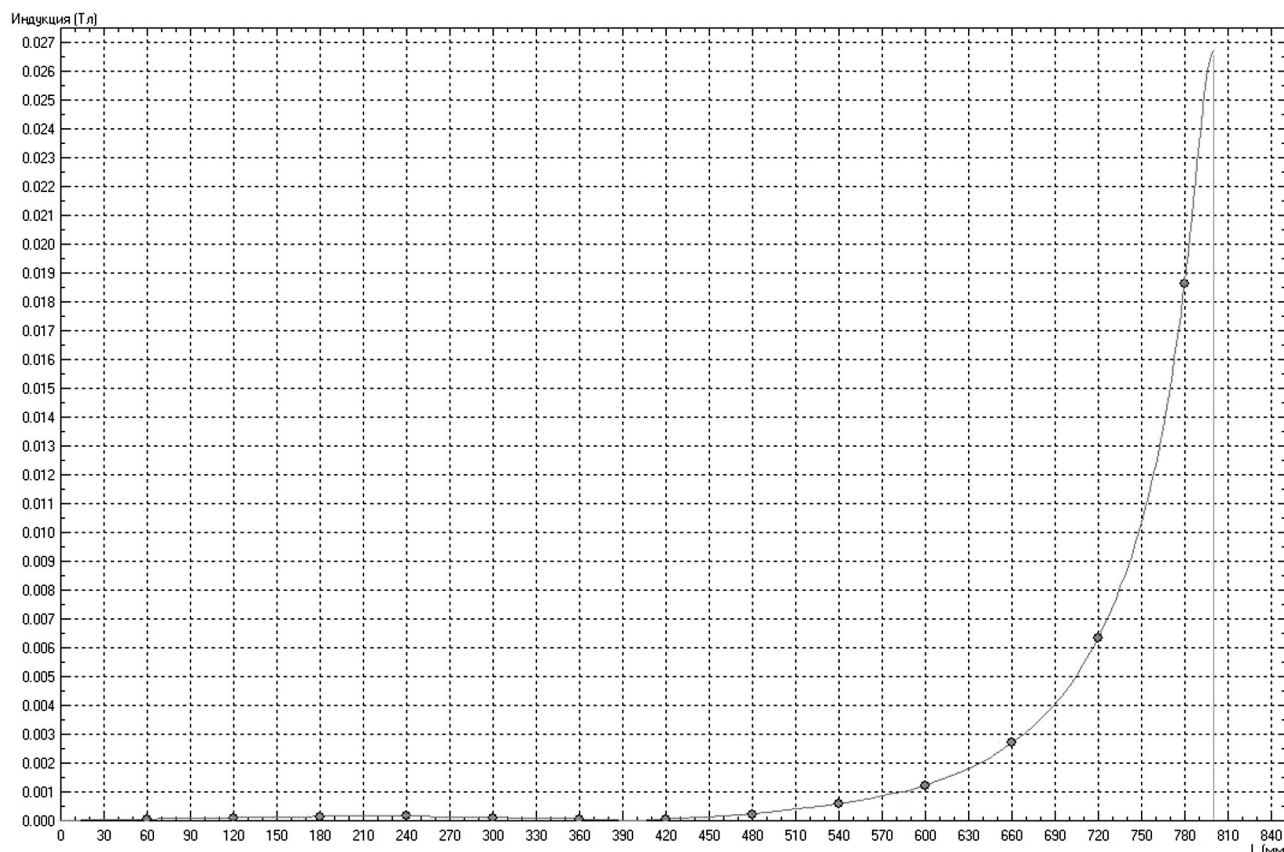


Fig 2 The values distribution of the pulsed magnetic field by the flat spiral coil of the MIO device.

