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Long-Term Strength Prediction of Wood Based Composites Using the Kinetic Equations

Sergiy Kulman[1*], Liudmyla Boiko[1], Ján Sedliačik[2]

[1]Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine

[2]Technical University in Zvolen
960 53, 24 T.G. Masaryka Str., Zvolen, Slovakia

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Abstract. The existing behaviour models of the structures under constant load (creep) have a fairly wide forecast horizon and low accuracy. As a rule, they consider the transition from an undestroyed state of an element to a destroyed one, in one stage. The purpose of this study is to substantiate and develop a new approach to predicting long-term strength based on kinetic equations, which, in turn, should consider the multistage nature of the process of gradual destruction of structure elements. To achieve this purpose, the study solves the tasks of creating a multistage kinetic transition of individual structure elements from an initially elastic state to a viscoelastic state, and then to a fractured state. When describing this process, the authors employed the methods of formal kinetics and the theory of continuum damage mechanics, including the method of basic diagrams. Wood-based composites were used as the materials under study. Based on the results of the conducted full-scale and computational experiments, the study discovers that a mathematical model based on kinetic equations adequately describes the behaviour of the materials under study for long-term strength; the proposed two-stage model determines the forecast horizon much more accurately than the available one-stage models. The kinetic parameters that determine the rate of transition of a structural element from an elastic state to a viscoelastic state, and then to a destroyed state, were determined based on experimental base chart. The time to fracture was determined at three-point bending at a load equal to 70% of the flexural strength at temperatures of 20°C and 60°C, constant humidity RH 65% and moisture content MC 8%. When building control charts, the load increased by another 15%. The method allows narrowing the forecast horizon and determining the moment of transition of a structure from a stationary state to a blow-up regime with a higher accuracy

Keywords: models of fracture kinetics, fracture criteria, multistage fracture, creep, long-term strength

*Corresponding author

INTRODUCTION

Fracture simulation of structured materials is critical for technical applications. This includes issues not only of the short-term strength of composite materials, but also of their long-term strength and creep. The theory of damage gives a phenomenological description of the evolution of scattered defects, pores, and microcracks, the number of which in any elementary volume is assumed to be extremely large. Initially, the concept of damage was associated with the proportion of voids appearing in the body section under the action of intense loads [1; 2]. In case of a multidimensional stress-strain state, this visual interpretation of damage encounters difficulties associated with the need to determine the fraction of voids in sections of a material element with different orientations of the normal. The study proposes various definitions of material damage, which are tensor quantities obtained by averaging the parameters of the microstructure [3]. However, the interpretation of damage based on microstructural concepts appears to be unnecessary.

Admittedly, at the phenomenological level, the presence of micropores and microcracks leads to two main effects: degradation of elastic moduli and residual deformations. In addition, in applied problems, as a rule, the issue of the preferred orientation of microdefects is not acute. This fact is conditioned upon the structure of the material, which is often known in advance. For example, a beam made of wood (this also applies to other composites) is predominantly destroyed by splitting along the fibres (delamination of the fibre from the binder matrix). In addition, the presence of planes of weakening (healed or open cracks and faults), which are oriented in a special way, considerably affects the result of technogenic impact on the wood-based composites (WBC).

The studies [4-6] discuss a model of an isotropic damaged body, wherein a scalar damage parameter is used, which is closely related to the energy spent on the appearance of new surfaces during cracking. At this stage, a model of the initially damaged isotropic material with strength anisotropy is constructed using the scalar damage parameter, which is considered to be related to the surface energy of microdefects. The type of anisotropy that a material acquires is determined by its structure. In this case, a medium composed of identical plane-parallel layers is considered to be "glued" to each other. The interlayer tensile and shear strength is considered lower than the strength of the material, which the layers themselves are composed of, thereby dictating the predominant orientation of microdamage. In this case, there is no need to introduce a tensor measurement of deformation, and the scalar measurement of damage becomes possible, while in the anisotropic case, the measurement can be interpreted in terms of the irreversible energy consumption for the appearance of new surfaces.

One of the first theories of strength was formulated by Griffith [7]. According to this theory, strength is defined as the stress under which the condition of equality of two energies is fulfilled: the energy expended on the formation of a new surface of a growing crack, and the elastic energy released during a crack growth. According to this theory, destruction is interpreted as a critical event, which follows a critical tension.

