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Influence of Factors Determining Weeds' Plant Tissue Reaction to the Electric Pulse Damage Impact

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Abstract: Due to the emerging danger to the life of animals and people, today there is a turn to safe technologies for controlling weeds by physical methods, both from the point of view of ecology and food safety, which include the destruction of plants using an electric current, in particular, high-voltage electrical pulses. The purpose of the study presented in the article is to identify and evaluate the effect of high-voltage electrical pulses on the irreversible damage to the intracellular structures of the plant tissue of weeds and unwanted grasses during their electric weed control, characterizing and evaluating the parameters and modes associated with such processing. Experimental studies were carried out using a laboratory experimental setup that consists of a pulse voltage generator, a control circuit for a spherical forming spark gap, and schemes for measuring the electrical resistance of the plant tissue of the weed sample. The lesion level made it possible to control the depth of irreversible damage to the internal structure of the plant tissue of weeds by measuring its tolerance (the conductivity of the tissue increased with increasing damage to the cellular components of the tissue).The irreversible damage to the plant tissues of weeds for weeds of various biological groups, which is characterized by reaching the value of at least 4.0–7.5 degrees of damage to their tissues, can be acted on them with high-voltage electrical pulses in the treated tissue of an electric field intensity of at least 3.74 kV/cm, while ensuring specific processing electric energy for the reliable processing of weeds: for *Euphórbia virgáta*, thise quals 5.2. . . 17.5 J/cm^3; for *Amaránthus retrofléxus*, it is 3.5. . . 7.7 J/cm^3; for *Cirsium arvense*, it is 2.7. . . 10.9 J/cm^3;for *Sónchus arvénsis*, it is 3.7. . . 15.8 J/cm^3; and for *Lactúca tatárica*, it is 3.3. . . 8.1 J/cm^3.

Keywords: high-voltage electrical pulse; processing; plant tissue; irreversible damage; intracellular structure

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1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO), potential crop losses are 13.8% from pests, 11.6% from diseases, and 9.5% from weeds. Every year, weeds cause great damage to the yield and quality of agricultural crops, so the average percentage of crop losses in different countries is estimated over the past decade: for spring wheat, it ranges from 7.9% to 47.0%; for winter wheat it ranges from 2.9% to 34.4%; and the average global loss of total production of corn is about 37%, of peanuts it is 36%, of soybeans it is 31%, etc. [1,2].Currently, serious attention is being paid to reducing environmentally unsafe impacts in the crop industry of the agrarian sector, especially when growing organic products. One of the main technological operations in agriculture is weed control, which is implemented mainly through the use of artificially synthesized herbicides. The most popular herbicide in the world today is glyphosate. In 2015, the International Agency for Research on Cancer (IARC) stated that glyphosate is the active chemical in "Roundup" and is "probably carcinogenic". Food and Agriculture Organization of the

United Nations (FAO), the European Chemicals Agency, and the European Food Safety Authority (EFSA) concluded that it is "unlikely to pose a carcinogenic risk" to humans when eating foods grown with it [3]. In 2022, the European Union considered a possible phasing out of the use of designated glyphosate pesticides. That is why today, from the point of view of ecology requirements and food safety, there is a turn to safe effective technologies for controlling weeds by various physical methods, including the destruction of plants using electric currents, in particular, high-voltage electrical pulses [4].

The application of electric impact to control weeds and unwanted vegetation has been known since the 1800s, but there are still a lot of unresolved issues, such as, first of all, what the mechanism of the processes that lead to plant death is; whether there is a certain consistency in the sensitivity of plant tissues of weeds to electrical impact; how the lesion levels of plant tissue can be assessed, using methods that are understandable to all with a simple means of control; how the change in the electrically conductive properties of plant tissue depends on the parameters of the electrical impact, etc. Comparison with the electrical impact types, direct current, sinusoidal voltage, and electrical pulses, made it possible to give priority to high voltage pulses, since it is the processing of this type of electric action that allows deeper irreversible lesions to plant tissue and at the same time, a smaller amount of electrical energy is spent on the process [4,5].

To consider the processes occurring in plant tissues during the destruction of weeds using high-voltage electrical pulses [6–8], it is necessary to study the sensitivity of the processed plant tissue to the electrical effects and assess the lesion level of the normal functioning of its intracellular components depending on the main damaging factors of electrical action—the electric field intensity and the quantity of energy absorbed by the processed tissue [5,9–12].

In the global practice of scientific and applied research on the study of the effect of high-voltage electrical pulses on the intracellular structure of plant objects and materials, research works carried out in the interests of the processing industry in the production of food and semi-finished products are the most studied, in particular, the processing of fruits and vegetables, for example, citrus and gourds, grapes, apples, cherries, sugar beets, etc. [13–17]. The main objective of this research was to study the effect of electrical pulses on the internal structure of plant materials for the purpose of irreversible damage (destruction) and subsequent release of intracellular fluid for additional juice yield, drying acceleration, non-thermal pasteurization of products, etc. [18–20]. As a quantitative indicator characterizing the "destruction" of intercellular and intracellular structures of plant tissues, research scientists use such an indicator as the degree of disintegration [9,21–23], the value and change of which directly depend on the electric field intensity, duration of exposure, pulse form, and the quantity of energy absorbed by the processed object [9,10,12,24–29].

Weeds cause serious harm in semi-arid and arid regions of the Russian Federation, one of which is the Lower Volga region. An essential feature of all methods of tillage in the region is that each operation aimed at combating weeds must ensure not only the complete destruction of weeds, but also the preservation of soil moisture, the lack of which adversely affects the development of cultivated plants. In the fight against weeds, mechanical and chemical methods are widely used. Cultivation is the most effective since, in addition to the destruction of weeds, the soil is loosened, as a result of which metabolic processes in it are improved, which positively affects the growth and development of crops. Weeds themselves are cut by the operating bodies of machines for surface tillage. However, this method is not always effective, since when the field is infested with root shoot weeds, the main weeds of the soil areas of the Lower Volga region, after processing by the operating bodies of cultivators, after some time, new, large foci appear. Root weeds propagate vegetatively, and the most effective is to extract them from the soil together with the root, i.e., combing. However, in the modern system of agricultural machines, there are no tools that allow combing out weeds from the soil along with the root in various phases and periods of their development.

In this paper, the sensitivity of plant tissue of weeds to damaging electric pulse effects was studied. This article did not set a detailed consideration of the technology of electric pulse weed control, design a unit for its implementation, and conduct an economic comparison with known control methods. However, answering the question of respected reviewers, we can say that the introduction of electric pulse weed control into the technology of preparing sown areas (care for fallow lands) for growing crops makes it possible to increase the efficiency of weed control in terms of human labor costs by 62% compared to chemical treatment, and it is practically comparable with cultivation: in terms of direct energy costs, by 83% compared to62%, and in terms of the cost of manufacturing technical means for each method, by 35% compared to41%, respectively. Electric pulse fallow weed control can reduce the total energy costs, for example, when cultivating winter wheat on an area of 100 hectares by 12.89% compared to chemical weed control and by 5.13% compared to conventional cultivation.

The research hypothesis is as follows: during electric pulse processing, the intracellular components of weed plant tissues are primarily damaged, and their change (the ratio of the number of damaged and not yet destroyed cells) should determine the change in the electrically conductive properties of the processed tissues. The depth of processing will be determined by the parameters of the electric pulse impact: the amount of energy absorbed by the plant tissue and the strength of the electric field in it.

