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Theoretical foundations of electropulse impact on plant objects

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Abstract. This article considers the theoretical foundations of the electropulse effect on plant objects. The influence of the energy absorbed by a living system on the degree of damage to plant cells and tissues is studied. It has been established that the impact of many damaging factors accompanying a high-voltage electrical impulse determines the degree of damage to plant tissue. The authors propose to consider the process of electrical processing from the standpoint of the law of conservation of energy and accept the initial conditions that describe the properties of a plant object. However, the research results do not allow theoretically assessing the dependence of the coefficients included in the formulas on all the parameters that determine their values.

1. Introduction

A large number of works by scientists of various specialties are devoted to the study of the properties of living cells and tissues [1, 2, 3, 4, 7, 21]. However, the mechanism of functioning of both the cell itself and living tissue as a whole, as well as the mechanism of the influence of electrophysical factors on them, has not yet been fully disclosed. Recently, applied works have been greatly developed, using the positive effect of the action of electric current and electric discharges on plant tissue.

For rational application, quantitative and qualitative assessment of the electrical impact on living plant tissue, it is necessary to know its main acting factors. There is no consensus among researchers on this issue. The nature of the processes occurring in cells and tissues depends on the magnitude and type of electric current (constant, alternating, pulsed), the magnitude of the electric field, the duration of exposure, structural features of individual cells and tissues, and other reasons.

It has been established that there are electrical charges on colloids and protein particles that determine the electrical properties of living cells of plant tissue and are the driving forces of metabolic processes

[5, 6, 8]. For example, the protoplast of a cell has a negative charge. The impact of an electric current of a certain magnitude on a cell suppresses its electric field and thereby disrupts vital activity. The cell protein becomes electrically neutral (isoelectric point), which leads to the aggregation of protein particles of protoplasm and their coagulation. That is, under the influence of direct or alternating electric current, the structure of plasma shells changes, which increases their permeability and reduces electrical resistivity [9, 10, 11].

Studies by many authors [1, 2, 15, 18] have shown that the bulk conduction current is the main acting factor in electrospark processing of plant tissue. Depending on the magnitude of the electric current passing through the living plant tissue, which is determined by the magnitude of the voltage gradient, and the time of its action, electroplasmolysis can proceed either with a predominance of thermal phenomena, or with a predominance of electrokinetic phenomena.

But according to a number of researchers [12, 13, 14, 15, 16], the destruction of cells under electropulse action occurs mainly under the action of hydrodynamic forces resulting from the microhydraulic effect in the cell or intercellular space. Moreover, the degree of destruction of cells depends on their size, turgor pressure and thickness of the membranes.

It has been established that the degree of damage to plant tissue does not depend on the shape of the acting voltage pulse and is directly proportional to the capacitance of the storage capacitor and the discharge voltage, that is, it depends on the factors that determine the energy of the pulse [17, 18]. The efficiency of electropulse processing increases with an increase in the total energy of the pulses and with an increase in their voltage. Moreover, the influence of voltage is much stronger than the energy of pulses /6/. This is explained by the specific effect of electrical impulses on living tissue cells, which consists in the direct interaction of the electric field with the electrically charged system of protoplasm, leading to electrical interaction and force deformation.

Exposure of plant tissue to high voltage pulses is also accompanied by high temperature, visible and ultraviolet radiation, high electric and magnetic fields, high electric current density, ultrasound, pressure at the shock wave front, and ionization processes [19, 20]. The predominance of one or another factor depends on the parameters of the electrical impulse, the properties of the plant tissue and is of a random probabilistic nature.

It is known that cell damage is largely independent of the nature of the influencing factor and is determined only by its intensity. That is, the result of the impact on a living system is determined by the amount of energy absorbed by this system. It has been established that the effect of successive stimulations by small portions of energy absorbed by biological objects and leading to the destruction of membranes is summed up [21].

Thus, the degree of damage to plant tissue during electrical impulse exposure is determined by the sum of the effects of many damaging factors that accompany a high-voltage electrical impulse. It is not possible to isolate the effect of the impact of each individual factor, since the process is of a random probabilistic nature. As an integral factor that determines the degree of damage to plant tissue by high-voltage electrical impulses, the value of the energy of a single discharge can be taken.

2. Materials and methods

This article does not contain research methods, it describes the theoretical foundations of the electropulse effect on plant objects and discusses possible relationships between the parameters of this effect and the degree of damage to plant tissue.

To obtain the dependence of the degree of damage to a living plant object by high-voltage electrical impulses, taking into account the initial state of the object, we consider the process of electrical processing from the standpoint of the law of conservation of energy.

We accept the following initial conditions:

1. A plant object consists of a finite number of cells that have the same properties, size and structure.
2. Plant tissue is homogeneous and isotropic.
3. Cell damage occurs instantly.

4. All energy supplied to the object passes through the tissue.

Since the object is exposed to pulses, the factor that integrally determines the duration of exposure is the number of pulses n.