This interpretation is not confirmed by experience, because it is known that the accumulation of molecular and supramolecular defects occurs long before the moment of destruction. Therefore, destruction develops over time and does not constitute a critical event. The introduction of a temporary scale of the fracture process led to the creation of a kinetic theory of strength. Temporal dependencies were proposed by A. Aleksandrov [8] upon describing the relaxation properties of viscoelastic deformation of solids in the form of generalised Maxwell equations. The clearest physical interpretation and development of these ideas was provided by Professor S.M. Zhurkov, who is the founder of the kinetic theory of strength [9]. This theory considers destruction as a temporary accumulation of molecular and supramolecular defects. The durability of stressed bodies is defined as a fundamental parameter of strength and reflects the average rate of destruction at all structural levels: molecular, supramolecular, and macroscopic.

A fundamental form of kinetic strength theory is the Zhurkov equation. Moreover, the Zhurkov equation, which is created to describe the mechanism of destruction at the molecular level, is automatically transferred to describe the mechanism of destruction of meso- and macro-levels, and does not take into account the way the relaxation processes occur at these levels. In addition, this equation assumes that the process passes within one stage. In particular, the connections between the elements are considered to be either not destroyed, and are under the action of thermo-force load or destroyed after a time determined by the Zhurkov formula.

The purpose of this study is to substantiate and develop a new approach to predicting long-term strength based on kinetic equations, which, in turn, should consider the multistage nature of gradual destruction of structure elements. To achieve this purpose, the study solves the tasks of creating a multistage kinetic transition of individual structure elements from an initially elastic state to a viscoelastic state, and then to a fractured state.

THEORETICAL OVERVIEW

To create a kinetic model of the relaxation behaviour of a polymer under the action of thermomechanical action, several different states of its individual structure element (SE) are to be considered. Individual elements of a structure are understood as local body volumes, whose local stresses differ. For a crystalline polymer

under load, these can be both crystalline and amorphous regions [10].

The initial (input) state of a structure element is a state wherein no external mechanical effect occurs. In this case, all the individual structure elements of the target are in thermodynamic equilibrium. Elastic steady state (E) of a structure element is a structure element that has been in an elastic state for a certain time. The viscoelastic steady state of a structure element (VE) is a structure element in a viscoelastic state, i.e., a state of relaxation of internal stresses. Destructed steady state of a structural element (D) is a destroyed structural element formed from a viscoelastic one, whose stresses at the time of destruction are redistributed between those structure elements that are in elastic and viscoelastic states at that moment [11; 12].

The authors consider a solid not in the form of an uninterrupted continuum, but in the form of a solid structure, comprising separate supporting structure elements, interconnected in a particular way. Then, due to internal heterogeneity, the action of external loading on the surface of the body causes its internal structure elements to experience internal stresses of various magnitude and vectors [13; 14]. Structure elements with stresses greater than the tensile strength will be immediately destroyed. After their destruction, external forces will be redistributed between the remaining undamaged structure elements so that each of them bears a new load on the part of neighbouring SE [15; 16]. The behaviour of polymers over time is usually described in the form of combinations of primary rheological bodies, such as the elastic body of Hook, the viscous body of Newton, or combinations thereof (Maxwell or Voigt bodies).

By combining these primary rheological bodies, one can create a certain rheological model, the behaviour of which in time (kinetics) would accurately describe the behaviour of the real body under the influence of external loads. It is generally recognised that during a period of constant creep, a solid body, under the action of external temperature-force loading, behaves as if it were consistently in an elastic, viscoelastic, or plastic state. Therewith, it is assumed that the total deformation of the body, as a rule, comprises three different parts: instantaneously reversible (elastic), highly elastic, reversible in time, i.e., relaxing in time (viscoelastic), and irreversible (plastic) [17; 18]. In this case, total deformation is understood as the total deformation of the entire body, and not of its individual parts or structure elements.

The main hypothesis of the deformation is formulated as follows: firstly, the body is deformed and destroyed into separate structure elements. In particular, only into those elements where the local stress first reaches the limits of proportionality, and then the limits of strength. In this case, the individual structure element is first elastically deformed, and then passes in series into a viscoelastic or plastic state, and then collapses. Secondly, a single destroyed structure element is surrounded for a certain time by non-destructive structure elements that are in an elastic or viscoelastic state. Thirdly, the body is considered destroyed if the number of destroyed structure elements exceeds certain predefined values.