The authors of the paper proposed assessing the susceptibility of plant tissue of weeds to damaging electrical effects using such a quantitative indicator as its lesion level, which is understood as the value Sn. The numerical value of this indicator is determined by the ratio of the total electrical tolerance of the plant tissue or its active component, recorded before the start of processing, to the tolerance of the same tissue, which changes during processing, at the particular measuring current frequency, in this case at the frequency of f = 10 kHz [5,24,30,31].

The purpose of the study is to identify and evaluate the effect of high-voltage electrical pulses on the irreversible damage to the intracellular structures of the plant tissue of weeds and unwanted grasses during their electric weed control, characterizing and evaluating the parameters and modes associated with such processing.

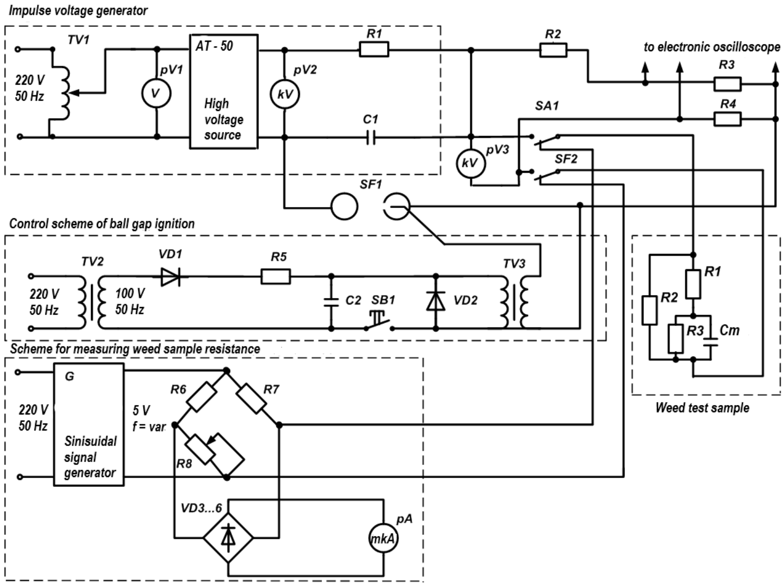
2. Materials and Methods

Laboratory experimental setup. Experimental studies were carried out in accordance with the procedures of the experimental setup (Figure 1), which were described in detail in articles [30,31]. The laboratory experimental setup consists of three principal components (blocks): (1) pulsed voltage generator (IVG); (2) control circuit for a spherical forming spark gap; and (3) schemes for measuring the electrical tolerance of the plant tissue of the weed sample. Each of the listed blocks performs its functional purpose.

The experimental setup is powered from a single-phase alternating voltage grid, the required voltage value of which was set at the circuit terminals using a laboratory autotransformer. A digital voltmeter was used to visually control the value of the supply voltage. The standard AT-50 apparatus was used as a source of high direct voltage, at the output of which voltage up to 50 kV can be obtained.

High-voltage capacitors were used as the storage capacities of the discharge circuit of the pulsed voltage generator (GVP). To obtain different values of electrical energy, the capacity of the discharge circuit required for processing weed samples was changed by switching the number of capacitors into batteries. A high-voltage resistor was used as a charging current limiter.

An important role in the GVP is played by spark gaps, which act as a switch and switch capacitors from the charge mode to the discharge mode. The stability of the amplitude of the output pulses of the generator depends on their stable operation.



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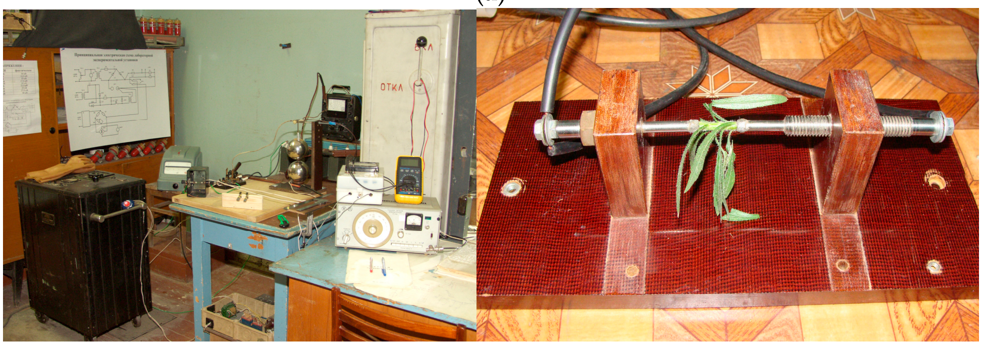


(**b**)

Figure 1. Schematic diagram of the laboratory experimental setup (**a**) and the appearance of the laboratory experimental setup (**b**).

To control the moment of discharge in the GVP in order to synchronize its operation with the recording oscilloscope, as well as to calculate the number of pulses affecting the plant tissue of the studied weeds, a controlled spark gap was used. In the laboratory experimental setup, a standard adjustable spark gap was used, which was assembled on the basis of two spherical electrodes with a diameter of 100 mm, the surfaces of which were chrome-plated.

The moment when the starting pulse was supplied corresponded to the end of the charging time of the GVP capacitors. The ball gap control circuit was assembled using a *TV3* pulse transformer. The principle of the circuit operation is as follows: the voltage U is supplied from the secondary winding of the step-down standard transformer *TV2*, and the capacitance *C2* is charged through the resistance *R5*. After the SB1 button was switched on (ignition coil), the capacitance was discharged to the primary winding of the *TV3* pulse transformer, and the current flowing through it at the moment of switching contributed to the occurrence of a high-voltage pulse in the secondary winding. The created high voltage pierced the gap between the main and igniting electrodes of the lower ball of the main discharge gap *SF1*, which was ionized, and the main discharge occurred in it, as a result of which the energy stored in the storage tanks *C1* of the GVP was applied to the plant tissue sample. Diode *VD2*, connected in parallel with the primary winding of the ignition coil, acted as a shunt to prevent the *TV3* pulse transformer from failing. The ignition circuit was mounted in a separate housing, and high voltage was supplied to the spherical spark gap using a high-voltage wire.

Methodology for preparing and conducting this study is as follows. The fragment of the weed plant tissue carved with a surgical scalpel from the plant was placed in the interelectrode space in the working spark gap *SF2* of the discharge grid. The electrodes played the role of both working and measuring electrodes and were spring-loaded stainless-steel rods at the ends of which grooves or blackened platinum mesh segments were used, to which felt pads were attached. To reduce the "plant tissue-electrode" contact resistance and to ensure high-quality contact with plant samples, when using felt pads, the contact surface of the overlays was moistened with 5% NaCl solution after each experiment. Galvanic isolation between the discharge circuit of the GVP and the measuring circuit was carried out using a three-position switch.

The species composition of weeds that are typical for the five-year period of research and found everywhere in crops and fallows in the Lower Volga region is diverse. The dominant types of weeds are (1) dicotyledonous perennial root weeds: *Sónchus arvénsis,* which fill43–54% of weedy areas; *Convōlvulus arvēnsis* fills 26–32%; *Cirsium arvense* fills 12–23%; *Euphórbia virgate* fills 13–19%; and *Lactúca tatárica* fills 4–8%; (2) dicotyledonous annual weeds: *Oxýbasis úrbica*, *Chenopódium úrbicum*, etc. fills 16 . . . 23%; *Amaránthus retrofléxus*, etc. fills 15–30%; *Thláspi*, *Barbaréa*, *Raphanus raphanistrum*, etc.–3 . . . 9%, etc.