3. Results and discussion

The energy balance equation for the exposure duration dn has the form:

$$dE_1 = dE_2 + dE_3 \tag{1}$$

where E_1 – energy eaten up to the object in dn pulses, J;
E_2 – energy absorbed by tissue cells, J;
E_3 – energy that has passed through the tissue, but not absorbed by the cells, J.
The components of the energy balance (1) are determined by the following expressions:

$$dE_1 = E_i dn, \tag{2}$$

where E_i - energy of one impulse, J;

$$dE_2 = PdN_d \tag{3}$$

where P - the energy required to destroy one cell, J;
dN_d - change in the number of dead cells per dn pulses;

$$dE_3 = \varphi E_i dn \tag{4}$$

where φ - dimensionless coefficient that determines the fraction of the energy not absorbed by the cells of the object from the value of the imparted energy per dn pulses.

Plant tissue cells absorb only the energy that passes through them. The energy that has passed through the intercellular space or through the vacuolar juice of destroyed cells, by which undamaged cells are shunted, is not absorbed by them and does not destroy them. That is, the amount of unabsorbed energy depends on the structural features of the tissue and cells and the number of damaged cells. Then one can write

$$\varphi = \alpha\left(N_d - N_{dp}\right) \tag{5}$$

where α - a dimensionless coefficient showing by what part of $E_i dn$ the unabsorbed energy increases during the destruction of one cell (depends on the structural features of the tissue, cells and characteristics of the electrical impulse);
N_{dp} - the number of affected tissue cells before the start of its electrical pulse processing;
N_d - the number of affected tissue cells after exposure to dn pulses.
Equation (1) can be represented as:

$$E_i dn = PdN_d + \alpha\left(N_d - N_{dp}\right)E_i dn \tag{6}$$

or

$$\frac{P}{\alpha E_i} \cdot \frac{dN}{dn} + N_d - \alpha\left(N_{dp} + \frac{1}{\alpha}\right) = 0 \tag{7}$$

Let us denote

$$K = \frac{P}{\alpha}, \tag{8}$$

$$N_{d\max} = N_{dp} + \frac{1}{\alpha} \tag{9}$$

where K - duration constant of the energy impact, J (numerically equal to the energy required to destroy all the cells of the object, provided that all the energy communicated to the object is absorbed by the cells);

$N_{d\max}$ - the number of affected cells of dead plant tissue, that is, the number of cells that make up the object of treatment.

Then equation (7) can be written as

$$\frac{K}{E_i} \cdot \frac{dN_d}{dn} + N_d - N_{d\max} = 0, \tag{10}$$

The solution to this first order differential equation is

$$N_d = N_{dp} \exp\left(-\frac{E_i n}{K}\right) + N_{d\max}\left(1 - \exp\left(-\frac{E_i n}{K}\right)\right). \tag{11}$$

Dividing all the terms of equation (11) by the number of cells that make up the plant tissue of the processing object N, we obtain

$$\frac{N_d}{N} = \frac{N_{dp}}{N} \exp\left(-\frac{E_i n}{K}\right) + \frac{N_{d\max}}{N}\left(1 - \exp\left(-\frac{E_i n}{K}\right)\right) \tag{12}$$

The ratio of the number of damaged N_d cells to the total number of tissue cells N represents the degree of damage to the plant tissue, i.e. the values $\frac{N_{dp}}{N}$, $\frac{N_{d\max}}{N}$, $\frac{N_d}{N}$ express, respectively, the initial S_0, the prolongation S_{max}, and the current S degree of damage to plant tissue, expressed in relative units.

Equation (12) can be written

$$S = S_0 \exp\left(-\frac{E_i n}{K}\right) + S_{\max}\left(1 - \exp\left(-\frac{E_i n}{K}\right)\right) \tag{13}$$

The characteristic of the processing object in equation (13) is the parameter K, expressed by dependence (8) and in the general case depending on the structural features of the plant tissue and cells, as well as on the parameters of the acting electrical impulses.

After each electrical impulse, the state of the object changes qualitatively, that is, the value of α must change (increase). Then the value of the parameter K in the process of electropulse processing also changes (decreases), since the value of P remains constant.

Experimental and theoretical studies have established that the value of K depends on the parameters of the electric pulse processing. For example, for grape varieties "Tyfi pink" the regression equation describing this relationship is:

$$K = 25{,}996 - 12{,}904U - 31{,}64C - 0{,}843n + 1{,}259U^2 + 42{,}887C^2 + \\ + 0{,}037n^2 - 1{,}765UC - 0{,}074Un - 1{,}059Cn$$

The results of numerous studies by various authors who have studied certain aspects of the action of electric current and electric discharges on living plant organisms do not make it possible to theoretically evaluate and obtain the dependences of the coefficients included in formulas (5), (8) and (13) on all parameters that determine their values. For this, it is necessary to conduct complex special studies with the wide involvement of scientists from many specialties.

4. Conclusions

Damage to plant tissue during electropulse exposure depends on the intensity of exposure, which is determined by the amount of energy absorbed by the system.

The degree of damage to plant tissue during electrical impulse exposure is determined by the sum of the effects of many damaging factors that accompany a high voltage electrical impulse.

Based on the law of conservation of energy, it is possible to obtain the dependence of the degree of damage to a living plant object by high-voltage electrical impulses, taking into account the initial state of the object.

The dependence (13) obtained theoretically, which describes the process of electropulse processing of plant tissue, agrees quite accurately with the results of experimental studies.

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