Thus, the destruction kinetics of the body under the action of thermomechanical loading will comprise different variants of the transition sequence of the elastic structure elements (*E*) into the viscoelastic structure elements (*VE*), and then in the destroyed structure elements (*D*):

$$E \rightarrow VE \rightarrow D \qquad (1)$$

Thus, in the process of destruction, the number and, consequently, the concentration of structure elements in different rheological states are constantly changing. The concentration of changes of a particular structure element can be determined experimentally by measuring values that correlate with the fracture parameters of a particular type of body deformation.

In this case, according to the law of conservation of masses, the total number of structure elements in different states must remain constant at each moment. Consideration of the fracture process from the standpoint of combining cracks, for example, smaller ones into larger ones, does not change the number of structure elements, but only examines them in different states.

Mathematical model of deformation-destruction process. The main variables describing the state of the system, determine the substances Ai, that is in different rheological states. The number SE in different states shall be denoted as N_i; n is the vector of quantities components. The concentration is denoted as follows: $C_i \equiv N_i/V$. Each stage of the system is matched by its speed $W_s(C, T)$. The velocity of the stage is intense and is defined as a function of intense quantities – concentration and temperature.

The kinetics equations have the following in coordinate form:

$$\frac{dN_i}{dt} = V\sum_s \gamma_{si} W_s\left(C,T\right), \quad i = 1,\ldots,n \qquad (2)$$

Where γ_{si} is the stoichiometric vector with components $\gamma_{si}=\alpha_{si}-\beta_{si}$; s is the stage; are the non-negative integers and stoichiometric coefficients. In the absence of autocatalysis, as in this case, this vector completely determines the stoichiometric equations of the stage.

For each material, there are a priori restrictions on vectors linear conservation laws (balance ratios). If N_{si} is the number of structure elements that are in a certain rheological state and k is a species in the molar volume of a substance A_i, then for any s and k:

$$\sum_i \alpha_{si} N_{ki} = \sum_i \beta_{si} N_{ki} \quad \text{or} \quad \sum_i \gamma_{si} N_{ki} = 0 \qquad (3)$$

The balance relations (2) give rise to linear conservation laws for system (1), that is, for any k: $\sum_i \alpha_{ki} N_i = const$,

which means:

$$\frac{d}{dt}\sum_i \alpha_{ki} N_i = V \sum_{s,i} \alpha_{si}\gamma_{ki} W_s = 0 \quad (4)$$

Then the following kinetic model of the DD process will correspond to the transformation scheme (1):

$$\frac{dCA(t)}{dt} = -k_1 CA(t) \quad (5)$$

$$\frac{dCB(t)}{dt} = k_1 CA(t) - k_2 CB(t) \quad (6)$$

$$\frac{dCC(t)}{dt} = k_2 CB(t) \quad (7)$$

with initial conditions t=0; $CA(0)$=1; $CB(0)$=$CC(0)$=0, and boundary conditions $CA(t)$+$CB(t)$+$CC(t)$=1, where $CA(t)\in(1...0)$ is the current concentration of structure elements that are in an undamaged, elastic state at time t; $CB(t)\in(0...1)$ is the current concentration of structure elements that are in a non-destructive, i.e., viscoelastic state at time t; $CC(t)\in(0...1)$ is the current concentration of the structure elements that are in a destroyed state at time t; is the rate constant of the transition of structure elements from elastic state to viscoelastic, s^{-1}; k^2 is the rate constant of the transition of the structure elements from the viscoelastic state to the destroyed, s^{-1} [19].

MATERIALS AND METHODS

Materials. For the present study, Kronospan UA Ltd. provided three commercially produced structural particleboards bonded with urea formaldehyde resin (UF): melamine faced particleboard (MF PB) according to EN 14322; veneered by oak particleboard (VF PB) according to EN 316, EN 622-5, and particleboard P2 (P2 PB) according to EN 312, type P2; EN 13501-1: class D-s1, d0. For each type, two regular-size (2750 mm × 1830 mm) boards with thicknesses of 18 mm were cut into 450 mm (length) × 50 mm (width) pieces. Before cutting, boards were stored in a conditioning room maintained at 20°C and 65% RH. Static 3-point bending tests were performed in the special test machine with temperature-controlled chamber. Specimens were prepared and cut according to ASTM D 1037-99. Loading and deflection were measured, and MOR and MOE were calculated according to Section 9 in ASTM D 1037-99 [19]. The temperatures analysed were 20°C and 60°C.