Table 2 The plan factorial experiment

Experiment number	Planning matrix			Natural values of variables		
	x1	x2	x3	Frequency (Hz)	Dutycycle	Induction (mT)
1	+1	+1	+1	18	20	6
2	-1	+1	+1	14	20	6
3	+1	-1	+1	18	12	6
4	-1	-1	+1	14	12	6
5	+1	+1	-1	18	20	4
6	-1	+1	-1	14	20	4
7	+1	-1	-1	18	12	4
8	-1	-1	-1	14	12	4

where x_i , value of the i -th factor in coded form; X_i , value of the i -th factor in natural form; ΔX_i , variation interval of the i -th factor.

Then the coefficients of the mathematical model were calculated. After obtaining the mathematical model, the significance (different from zero) of the model coefficients and its adequacy was checked. The coefficients were checked for significance by means of the Student's criterion (t-criterion), which is calculated by the formula:

$$t_i = |b_i|/S\{b_i\} \quad (2)$$

where b_i , i -th coefficient of the mathematical model; $S\{b_i\}$, mean-square deviation in the definition of coefficients.

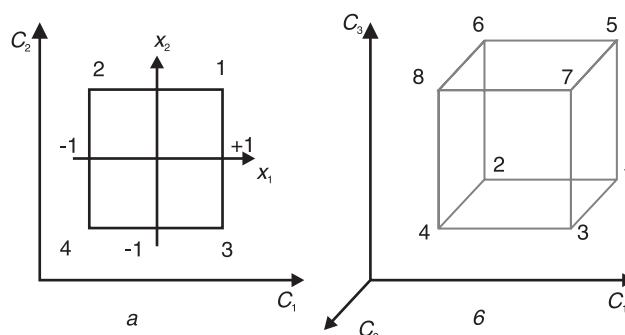


Fig 3 Factor space for a complete factorial experiment

The mean-square deviation in determining the coefficients of the response function is determined by the formula:

$$S\{b_i\} = \sqrt{C_i \cdot S_B^2} \quad (3)$$

where C_i , values given for the experimental plan (Table 3); S_B^2 , dispersion of reproducibility in parallel experiments.

Dispersion of reproducibility in parallel experiments is calculated by the formula

$$S_B^2 = \frac{1}{N(m-1)} \sum_{u=1}^N \sum_{j=1}^m (y_{uj} - \bar{y}_u)^2 \quad (4)$$

where N , experiments number in the plan; m , number of parallel measurements in each experiment; y_{uj} , value of the output parameter in the u -th experiment, j -th parallel

Table 3 Values Ci for the experiment plan

b0	b1	b2	b3	b11	b12	b13	b22	b23	b33
0,868	0,159	0,159	0,159	0,594	0,226	0,226	0,594	0,226	0,594

measurement; $\bar{y}_u$, average value of the output parameter in the u -th experiment.

The calculated value of the t -criterion is compared with the tabulated t_{table} for the selected significance level (usually 5%) a given number of freedom degrees $N(m-1)$. If $t_1 < \text{coefficient } t_{table}$ is considered significant.

The adequacy of the mathematical model is checked by the Fisher's criterion (F-criterion). For this purpose, a variance of adequacy is calculated by the formula:

$$S_{ad}^2 = \frac{m}{N-n_3} \sum_{u=1}^N (\bar{y}_u - \hat{y}_u)^2 \quad (5)$$

where n_3 , number of significant coefficients; $\hat{y}_u$, response value predicted by the equation of the mathematical model.

In turn, the Fisher's [11] is calculated as a relation:

$$F = \frac{S_{ad}^2}{S_b^2} \quad (6)$$

The calculated value of F-criterion is compared with the tabulated t_{table} for the selected significance level (usually 5%) and the degrees numbers of freedom and $N(m-1)$ and $N-n_3$. If $F > t_{table}$ the equation of the mathematical model is considered adequate [11].

Processing of data from the planned experiment was carried out in MatchCad 15.

To find a combination of factors providing the optimal value of the output parameter, response surfaces were constructed. In the construction, one of the factors was left at a fixed level, while the other two changed within the limits indicated in Table 1.