Experiments were carried out with weeds, which are most often found on the lands of agricultural fields of the Lower Volga region. These are annual weeds: *Amaranthus retroflexus*, *Oxýbasis úrbica*, *Cánnabis ruderális*, *Fallópia convólvulus*, and *Xánthium strumárium*, as well as perennial, root shoot weeds, *Cirsium arvense*, *Sónchus arvénsis*, *Euphórbia virgáta*, *Lactúca tatárica*, and *Convōlvulus arvēnsis*.

Weeds grew in the fields of the All-Russian Research Institute of Irrigated Agriculture, on rain-fed fallow lands, with an average or even high degree of infestation by weeds of the same predominant type, which were approximately in the same phase of development.

The studied weeds were in the following phases (periods of development): the beginning of budding, flowering, and the beginning of fruiting. To study the response and sensitivity of the plant tissue of weeds to electrical pulses, experiments were carried out not with the whole plant, but with a separate part—a certain volume of the leaf–stem part, the area with the root neck, and part of the root system. The size of the studied part of the weed plant was taken into account in the form of its certain volume, for which the recorded energy absorbed by the plant tissue was recalculated in the form of its specific value (J/cm^3).

Whole weeds, together with the root system extracted from the soil, were dug up in the experimental field, housed in a portable container, and delivered to the laboratory, which was located within walking distance of 100–150 m. In the laboratory on the preparation machine (fixed pair of scalpels), fragment of the plant tissue of the stem, root collar, and root was cut out and placed in the processing chamber between spring-loaded immersion electrodes. After measuring the tolerance of the studied area of the plant, the electrodes were disconnected from the measuring complex and connected to the discharge circuit, in which the plant sample was electro pulsed. Then, the reverse switching followed, and the tolerance of the plant tissue was measured after the electrical action. The impact on the plant sample was continued until subsequent exposures did not lead to the change in the tolerance of the plant tissue of the sample, that is, when the level of irreversible damage to plant tissue reached its maximum value.

Methodology for processing research results and its justification is as follows. The lesion level of the plant tissue damage was found as the ratio of the tolerance of undamaged (living) tissue to the tolerance of damaged tissue.

To establish the dependence of the lesion level of the plant tissue of weeds on the electric field intensity in it and on the quantity of energy absorbed by it, the analytical expression that relates the lesion level to the intensity of the influencing factor and the duration of its action was applied. The applicability of the proposed approach to the analysis of the irreversible electrical pulse damage process to the intracellular structures of weed plant tissues was previously substantiated in the study of the susceptibility of sunflower and tobacco plant tissues to electric pulse exposure [5,30,32]:

$$S = k_s \cdot E^n \cdot t^q \tag{1}$$

where $E = U_0/l_{pm}$ is the average electric field intensity in the plant tissue of the studied weed area, which is characterized by the length l_{pm}, coinciding with the length of the path of the processing current, and the cross-sectional diameter of the processed sample averaged over this length d_{pm}, kV/m; U_0 is initial voltage or voltage on the output capacitor of the discharge circuit applied to the studied sample of plant tissue, kV; t is time period of the electrical action or the duration of the acting pulse, s; n is exponent degree n = const, determining the dependence of the electric field intensity change in plant tissue on the lesion level; q is exponent degree q = const, which determines the dependence of the exposure time to plant tissue on the lesion level; and k_s is proportionality factor, $(\mathrm{cm/kV})^{\mathrm{n}} \cdot \mathrm{s}^{-1}$.

The distinctive point in the application of Equation (1) for the conducted analysis should consider the fact that electric pulse weed control is a process of longitudinal electrical processing of weed tissues, and not their processing across, as described in [5,30,32]. In the analytical Equation (1), to make analysis more convenient, the exposure time t should be considered to the power q = 1, which corresponds to the main linear section of the dependence $S_n = f(E, t)$, characterizing that part of it when the transition from the end of the initial phase of processing to its completion is clearly distinguished. Such an assumption is quite possible, since the studied plant tissues of weeds were affected by single pulses that had the same duration in each series of experiments:

$$S = k_s \cdot E^n \cdot t = k_s \cdot \left(\frac{R_m \cdot i}{l_m}\right)^n \cdot t = k_s \cdot \left(\frac{R_m^{n-1} \cdot i^{n-2}}{l_m^n}\right) \cdot W = k_s \cdot \left(\frac{\rho_m}{l_m \cdot S_m}\right) \cdot m \cdot W_1 \cdot {}^{n-2} \tag{2}$$

or

$$S = k_s \cdot \left(\frac{R_m^{n-1} \cdot i^{n-2}}{l_m^n}\right) \cdot m \cdot W_1 = k_s \cdot \left(\frac{R_m \cdot C_k}{2}\right) \cdot m \cdot {}^{n} \tag{3}$$

where i is the average current value through the plant tissue, A; $R_{\mathrm{PT}} = (\rho_{\mathrm{PT}} \cdot l_{\mathrm{PT}})/S_{\mathrm{PT}}$ is tolerance of the investigated area of plant tissue with electrical resistivity ρ_{PT}, length l_{PT}, and cross-sectional area S_{PT}, Ohm; $W_1 = i^2 \cdot R_{\mathrm{PT}} \cdot t = 0.5k_{\mathrm{p}} \cdot C_k U_0^2 = (0.45–0.475) \cdot C_k U_0^2$ is single pulse energy, J; k_{p} is the degree of discharge of the capacitor of the discharge circuit (in terms of voltage), usually taken as equal to k_{p} = 0.9–0.95; C_k is storage capacity of the discharge circuit, F; and m is number of acting pulses.

Elements of planning experiments are as follows. The required reproducibility of measurements depends on the standard of measurement and the desired reliability of the result; therefore, based on the accepted values of the specified reliability of the result and the marginal error, the numbers of reproducibility in the experiments were3–5 measurements.

The five-year research period was determined by the fact that the growth and development of plants depend on various soil and climatic conditions, which can change significantly from year to year, and therefore all experiments during this five-year period were carried out according to the same methodology with the same repetition on plants growing on the same soil area, in the same periods of development and the same tillage period, so that it is possible to determine the variability of the studied parameters to determine the possible deviation of the obtained results. The results deviated from year to year, and according to the results of the entire experiment, this deviation ranged from average data to 10–15%. As a result, it was concluded that the obtained data on the value of the lethal dose, the specific energy of processing, and the value of the lesion level to plant tissue are reliable and do not change above the established margin of error over the years.

The character of all obtained dependencies is the same for all studied weeds. The difference is only in quantitative indicators (different lesion levels with the same influencing factors). Therefore, the paper presents the dependencies of the most resistant weed that requires more energy consumption—*Euphorbia virgáta*—as a typical example.

3. Results of the Research

Preliminary analysis of Equations (1) and (2) shows that the lesion level of plant tissues S_n of weeds depends on the electric field intensity E in them, and the nature of the dependence is determined by the value of the certain exponent n, as well as from the total quantity of damaging energy W, which is determined by the product of the number of influencing pulses m and the power of the single pulse W_1.

The quantitative lesion level and the nature of the dependence behavior $S_n = f(E)$ (Figure 2) is determined by the value of the exponent n, which was previously found empirically for plant tissues to be as follows: for tobacco, $n = 1.26$; for sunflower, $n = 1.5$; for "aloe" plant, $n = 0.75$; and for apple pulp, $n = 2.45$ [5,30]. Here, it is necessary to note an obviously traceable fact—considering the electrical processing of various plant objects, it can be noticed that the n exponent depends on the number of influencing impulses m or the energy W supplied to the processing object. Therefore, the found values of the n indicator should be characterized as averaged for a specific process of electric pulse processing of the specific plant material.