Specimens were preheated in the chamber until they reached equilibrium with the target temperature. The preheating times were determined from preliminary experiments by an embedded thermocouple, and the prediction model was developed in a previous study [20]. Table 1 presents the results of tests performed on the samples to establish their mechanical properties in the chamber at the target temperature. 150 specimens were cut from each type of board. 10 specimens were prepared for testing modulus of elasticity (MOE) and rupture (MOR) before main testing. All specimens were conditioned at 20°C and 65% RH prior to use. The average densities of specimens were 757 kg/m^3, 792 kg/m^3, and 733 kg/m^3, respectively, in an air-dried condition moisture content of about 5%.

Table 1. *Properties of particleboard used in study*

Board type	Density[d], kg/m^3	Number of samples	Thickness[d], mm	MOR[d], MPa	MOE[d], MPa
MF PB[a]	757±7	10	18.1±0.1	17.1±1.1	2 110±29
VF PB[b]	792±8	10	18.5±0.1	20.5±1.9	2 520±15
P2 PB[c]	733±6	10	18.1±0.1	16.2±0.6	2 020±22

Notes: *[a]MF PB – Melamine Faced Particleboard; [b]VF PB – Veneered Faced Particleboard; [c]P2 PB – Particleboard according to EN 312, type P2; [d] Thickness, density, MOR and MOE was measured after specimens reached equilibrium at 65% RH, temperature 20°C and moisture content 5%*

Tests were performed according to the scheme of three-point bending per ASTM D 1037-99 loads equal to 75% of the maximum allowable. The nature of the behaviour of the system under the action of constant load was described by the movement of the midpoint in time until rupture.

Methods. Considering the curve of long load, it can be established that its initial section contains structure elements only in the elastic state, which return to the undeformed state after the load is removed. During this period of elastic deformation, there is no transition of structure elements to a viscoelastic state. Therefore, the beginning of the kinetics of the DD is taken to be the end time of the elastic deformation and the beginning of the site of viscoelastic deformation, i.e., the time of the beginning of the process first unsteady and then steady creep. Throughout the process of creep, there is a decrease in the number of non-destructive structure elements, i.e., those in elastic or viscoelastic states and an increase in structure elements in the destroyed state.

To describe the kinetics of deformation, it is possible to compare the change in the concentration of SE in the elastic state and the destroyed state with the change in the magnitude of the deformation over time. In this case, the rate of change of the concentration over time of elastic SE will be proportional to the change in the rate of deformation due to the transition of elastic SE in viscoelastic, and the decrease in the concentration

of elastic SE will be proportional to the increase in the absolute deformation of the DD process, that is, $CA(t) \propto \varepsilon(t)$.

Since the change in the SE concentrations in a certain state can be given as a first-order kinetic dependence [21], the following equation can be written:

$$\frac{dCA(t)}{dt} = -k_1 \cdot CA(t)$$

$$\frac{d\varepsilon_e(t)}{\varepsilon_e(t)} = -k_1 t, \int_{\varepsilon_1}^{\varepsilon_2} \frac{d\varepsilon_e(t)}{\varepsilon_e(t)} = -\int_{t_1}^{t_2} k_1 dt, \quad \ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right) = -k_1(t_2 - t_1), \quad k_1 = -\frac{1}{(t_2 - t_1)} \ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right) \tag{9}$$

Evidently, when the deformation changes ε_1 and ε_2 the same number of times, the value k_1 does not change. This allows creating a kinetic model of deformation-destruction to replace concentrations proportional to their values – deformations, stresses, acoustic, or electromagnetic emission pulses, quantities of matter, etc. [19].

The magnitude inverse of the first order reaction rate constant, $\tau_e = 1/k_1$, is a temporal measurement describing the average life expectancy of SE that are in an elastic state before their transition to a viscoelastic state. Similarly, the inverse of the rate constant of the transition of the viscoelastic state of the SE to the destroyed determines the average life expectancy of the structure elements in the viscoelastic state: $\tau_{ve} = 1/k_2$.