RESULTS AND DISCUSSION

On the 18th day of accounting, the germination energy of strawberry seeds treated with a low-frequency pulsed magnetic field exceeded the control indicators by 21%.

The appearance of strawberry seedlings in the laboratory FSAC VIM is shown in Fig 4.

Based on the calculated coefficients of the mathematical model, the response function, the equation of the mathematical model are found:

$$y = (35.807) + (-3.082) \cdot x_1 + (0.568) \cdot x_2 + (-0.939) \cdot x_3 + (-4.646) \cdot x_1^2 + (-7.736) \cdot x_2^2 + (6.197) \cdot x_3^2 + (0.021) \cdot x_1 \cdot x_2 + (-1.46) \cdot x_1 \cdot x_3 + (0.531) \cdot x_2 \cdot x_3$$

The main indicators obtained as a result of statistical data processing are presented in Table 4.

According to Fisher's criterion, the mathematical model is recognized as adequate ($F = 1,35 < F_{Table} = 2,71$).

The equation of the mathematical model is a quadratic function of three variables. For the purpose of visual simplification and convenience of work with mathematical

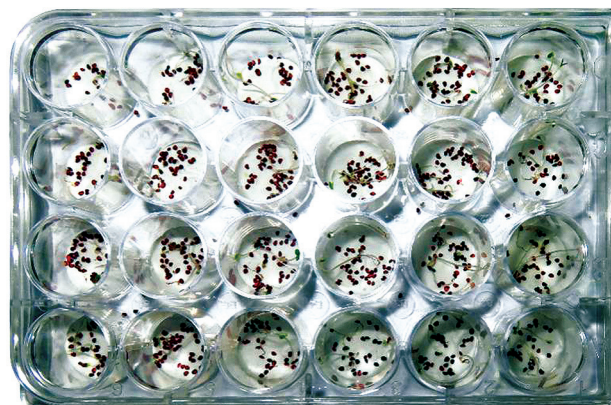


Fig 4 Sprouts of strawberry seeds on the 18th day.

Table 4 Results of factor analysis

Reproducibility dispersion in parallel experiment	7.778
Number of freedom degrees	20
Table value of the Student's criterion	2.09
Dispersion of the adequacy of the mathematical model	10.493
Degrees number of freedom with significant coefficients	5
The table value of the Fisher's criterion	2.71
The calculated value of Fisher's criterion	1.35

model graphic interpretation of function of three variables and the diagram of lines of equal level (isolines) representing projections of three-dimensional surfaces on a plane is constructed.

The factors x_1 , x_2 , x_3 are alternately represented by constants and their values are given within the variation interval in coded and natural form. As a result of the transformation, three variants of the mathematical model were obtained: $y=f(x_2, x_3)$ when $x_1=\text{const}$, $y=f(x_1, x_3)$ when $x_2=\text{const}$, $y=f(x_1, x_2)$ when $x_3=\text{const}$ (Fig 5). Equations of mathematical model taking into account a constant factor (Frequency, 16 Hz, Duty cycle 16, Induction, 5mT):

when $x_1 = \text{const}$;

$$y = (35.807) + (0) + (0.568) \cdot x_2 + (-0.939) \cdot x_3 + (0) + (-7.736) \cdot x_2^2 + (6.197) \cdot x_3^2 + (0) \cdot x_2 + (0) \cdot x_3 + (0.531) \cdot x_2 \cdot x_3;$$

when $x_2 = \text{const}$;

$$y = (35.807) + (-3.082) \cdot x_1 + (0) + (-0.939) \cdot x_3 + (-4.646) \cdot x_1^2 + (0) + (6.197) \cdot x_3^2 + (0) \cdot x_1 + (-1.46) \cdot x_1 \cdot x_3 + (0) \cdot x_3;$$

when $x_3 = \text{const}$;

$$y = (35.807) + (-3.082) \cdot x_1 + (0.568) \cdot x_2 + (0) + (-4.646) \cdot x_1^2 + (-7.736) \cdot x_2^2 + (0) + (0.021) \cdot x_1 \cdot x_2 +$$