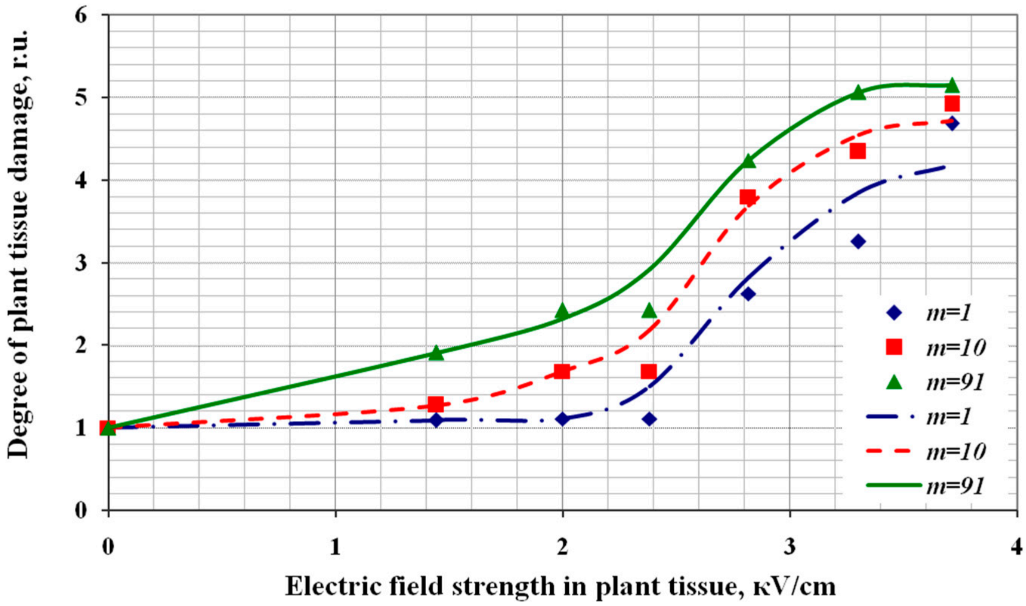
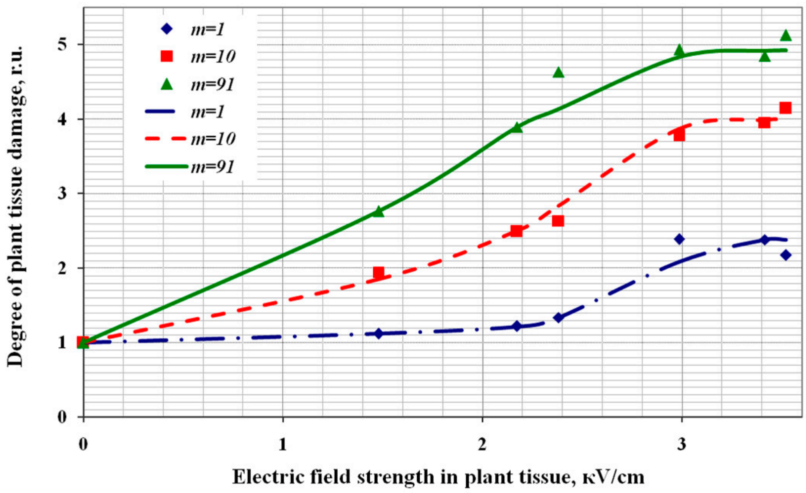


Figure 2. Dependencies of the lesion level of the plant tissue of the root system of *Cirsium arvense* on the electric field intensity in the tissue at different numbers of acting pulses (m). The IVG was characterized by the discharge circuit capacitance of 500 pF and inductance of 110 μH.

To confirm the above preliminary hypothesis about the different sensitivity to electric pulse lesions to the plant tissue of weeds, the experimental results were grouped, and experimental dependencies $Sn = f(E)$ were built on them for weeds of different biological groups [32], some of which, as showing the most qualitatively and theoretically the justified nature of the behavior (1–3), are presented in Figure 3.

From the point of view of optimizing the technological process of electric pulse destruction of weeds, it is interesting to analyze the influence on the lesion level S_n of the initial voltage of the discharge circuit U_0 and, consequently, as mentioned earlier, the electric field strength in their plant tissue. To elucidate the essence of this influence, a set of experimental studies were carried out, in which the capacitance of the circuit C_k remained constant, and the processing voltage U_0 changed. As a result of these studies, a set of dependencies $S_n = f(m)$ was obtained (Figures 4 and 5).



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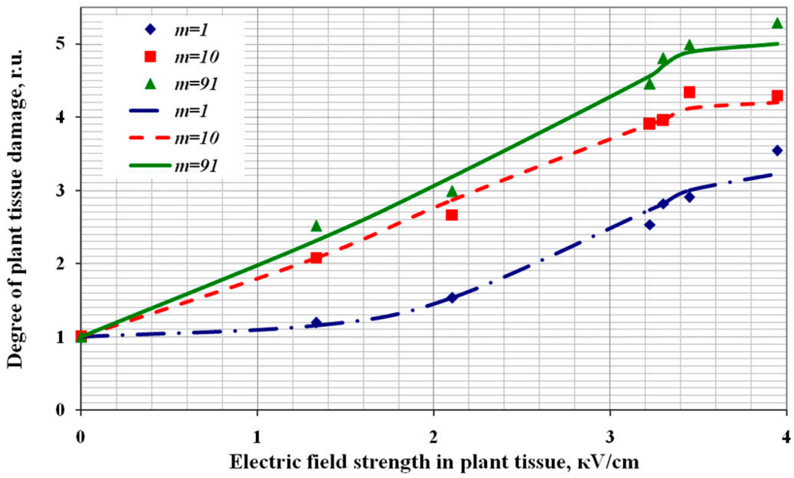

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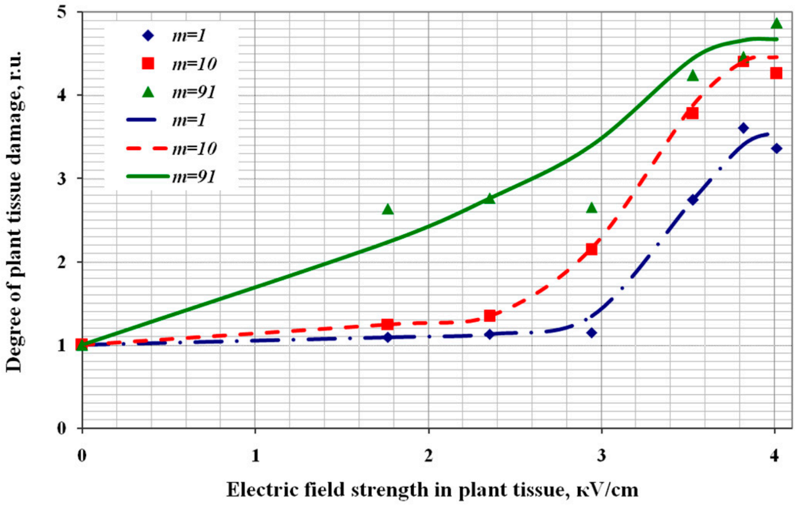

(**c**)

Figure 3. Dependencies of the lesion level of the plant tissue of the root system of weeds: (**a**) *Euphórbia virgáta*; (**b**) *Cirsium arvense*); and (**c**) *Amaránthus retrofléxus* from the electric field intensity in the plant tissue with a different number of influencing pulses (m). The IVG was characterized by the discharge circuit capacitance equal to 1000 pF and inductance of 110 μH.