Since time is included in Eq. (9) as a difference rather than a relation to a deformation, a dimensionless time is introduced to eliminate the dimension factor: $\tau_i = t_i/t_{cr}$. Therewith, total creep deformation can be represented as the sum of total elastic and viscoelastic deformations, i.e., deformations due to the destruction of elastic and viscoelastic SE:

$$\varepsilon_e + \varepsilon_{ve} = \varepsilon_{cr} \tag{10}$$

$$t_e + t_{ve} = t_{cr} \tag{11}$$

Because according to Eqs (8), (10):

$$\frac{1}{k_1}\dot{\varepsilon}_e + \frac{1}{k_2}\dot{\varepsilon}_{ve} = \varepsilon_{cr},$$

then

$$\frac{1}{k_1} + \frac{1}{k_2} = \frac{\sum_{t_1}^{t_{cr}} t_{e_i} + \sum_{t_1}^{t_{cr}} t_{ve_i}}{t_{cr}} = 1 \tag{12}$$

The expression for k_2 is obtained by solving the system of two Eqs (13), (16) as follows:

$$k_2 = \frac{ln\left(\frac{\varepsilon_2}{\varepsilon_1}\right)}{t_1 - t_2 - t_{cr} * ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right)} \tag{13}$$

The solution of the system of differential equations (5), (6), (7), for example, by the operating method, allows obtaining the values of current concentrations of SE, which are in elastic, viscoelastic, and destroyed states:

or, having undergone a proportional deformation:

$$\frac{d\varepsilon_e(t)}{dt} = -k_1 \cdot \varepsilon_e(t) \tag{8}$$

The equation (12) is integrated after the separation of variables (time, deformation) (9):

$$CA(t) = CA(0)e^{-k_1 t} \tag{14}$$

$$CB(t) = CA(0)\left(\frac{k_1}{k_1 - k_2}e^{-k_2 t} - \frac{k_1}{k_1 - k_2}e^{-k_1 t}\right) \tag{15}$$

$$CC(t) = CA(0)\left(1 - \frac{k_1}{k_1 - k_2}e^{-k_2 t} + \frac{k_2}{k_1 - k_2}e^{-k_1 t}\right) \tag{16}$$

Moreover, given the initial conditions $t=0$; $CA(0)=1$; $CB(0)=CC(0)=0$, and boundary conditions $t \in (0...1)$: $CA(t)+CB(t)+CC(t)=1$ in the coordinates of dimensionless time, one can obtain as follows:

$$\int_0^1 CA(t)dt + \int_0^1 CB(t)dt + \int_0^1 CC(t)dt = 1 \tag{17}$$

therefore, $k_1^{-1}+k_2^{-1} = 1$. Thus, in real time coordinates $k_1^{-1}+k_2^{-1}=t_{cr}$.

The method involves determining the damage characteristics and predicting the time of reaching the critical mark of the measure of damage. While as a scalar value ψ is a preventive comparison of the degree of damage equal to the ratio of the current concentration of destroyed structure elements to the current concentration of non-destructive structure elements. The resource is considered to be exhaustive value describing the extent of damage exceeding [22]:

$$\psi = \frac{CC(t)}{CA(t) + CB(t)} \geq \psi_f = 1 \tag{18}$$

where ψ_{fis} the measure of permissible damage; $CA(t)$, $CB(t)$, $CC(t)$ are determined by formulas (14), (15), (16), respectively; $k_1 = \frac{1}{t_1 - t_2}\ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right)$ is the rate constant of transition of structure elements from elastic state to viscoelastic creep diagram, s^{-1}; t_1 is the time of the end of the section of elastic deformation and the beginning of the section of viscoelastic deformation, s; t_2 is the time of measurement of deformation at the site of constant creep; ε_1 is the deformation at time t_1; ε_2 is the deformation at time t_2; $k_2 = \alpha^{-1} k_1$ is the rate constant of the transition of the structure elements from the viscoelastic state to the destroyed, s^{-1}; α is the parameter describing the rheological properties (features) of the material, the degree of its inelasticity.

In this case, the rate constants of the transition of local structure elements from one state to another, depending on the load and temperature, are determined according to the long-term strength chart, which establishes the dependence of the change in the rate of deformation in time.