Table 5 Student's criterion and the significance of the model coefficients (1/0 - significant / insignificant)

t-criterion	13.7	2.77	0.51	0.84	2.16	0.01	1.10	3.59	0.4	2.88
Significance	1	1	0	0	1	0	0	1	0	1

$(0) \cdot x_1 + (0) \cdot x_2$;

with isoline diagrams taking into account constant factors:

a - $y = f(x_2, x_3)$ when $x_1 = \text{const}$; b - $y = f(x_1, x_3)$ when $x_2 = \text{const}$; c - $y = f(x_1, x_2)$ when $x_3 = \text{const}$;

To determine the coordinates of the extremum point, the first derivative for each of the factor values was calculated. The roots of the obtained system of equations are the coordinates of the extremum point of the regression equation under study. Table 6 shows the values of the extremum of the response function and the corresponding values of the factors in coded and natural form.

The extremum of the response function is within the range of variable factor variation.

The experiment showed that the impact on the seeds of strawberry garden low-frequency pulsed magnetic field positively affects the shoot energy and the germination of strawberry garden seeds. On the 18th day of registration, the shoot energy of seeded strawberry seeds processed with a low-frequency pulsed magnetic field exceeded the control values by 21%, and the germination capacity by 22%.

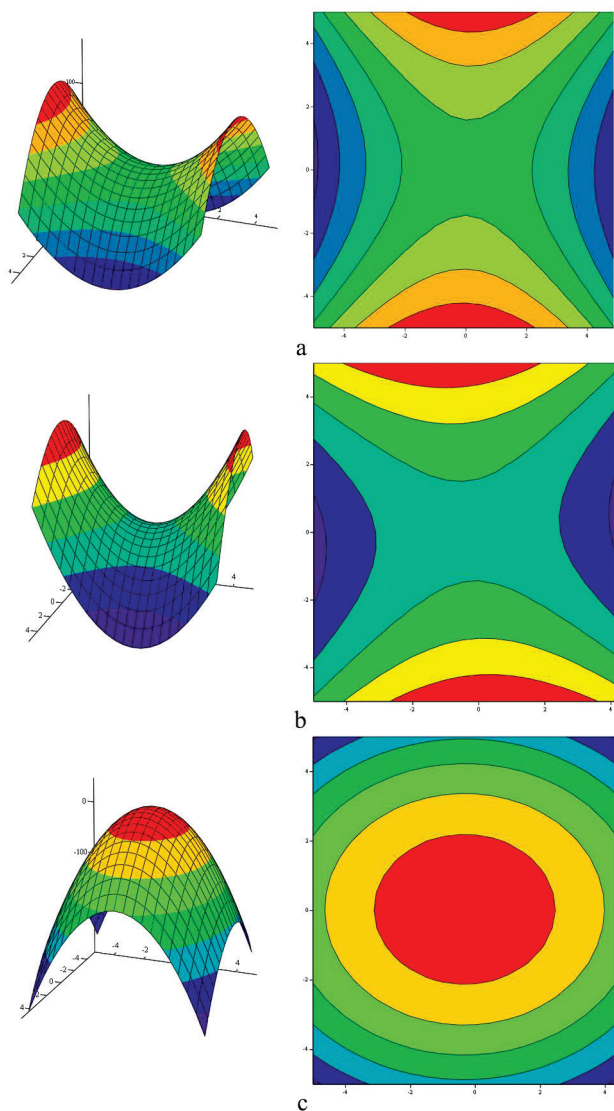


Fig 5 Graphical representation of the regression equation

Statistical analysis of the data from the factor experiment showed that the parameters of the MIO device with a frequency of 15.325 Hz, a duty cycle of 16.145, and magnetic induction in the irradiation zone of 5.05 mT are the most effective for increasing the germination and shoot energy of the seeds.

Several varieties of MF, which can be obtained as a result of possible combinations of time-frequency parameters.