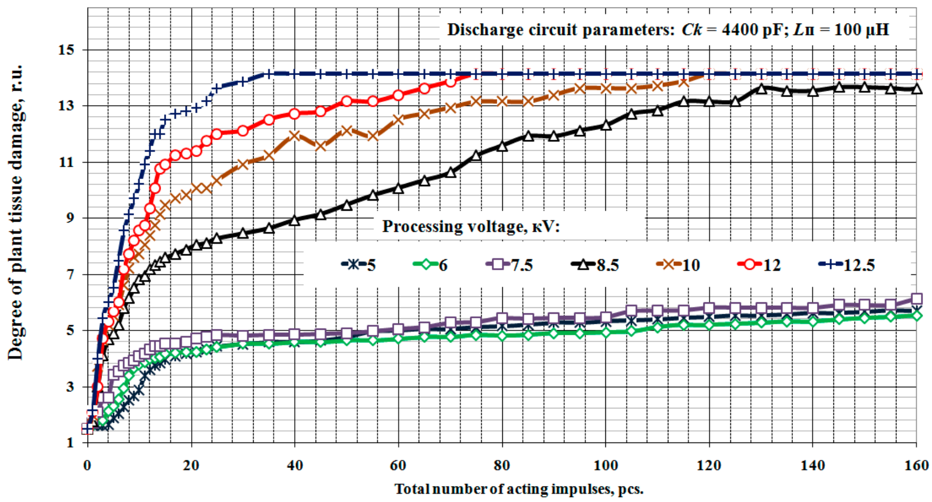

Figure 4. Dependencies of the plant tissue lesion level of the stem of *Euphórbia virgáta* on the total number of acting pulses at diverse values of the processing voltage, provided that the initial resistance values of the processed areas are different.

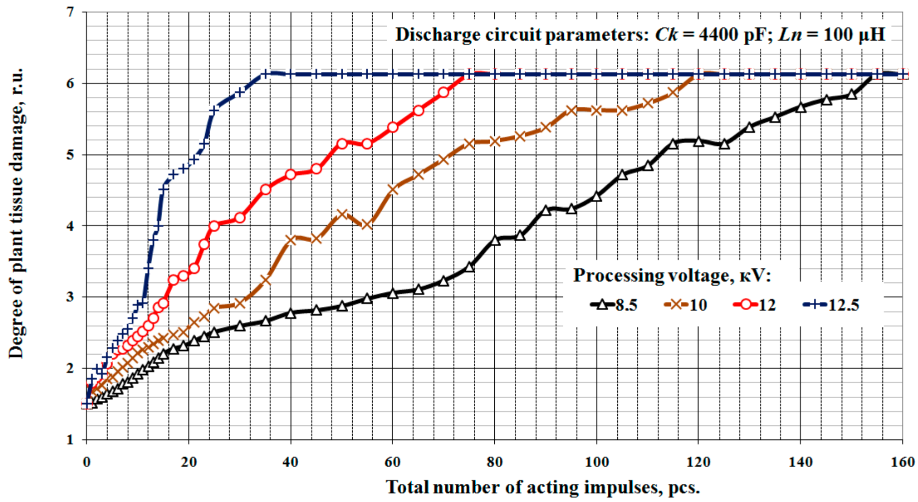

Figure 5. Dependencies of the plant tissue lesion level of the stem of *Euphórbia virgáta* on the total number of acting pulses at diverse values of the processing voltage, provided that the initial resistance values of the processed areas are the same.

In the studied example, in the first series of experiments (Figure 4), samples of plant tissue of the stem of *Euphorbia virgáta* were subjected to electrical processing, while the samples were cut from an adult plant of approximately the same period of development and recorded from the electrical resistance, which was of different values for each of them. In the considered example, samples of plant tissue of the stalk of *Euphórbia virgáta* were subjected to electrical treatment, the studied fragments of which were affected by electrical pulses with unit energy of W_1 = 0.055; 0.079; 0.124; 0.159; 0.22; 0.317; and 0.344 J, and the discharge circuit of the pulse voltage generator had the following parameters: C_k = 4400 10–12 F; L_p = 100 10–6 H; and U_0 = 5; 6; 7.5; 8.5; 10; 12; and 12.5 kV.

To confirm the assumption that if the studied samples of weeds had the same initial resistance, then in the process of electrical processing, their plant tissue could reach the same limiting lesion level, appropriate experiments were carried out. Electric influences were exerted on the plant tissue of fragments of the stems of *Euphórbia virgáta*, with equal initial resistances. Electrical pulse energy W_1 = 0.16; 0.22; 0.32; and 0.35 J (Figure 5). Discharge circuit parameters are C_k = 4400 10–12 F; L_p = 100 10–6 H; and U_0 = 8.5; 10; 12; and 12.5 kV.

4. Discussion of the Results and Analysis

The numerical values of the index n were determined by the calculation method on the main linearly increasing section of the dependence $S_n = k_s \cdot E^n \cdot t$. To conduct this, the graphic dependencies $S_n = f(E)$ were rebuilt on the logarithmic scale (Figure 2), and the n index was determined as the value of the slope tangent of the straight sections of the dependencies $S_n = f(E)$ to the abscissa axis. Each of the dependencies presented in Figure 3 was built for a specific number of acting electrical pulses m at the constant value of the capacitance of the capacitor bank of the discharge circuit C_k and the corresponding value of its inductance L_k.

Based on the results of the experiment and conducted calculations for various plots of different biological species of weeds growing in the Lower Volga region, the average values of the n index were determined and presented in Table 1 [32].

Table 1. Averaged *n* index values for various weed types.

Weed Type (in Latin)	Average *n* Index Valuesfor Various Weeds and Plant Tissues of Plots			
	Stem	**Plot with Root Neck**	**Root**	**Average Value**
Cirsium arvense	1.15	1.24	1.22	1.20
Sónchus arvénsis	1.19	1.23	1.25	1.22
Euphórbia virgáta	1.06	1.21	1.14	1.14
Lactúca tatárica	1.17	1.25	1.26	1.23
Amaránthus retrofléxus	1.22	1.40	1.21	1.28
Oxýbasis úrbica, *Chenopódium úrbicum*	1.30	–	1.27	1.29
Average value	1.18	1.27	1.23	1.23

The different values of the index *n* presented in Table 1, in our opinion, are explained by the different sensitivity of the tissues of the studied weed areas of different biological groups to the impact on them of high-voltage electrical pulses.

In Figure 6, the constructed graphical dependencies on the logarithmic scale are straight lines—the dependence of the n index value on the number of influencing pulses *m* or on the energy absorbed by the plant tissue is the same, since the impacts were organized by pulses with the same energy in each of them. Even a cursory analysis of the results presented in Figure 6 shows that the more acting pulses (energy) are supplied to the plant sample, the greater the value of the index *n*. As an example, consider the plant tissue of the root of *Euphorbia virgáta*; at $m = 10$, the exponent is $n = 0.63$, and at $m = 1000$, its value increases to $n = 1.796$.

To analyze the difference insensitivity for various tissues, the results were grouped, and the experimental dependencies $S_n = f(E)$ were plotted for weeds of different biological groups [32]. These dependencies (Figure 4) have a pronounced S-shaped character, which is determined by the presence in the initial section in the curves with the slight increase in the lesion level and the value of tension in the plant tissue of the section, which is often linear, with a very high rate of change in the lesion level, as well as of the section in which, with the increase in the value of the electric field intensity, the significant change in the lesion level is no longer observed.

The analysis of the character of the curves presented in Figure 4 makes it possible to draw the following conclusion: the plant tissue of the annual weed root system *Amaránthus retrofléxus*, when exposed to single pulses, reaches greater damage than the tissues of the perennial weeds *Euphórbia virgáta* and *Cirsium arvense*. For $m = 91$, the lesion level reaches one value, and the behavior of the dependencies becomes very similar to each other.