The method is implemented as follows. A basic deformation diagram is constructed at isothermal creep of a part under constant load at a fixed temperature in the coordinates: ε is the absolute deformation, μm; t is the time, *s*. In this case, the time to fracture and the maximum deformation at the time of fracture are determined. The moment of time of the end of elastic deformation is fixed, as well as the magnitude of the deformation at this moment t. After the base diagram is constructed, the moment is selected $t_2 = t_{cr}/2.5$ and at this point the deflection value is determined. Further, formulas (9) and (1) determine the value k_1 and k_2, as well as the value:

$$\alpha = k_1/k_2 \quad (19)$$

By measuring the change in the deformation of a part over time, a control chart of deformation is constructed. The moment of time t_{2k} is chosen at the point of constant creep and absolute deformation ε_{2k} at that moment is recorded. Eq. (16) allows obtaining a value k_{1k}, and Eq. (19) – $k_{2k} = k_{1k}/\alpha$.

Eqs (13), (14), (15) are used to determine the change in the current concentrations of SE, which are in elastic, viscoelastic, and fractured states. Based on Eq. (18), the estimated time t_ψ is determined reaching the limit value of the damage parameter ψ.

RESULTS AND DISCUSSION

The experimental factors levels and test results of studies long-term strength PB at constant load are presented in Table 2.

Table 2. *Experimental factors levels and test results for particleboards*

Test conditions				Test results[a]									
				Displacement, mm					Time displacement, h				
Board type	Number of samples	Stress level (MPa)	Temperature (°C)	In all ε_{cr}	Visco elastic ε_{ve}	%	Elastic ε_e	%	In all t_{cr}	Visco elastic t_{ve}	%	Elastic t_e	%
MF PB	20	12.8	20	2.46	0.79	32.1	1.67	67.9	127.1	98.4	77.4	28.7	22.6
	20		60	3.95	1.33	33.7	2.62	66.3	84	73.3	87.3	10.7	12.7
VF PB	20	15.4	20	1.5	0.59	39.3	0.91	60.7	477.82	380.9	79.7	96.92	20.3
	20		60	1.77	0.54	30.5	1.23	69.5	190.71	140	73.4	50.74	26.6
P2 PB	20	12.15	20	4.91	1.63	33.2	3.28	66.8	78.77	69.6	88.4	9.17	11.6
	20		60	1.57	0.51	32.1	1.07	67.9	35.75	24.2	67.8	11.51	32.2

Notes: [a]*The average test values for each group of 20 samples are presented*

Experimental studies of the long-term strength curve of PB have found that the material behaves in a complex viscoelastic manner during the creep. And the curve of its deformation contains the recurring sections, inherent in the curves of elastic and viscoelastic deformation (Fig. 1).

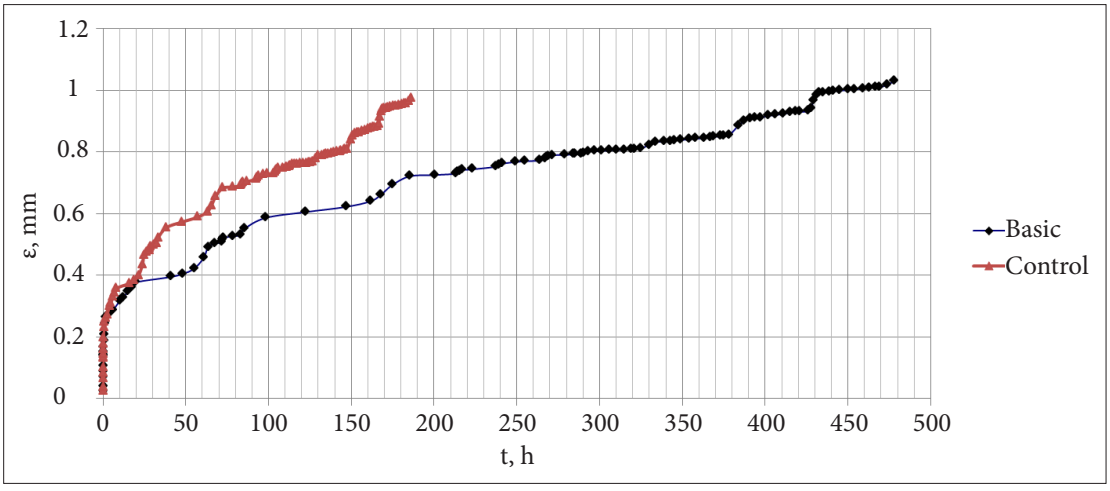

Figure 1. *Basic and control creep diagrams. Dependences of the average absolute deformation for one group of the samples VF PB by stress level SL = 15.4 MPa and temperature T = 20°C for basic diagram, and by stress level SL=17.7 MPa and temperature T = 20°C for control (predicted) diagram*