The authors of many papers confirm the biological effect of weak magnetic fields [12, 13, 14]. Organisms can distinguish between the magnetic field intensity and to feel the direction in which magnetic lines of force pass through their body. At that the maximum efficiency, as a rule, have magnetic fields with a tension close to the geomagnetic field of the earth (Fig 6).

Strong deviations of the electromagnetic field from the natural level in greater or lesser side, go beyond the optimum life limits of living organisms and are stress factors [15, 16].

In the publication (Esitken and Turan, 2004) when using MF with induction of 0.096 T with a frequency of 50 Hz, an increase in yield by 18% and the accumulation of calcium, magnesium ions in strawberry leaves was achieved. Impact on wild strawberry MF 0.096, 0.192 and 0.388 T in greenhouses increased the yield and the number of fruits per plant. With the increase of the magnetic induction value of more than 0.096 T, the yield and the number of fruits decreased. The increase in the power of the MF to 0.384 Tl increased the content of N, K, Ca, Mg, Cu, Fe, Mn, Na and Zn, but decreased the content of P and S [17].

Chao and Walker (1967) used a horseshoe-shaped magnet with magnetic induction of 0.06 T for preseeding stimulation of apple, peach and apricot seeds. Apple seeds, as a result of exposure to a magnetic field, germinated 5 days earlier than control seeds. Their germination lasted 18 days, which is shorter for a week than for unstimulated seeds. Germination of apricot seeds was observed earlier for 3 days [18].

Conducted researches of Federal State Budgetary Scientific Institution «All-Russian selection and technological Institute of horticulture and viticulture» (FSBSI VSTISP) (Donetskikh, 2016) showed that the efficiency improvement of pear in the conditions of tissue culture of viruses depended on the modes of magnetic-pulse processing. The application of MPP with a continuous linear increase in the frequency

Table 6 The extrema values of a response function

Response function extremum	Frequency in coded (natural form), Hz	Duty cycle in coded form (natural form)	Induction in coded form (natural form), mT
Yopt = 35.78	x1 = 0; (16);	x2 = 0.039; (16.15);	x3 = 0.074; (5.07);
Yopt = 36.31	x1 = - 0.34; (15.32) ;	x2 = 0; (16) ;	x3 = 0.036; (5.03);
Yopt = 36.32	x1 = -0.33; (15.33);	x2 = 0.036; (16.14);	x3 = 0; (5);

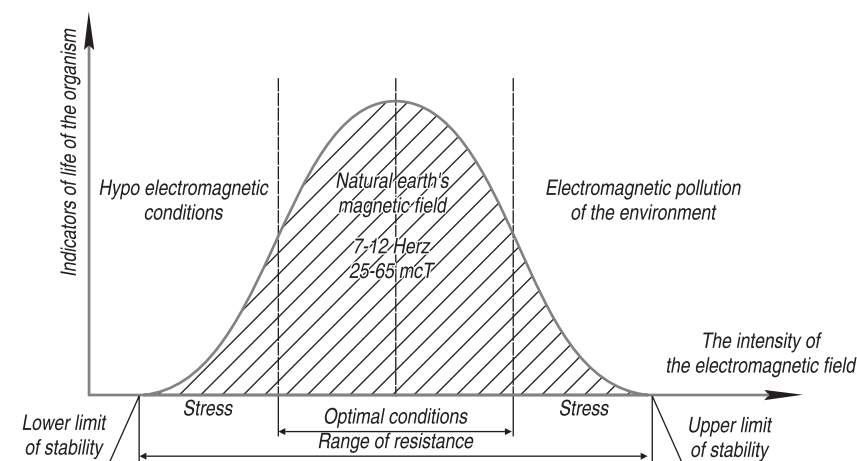


Fig 6 Classification of electromagnetic fields

in the range of 50-100 Hz is provided on the rootstock of pear English the greatest yield of healthy plants from the virus complex – 75%. The established modes of processing vertically directed upward magnetic induction pulses with a frequency of 16 Hz for 2 seconds were used in industrial plantations. An increase in yields by 29% was revealed due to an increase in the number of strawberries garden [19].