In the electrical treatment of weeds, characterized by the flow of current along plant tissues, the applied initial voltage of the discharge circuit U_0 determines the value of the electric field intensity E in them, at which the lesion level of the plant tissue reaches its maximum value $S_n = S_{nmax}$, and therefore its value is of research interest. The creation of such tension in the plant tissue of weeds leads to their death. To find these tension values, a separate series of experiments were carried out with samples from different plots of different weed species (Table 2). At the same time, it should be noted that plants of different years of research and periods of development, growing on different soil plots, have differences in damaging values of tension, with different expenditures of a minimum specific quantity of energy to damage the internal structure of weeds.

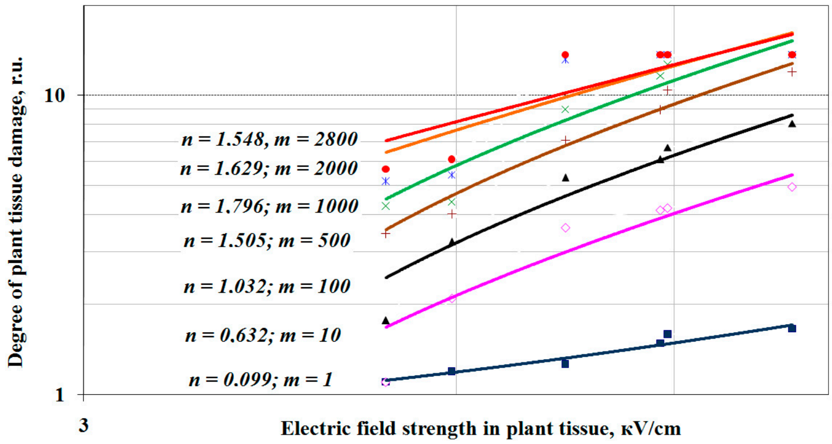

Figure 6. Dependencies of the lesion level of the root system plant tissue of *Euphórbia virgáta* on the electric field intensity in the tissue for diverse number of influencing pulses (m), plotted on the logarithmic scale. The IVG was characterized by the discharge circuit capacitance of 4400 pF and the inductance of 100 μH.

Table 2. The average electric field intensity and the maximum values of the lesion level of plant tissue in various areas of weeds.

Weed Type	Weed Area	Limit Lesion Level S_{nmax}, r.u.		Electric Field Intensity in Plant Tissue E, kV/cm	
		By Areas	Average	By Areas	Average
Cirsium arvense	stem	4.79	4.71	3.55	3.74
	passage	5.25		3.82	
	root	4.09		3.84	
Sónchus arvénsis	stem	7.71	7.51	3.52	3.66
	root	7.32		3.81	
Euphórbia virgáta	stem	4.60	4.59	3.68	3.53
	passage	5.39		3.37	
	root	3.77		3.55	
Oxýbasis úrbica, Chenopódium úrbicum	stem	7.38	7.31	3.41	3.55
	passage	6.89		3.53	
	root	7.65		3.72	
Amaránthus retrofléxus	stem	5.19	5.56	3.45	3.65
	passage	6.39		3.76	
	root	5.09		3.73	

According to the results of almost all experimental studies, the dependence of the lesion level S_n of the weed plant tissue on the number of acting pulses m–$S_n = f(m)$ or on the energy W–$S_n = f(W)$ absorbed by the plant tissue of weeds, which is the same, was plotted for variable values of the parameter bit circuit: U_0 = var or C_k = var. These dependencies have a clearly manifested S-shaped character, which manifests itself in three main areas: (1) in which the lesion level (S_n) changes slightly with the summing up of a certain number of high-voltage pulses; (2) on which there is a sharp increase in the lesion level (S_n) with the increase in the number of acting pulses or with an increase in the energy absorbed by the weed plant tissue (m or W); and (3) on which the lesion level (S_n), having reached its maximum value $S_n = S_{nmax}$, does not change. The steepness index of the second section or the growth rate of the lesion level (S_n) characterizes the sensitivity of the processed plant tissue to damaging electrical effects. The steeper the change in the behavior of the dependence $S_n = f(W)$ in this area, the more susceptible the plant tissue of the weed, in our opinion, to electro pulse exposure. From the point of view of ongoing violations of the normal existence of intracellular structures of plant tissue processes, the limit value S_{nmax} is an indicator that determines the greatest damage to the treated tissue when exposed to pulses with the same dose of electrical power. From an energy point of view, when the limiting value of lesion level to the plant tissue is reached, the electrical effect on the plant should end, since further processing of the weeds does not increase the damage, but only leads to an excessive consumption of electrical power. Additionally, this quantity of electrical power should be considered a lethal or damaging dose of energy for a particular species and part (leafy part or root system) of the treated weed.

Equation (2) determines the proportional rise in the S_n value resulting in a damaging energy increase. The quantity of this energy supplied to the plant by one acting pulse is affected by the circuit capacitance value C_k and the initial voltage U_0 supplied to the processed object. Subsequent influencing pulses result in irreversible lesion accumulation and disruption of its normal functioning in the plant tissue, reaching a critical lesion level value. The speed of reaching the limit values of the lesion level S_{nmax} is affected by the power of one acting pulse.

Of practical interest is information on the acting energy doses that result in the maximum value of the plant tissue lesion level, since the identification of the values of these doses allows the evaluation of the total energy costs and the design of technological requirements for the studied technology. The total impact energy value and its specific indicator (ratio of total impact energy to the volume of the processed plant sample) are used for analysis.

To assess the energy impact, the number of influencing pulses m with the specific energy of one pulse W_{1pulse} must be considered. The W_{1pulse} values were obtained by experimental studies performed with weeds growing in the Lower Volga region; the results were processed and are presented in Table 3 [32].

Table 3. The values of the total impact of the specific electrical power on the plant tissue of various areas of weeds and the limiting lesion level to this tissue.

Weed Type	Weed Plant Area	The Limiting Lesion Level of Plant Tissue, *Snmax*, r.u.		Specific Processing Electric Energy *Wsp*, J/cm^3	
		By Areas	Average	By Areas	Average
Cirsium arvense	stem	5.6…7.4	5.4…7.0	2.4…8.1	2.7…10.9
	passage	5.2…6.3		2.8…10.3	
	root	5.3…7.3		2.9…14.3	
Sónchus arvénsis	stem	4.8…7.7	4.7…7.5	3.3…15.2	3.7…15.8
	root	4.6…7.3		4.1…16.4	
Euphórbia virgáta	stem	4.8…4.7	4.3…4.5	4.9…24.7	5.2…17.5
	passage	3.9…4.5		5.6…12.7	
	root	4.3…4.3		5.1…15.2	
Lactúca tatárica	stem	5.6…7.4	5.5…7.3	3.8…6.8	3.3…8.1
	passage	5.8…6.9		3.3…8.4	
	root	5.0…7.7		2.6…8.7	
Amaránthus retrofléxus)	stem	4.1…7.1	4.0…6.8	3.4…8.2	3.5…7.7
	passage	4.4…6.7		3.1…7.2	
	root	3.6…6.6		3.9…7.8	

The results presented in Table 3 were obtained during five years of research. The scatter of the results is caused by diverse parameters of discharge circuits for each unit: in one case, the processing was carried out at voltages of 3–7.5 kV and 5–12.5 kV, respectively; in addition, capacitance values of the capacitors' discharge circuit differ.

In the case when samples of weeds with different values of initial resistance were processed, the limiting lesion level rose with the increase in the applied initial voltage U_0 (Figure 5). At the same time, the dependence was quite clearly traced: with the rise in the energy of the acting pulses, the rate of reaching the limiting value of the lesion level also increased.

The character of the obtained experimental dependencies (Figure 6) fully confirmed the above hypothesis: assuming that the studied samples of weeds would have the same initial resistance (even despite the difference in their biometric parameters, and the difference in periods and phases of development), then in the process of electrical processing, their plant tissue could reach the same limiting lesion level. The difference would be observed only in the rate of increase in the lesion level: the less sensitive the plant tissue is to electrical action, the slower the achievement of the limit value of the lesion level occurs, and the greater the amount of energy consumed for this. A slightly increased energy consumption to achieve the limit value of the lesion level S_{nmax} can be explained by the fact that the studied samples of weeds were in the phase of development of the "beginning of fruiting" and therefore had a slightly higher resistance value than in the previous experiment [11,29].

The obtained results on the study of the dependence of irreversible lesion level on the plant tissue of weeds are quite closely comparable with similar works on the use of an electric pulsed field in the food and processing industry [9,16,33,34]. When studying the sensitivity of weeds, this kind of analysis has not yet been carried out, and therefore it is not possible to compare the obtained results with data from similar studies. In the case comparing it with the work on food technology, it can be concluded that the nature of the dependencies is identical, but it is not correct to compare the obtained quantitative indicators that affect the change in the tissue level lesions, since in these experiments the technological tasks were often the extraction of juice or the removal of excess liquid, and in the electrical treatment of weeds, the main task was the need to irreversibly lesion and lead to the death of unwanted plants.

Assuming that the studied samples of weeds would have the same initial resistance (even despite the difference in their biometric parameters, and the difference in periods and phases of development), then in the process of electrical treatment, their plant tissue could reach the same limit lesion level. The difference would be observed only in the rise of the lesion level: the less sensitive the plant tissue is to electrical action, the slower the achievement of the limit value of the lesion level occurs, and the more energy is spent for this.

5. Conclusions

The lesion level of the intracellular structures of the plant tissue of the root system and the leaf–stem part of weeds of various biological groups increases with the increase in the value of the electric field intensity in their tissue, which reaches its limiting (maximum) value at E = 3.1. . . 3.8 kV/cm.

The greatest increase in the dependence $S_n = f(E)$ begins with the values of tension, for example, in the tissues of the root system of weeds: in *Euphorbia vine,* it is 2.2 kV/cm; in *Cirsium arvense,* it is 2, 0 kV/cm; and in *Amaránthus retrofléxus,* it is 2.9 kV/cm.

Exponent n characterizes the sensitivity of plant tissue of weeds to electrical damage. Having analyzed the values of the exponent n obtained by calculation on the basis of experimental results, it can be stated that the most sensitive plant tissue is for *Amaránthus retrofléxus* and *Oxýbasis úrbica*, and *Chenopódium úrbicum*: their average indexes are n = 1.28 and n = 1.29, respectively. The least sensitive plant tissues are in *Euphórbia virgáta*, n = 1.14. Plant tissues of *Euphorbia virgáta* are the most resistant to electrical damage, since the numerical values of the exponent n have the lowest values.

With the increase in the electrical power supplied to the weed plant, both by a single pulse and a series of pulses, the lesion level of the internal structures of the weed plant tissue increases. For reliable, irreversible damage to the intracellular structures of the plant tissues of the root system of the studied weeds, it is necessary to create an electric field intensity of at least 3.8 kV/cm in them during electric pulse treatment, and at least 3.7 kV/cm is needed to damage the aerial part. The plant tissue of the stem and root part of such weeds as *Cirsium arvense* and *Sónchus arvénsis*, as well as *Lactúca tatárica,* is most sensitive to electrical impacts, since the lesion level increases more intensively with each influencing pulse and reaches its limiting (maximum) value earlier than in plant tissues of the weed *Euphórbia virgáta* with equal energy impacts.

For reliable, irreversible damage to the intracellular structures of plant tissues of the studied weeds, it is necessary to spend at least 17.5 J/cm^3 of specific electrical power, and to achieve the value of the limiting (maximum) lesion level, at least 7.5 J/cm^3 is needed.

The speed of reaching the maximum value of the lesion level of the plant tissue of weeds depends on the voltage of the discharge circuit U_0—the larger this value, the faster the plant tissue reaches the limiting lesion level S_{nmax}.

The obtained results of the research allow us to discuss the clearly existing dependence of the irreversible lesion level to the plant tissue of weeds on the parameters of the electrical pulse impact. The sensitivity of the tissue to the effects of high-voltage electrical pulses on plants suggests that the implementation in practice of such a process of electrical processing of weeds will have a clear technological effect—the death of weeds and unwanted vegetation. At the same time, the specific values of electric energy and electric field intensity found to achieve the maximum lesion level in the plant tissue of weeds will allow us to evaluate the parameters of the technical device, such as the output parameters of the high-voltage pulse formation unit, and in general the parameters of the electric energy source.

The continuation of the study of the processes during electric impulse weed control of soil areas should be the coordination of the obtained specific indicators and parameters of the real electrical equipment of the electric pulse cultivator. At the same time, special attention should be paid to the study of the processes in case of lesions to weeds that occur when the unit and its electrode system are moved in relation to the weeds themselves in space and time; that is, to evaluate the dependence of the change in the lesion level to plant tissue on the parameters of electric pulse processing in dynamics.

The issue of using the obtained results for designing a control system for the modes and parameters of electric pulse processing deserves a separate discussion. The choice of the lesion level to the plant tissue of weeds, in this case, is the most acceptable option since, technically, it is most simple to implement a resistance measurement carried out at the same frequency but performed at different time intervals during processing to compare the result obtained with predetermined values of the limiting level processing of weeds prevailing on the soil massif, and form a control command to continue or stop the supply of high-voltage pulses to the system for supplying electrical energy to plants.

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References

1. El-Metwally, I.M.; Saudy, H.S.; Elewa, T.A. Natural Plant By-Products and Mulching Materials to Suppress Weeds and Improve Sugar Beet (*Beta vulgaris* L.) Yield and Quality. *J. Soil Sci. Plant Nutr.* **2022**, *22*, 5217–5230. [CrossRef]
2. Saudy, H.S.; El–Metwally, I.M. Effect of Irrigation, Nitrogen Sources, and Metribuzin on Performance of Maize and Its Weeds. *Commun. Soil Sci. Plant Anal.* **2022**, *54*, 22–35. [CrossRef]
3. Ojelade, B.S.; Durowoju, O.S.; Adesoye, P.O.; Gibb, S.W.; Ekosse, G.-I. Review of Glyphosate-Based Herbicide and Aminomethylphosphonic Acid (AMPA): Environmental and Health Impacts. *Environ. Health Impacts. Appl. Sci.* **2022**, *12*, 8789. [CrossRef]