As a result of the study it was found that the mechanism of the action of a pulsed magnetic field on strawberry is based on the establishment of EMF in individual cell structures, on the shift of equilibrium in biochemical reactions. The direct participation in all chemical reactions in the seeds is taken by water. Due to the change in the normal component of the ion velocity during magnetic processing, the kinetic energy of the relative motion of the particles changes. The molecules act on the force, which leads to deformation of the cell membrane, as a result of which the diffusion coefficient and the rate of the chemical reaction change. The permeability of the cell increases, the transport of ions accelerates, the concentration of mineral elements increases, resulting in the stimulation of seed development.

REFERENCES

- Baryshev M G and Dzhimak S S. 2012. *Investigation of the influence of a low-frequency electromagnetic field on biological objects*. Krasnodar: Kuban state University. pp 1–15.
- Beshnov G V, Upadyshev M T, Donetsk V I and Tsymbal A A. 2002. Magnetic impulse processing of planting stock of garden plants. *Horticulture and viticulture* 1: 15–8.
- Bingi V N. 2002. *Magnitobiology: Experiments and Models*, p 592. Moscow, MILTA.
- Brown F A, Barnwell F H and Webb H M. 1964. Adaptation of the magnetoreceptive mechanism of mud–snails to geomagnetic strength. *Biology Bulletin* v. 127. 2: 221.
- Chao L and Walker D R. 1967. Effect of magnetic field on germination on apple, apricot and peach seed. *Horticulture Science* 2: 152–3.
- Donetskikh V I, Upadyshev M T, Petrova A D, Metlitskaya K D and Selivanov V G. 2017 Application of AMIS-8 apparatus to combat Viruses when preparing planting stock of fruit crops machinery and equipment for rural area. 1: 16–23.
- Dospehov V A. 1985. *Method of Field Experiment*, p.336. Moscow, Kolos.
- Esitken A and Turan M. 2004. Alternating magnetic field effects on yield and plant nutrient element composition of strawberry (*Fragaria x ananassa* cv. Camarosa). *Acta Agriculturae Scandinavica B-S P* 54: 135–9.
- GOST 10842-89. 1991. Cereals, pulses and oilseeds. Method for determination of 1000 kernels or seeds weight. 8 p. Moscow.
- GOST 12041-82. 1983. Seed of farm crops. Method for determination of moisture content. 336 p. Moscow.
- GOST 12038-84. 1986. Agricultural seeds. Methods for determination of germination. p 49 . Moscow.
- Hort D O, Filippov R A and Kutyrev I A. 2017. Development of the device for magnetic-pulse processing of plants. *Innovations in Agriculture* 1(22): 144–51.
- Kholodov Y A. 1975. Reactions of the nervous system to electromagnetic fields. Moscow. *Science*. P. 207. (SOURCE DOUBT)
- Kutyrev A I, Hort D O, Filippov R A and Tsench Y S. 2017 Magnetic-pulse treatment of strawberry seeds. *Agricultural machines and technologies* N5: 9–15.
- Lyubimov V V. 1997. Biotropic natural and artificially created. 85 p. Electromagnetic fields Moscow, IZMIRAN.
- Novitsky Y I. 1978. Reactions of plants to magnetic fields. Reactions of biological systems to magnetic fields. Moscow, Science. pp 113–30.
- Gotlieb N D and Caldwell W E. 1967. Magnetic Field effects on the compass mechanism and activity level of the snail (*Helisoma duryie discus*). *Journal of Genetic Psychology*. v.11: 85.
- Palmer J D. 1963. Organismic spatial orientation is very weak magnetic fields. *Nature* 4885: 1061.
- Pavlovich N V, Pavlovich S A and Galiullin Y I. 1991. *Biomagnetic rhythms*. p.136. Moscow University.