4. Baev, V.I.; Yudaev, I.V. Efficiency estimation of type of the electrical exposure on plants at their processing. *AD ALTA J. Interdiscip. Res.* **2018**, *8*, 252–257.
5. Baev, V.I.; Yudaev, I.V.; Petrukhin, V.A.; Baev, I.V.; Prokofyev, P.V.; Armianov, N.K. Electrotechnology as one of the most advanced branches in the agricultural production development. In *Handbook of Research on Renewable Energy and Electric Resources for Sustainable Rural Development*; Kharchenko, V., Vasant, P., Eds.; IGI Global: Hershey, PA, USA, 2018; pp. 283–310.
6. Vincent, C.; Panneton, B.; Fleurat-Lessard, F. *Electrical Weed Control: Theory and Applications, in Physical Control Methods in Plant Protection*; Springer: Berlin/Heidelberg, Germany, 2001; 321p.
7. Sahin, H.; Yalinkilic, M. Using Electric Current as a Weed Control Method. *Eur. J. Eng. Res. Sci.* **2017**, *2*, 59–64. [CrossRef]
8. Stankovic, M.V.; Cvijanovic, M.; Dukic, V. Ecological importance of electrical devices innovative in the process of anti *Ambrosia artemisiifolia* L. *Econ. Agric.* **2016**, *3*, 861–870. [CrossRef]
9. Angersbach, A.; Heinz, V.; Knorr, D. Electrophysiological model of intact and processed plant tissues: Cell disintegration criteria. *Biotechnol. Prog.* **1999**, *15*, 753–762. [CrossRef]
10. Asavasanti, S.; Ristenpart, W.; Stroeve, P.; Barrett, D.M. Permeabilization of plant tissues by monopolar pulsed electric fields: Effect of frequency. *J. Food Sci.* **2011**, *76*, 98–111. [CrossRef] [PubMed]
11. Knorr, D.; Angersbach, A. Impact of High Electric Field Pulses on Plant Membrane Permeabilization. *Trends Food Sci. Technol.* **1998**, *9*, 185–191. [CrossRef]
12. Asavasanti, S.; Ersus, S.; Ristenpart, W.; Stroeve, P.; Barrett, D.M. Critical electric field strengths of onion tissues treated by Pulsed electric fields. *J. Food Sci.* **2010**, *75*, 433–443. [CrossRef]
13. Lebovka, N.I.; Bazhal, M.I.; Vorobiev, E.I. Estimation of characteristic damage time of food materials in pulsed-electric fields. *J. Food Eng.* **2002**, *54*, 337–346. [CrossRef]
14. Mohamed, M.E.; Eissa, A.H.A. Pulsed Electric Fields for Food Processing Technology. In *Structure and Function of Food Engineering*; IntechOpen: London, UK, 2012; pp. 275–306.
15. Bajgai, T.R.; Hashinaga, F. High electric field drying of Japanese radish. *Dry. Technol.* **2001**, *19*, 2291–2302. [CrossRef]
16. Barba, F.J.; Parniakov, O.; Pereira, S.A.; Wiktor, A.; Grimi, N.; Boussetta, N.; Saraiva, J.A.; Raso, J.; Martin-Belloso, O.; Witrowa-Rajchert, D.; et al. Current applications and new opportunities for the use of pulsed electric fields in food science and industry. *Food Res. Int.* **2015**, *77*, 773–798. [CrossRef]
17. Picart, L.; Cheftel, J.C. Pulsed electric fields. In *Food Preservation Techniques*; Zeuthen, P., Bogh-Sorensen, L., Eds.; CRC Press: Boca Raton, FL, USA, 2003; pp. 57–68.
18. Visockis, M.; Bobinaitė, R.; Ruzgys, P.; Barakauskas, J.; Markevičius, V.; Viškelis, P.; Šatkauskas, S. Assessment of plant tissue disintegration degree and its related implications in the pulsed electric field (PEF)—Assisted aqueous extraction of betalains from the fresh red beetroot. *Innov. Food Sci. Emerg. Technol.* **2021**, *73*, 1–10. [CrossRef]
19. Zderic, A.; Zondervan, E.; Meuldijk, J. Breakage of Cellular Tissue by Pulsed Electric Field: Extraction of Polyphenols from Fresh Tea Leaves. *Chem. Eng. Trans.* **2013**, *32*, 1795–1800.
20. Wiktor, A.; Sledz, M.; Nowacka, M.; Rybak, K.; Chudoba, T.; Lojkowski, W.; Witrowa-Rajchert, D. The impact of pulsed electric field treatment on selected bioactive compound content and color of plant tissue. *Innov. Food Sci. Emerg. Technol.* **2015**, *30*, 69–78. [CrossRef]
21. Barbosa-Canovas, G.V.; Zhang, H.Q. (Eds.) *Pulsed Electric Fields in Food Processing: Fundamental Aspects and Applications*; CRC Press: Boca Raton, FL, USA, 2019; 289p.
22. Yudaev, I.; Kokurin, R.; Daus, Y.; Ivanov, D. Automatizing process of electropulse treatment of plant raw materials. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *996*, 012022. [CrossRef]
23. Mañas, P.; Barsotti, L.; Cheftel, J.C. Microbial inactivation by pulsed electric fields in a batch treatment chamber: Effects of some electrical parameters and food constituents. *Innov. Food Sci. Emerg. Technol.* **2000**, *2*, 239–249. [CrossRef]
24. Yudaev, I.V.; Daus, Y.V.; Kokurin, R.G. Substantiation of criteria and methods for estimating efficiency of the electric pulse process of plant material. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *488*, 012055. [CrossRef]
25. Lebovka, N.I.; Praporscic, I.; Vorobiev, E.I. Enhanced expression of juice from soft vegetable tissues by pulsed electric fields: Consolidation stages analysis. *J. Food Eng.* **2003**, *59*, 309–317. [CrossRef]
26. Lebovka, N.I.; Shynkaryk, N.V.; Vorobiev, E. Pulsed electric field enhanced drying of potato tissue. *J. Food Eng.* **2007**, *78*, 606–613. [CrossRef]
27. De Vito, F.; Ferrari, G.; Lebovka, N.I.; Shynkaryk, N.V.; Vorobiev, E. Pulse duration and efficiency of soft cellular tissue disintegration by pulsed electric fields. *Food Bioprocess Technol* **2008**, *1*, 307–313. [CrossRef]
28. Raso, J.; Heinz, V.; Alvarez, I.; Toepfl, S. *Pulsed Electric Fields Technology for the Food Industry: Fundamentals and Applications*; Springer: Berlin/Heidelberg, Germany, 2021; 561p.
29. Vorobiev, E.; Lebovka, N. Pulsed-electric fields induced effects in plan tissues: Fundamental aspects and perspectives of applications. In *Electrotechnologies for Extraction from Food Plants and Biomaterials*; Springer: New York, NY, USA, 2009; pp. 39–81.
30. Yudaev, I.V.; Baev, V.I.; Brenina, T.P.; Eliseev, D.S. *Sornyerasteniyakakob"ektelektricheskoipropolki: Biologicheskieosobennosti i elektrofizicheskiesvoistva (Weeds as an Object of Electric Weeding: Biological Features and Electro-Physical Properties)*; Stanitsa-2: Volgograd, Russia, 2004.
31. Yudaev, I.V. Analysis of variation in circuit parameters for substitution of weed plant tissue under electric pulse action. *Surf. Eng. Appl. Electrochem.* **2019**, *55*, 219–224. [CrossRef]

32. Yudaev, I.; Daus, Y.; Kokurin, R.; Prokofyev, P.; Gamaga, V.; Armianov, N. Electrotechnology as one of the most advanced branches in the agricultural production development. In *Advanced Agro-Engineering Technologies for Rural Business Development*; Kharchenko, V., Vasant, P., Eds.; IGI Global: Hershey, PA, USA, 2019; pp. 396–430.
33. Bauer, M.V.; Marx, C.; Bauer, F.V.; Flury, D.M.; Ripken, T.; Streit, B. Thermal weed control technologies for conservation agriculture—A review. *Weed Res.* **2020**, *60*, 241–250. [CrossRef]
34. Hill, K.; Ostermeier, R.; Töpfl, S.; Heinz, V. Pulsed Electric Fields in the Potato Industry. In *Pulsed Electric Fields Technology for the Food Industry*; Raso, J., Heinz, V., Alvarez, I., Toepfl, S., Eds.; Food Engineering Series; Springer: Cham, Switzerland, 2022.