The nature of the deformation-destruction curves over time (Fig. 1) indicates that the process is non-stationary. The deformation process at all its stages, both at the subcritical (stationary creep process) and at the closed (active fracture process) behaves nonlinearly and has a stepped character. In Figure 1 it is shown that the general curve of dependence of deformation in time, consists of separate sections, which have different repetitive strain rates. Table 1 shows that the amount of viscoelastic deformation is on average 33% of the total amount of deformation. In this case, the time of viscoelastic deformation (behaviour) PB occupies about 80% of the total deformation time. And the value of both the magnitude of viscoelastic deformation and its time is in a very narrow range, which indicates the similarity of the deformation process and the destruction of PB under different conditions of its loading.

Analysing the deformation curves over time, it can be stated that the general deformation curve up to fracture periodically repeats cycles of elastic and viscoelastic behaviour. This confirms the assumption that the process is multi-stage.

According to the graph of the basic deformation diagram (basic long-term strength curve Fig. 1), the following quantities are defined: t_1=0.003*3600=10.8 [s], ε_1=80 [μm], t_2=200*3600=7.2*10^5 [s], ε_2=730 [μm], t_{cr}=477*3600=1,717*10^6 [s]. Eqs (9), (13), (19) yield the following results: k_1=0,307*10^{-5} s^{-1}, k_2=0.719*10^{-6} s^{-1}; α=4.273.

Figure 2 demonstrates a basic model diagram, constructed in the coordinates of the "concentrations of SE in different states – time" [19].

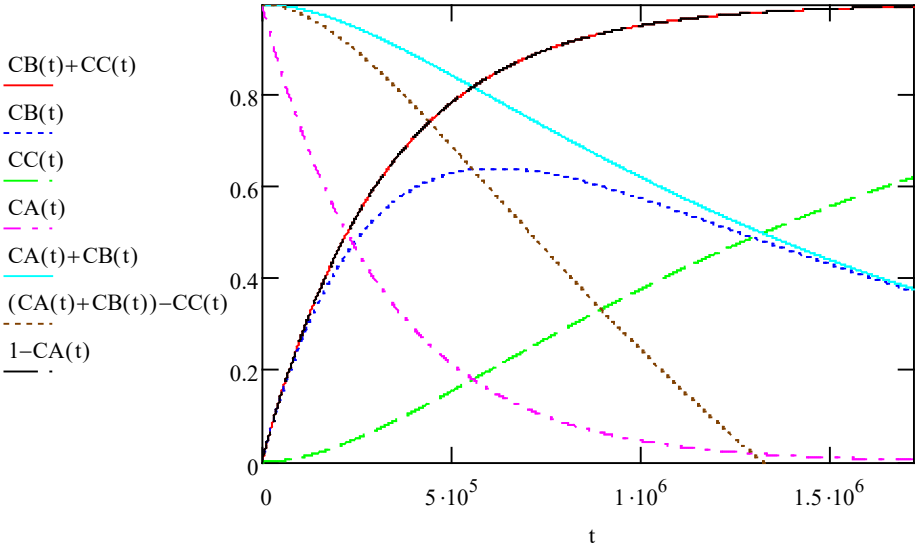

***Figure 2**. Basic model diagram of long-term strength (creep): change concentrations of SE in the states: elastic – CA(t), viscoelastic – CB(t), destroyed – CC(t) in time for the basic deformation diagram*

The deformation control chart was investigated for a similar part load exceeding the baseline by 15%. According to the control chart of deformation at the site of permanent creep at time – t_{2k}=100*3600=360000 [s], ε_{2k}=730 [μm].

The value of the rate constants k_{1k}, k_{2k} according to the control deformation chart are determined using Eqs (9), (19):

$$k_{1k} = -\frac{1}{(t_{2k} - t_1)} \ln\left(\frac{\varepsilon_1}{\varepsilon_{2k}}\right) = 0.614*10^{-5}\ \text{s}^{-1};\ k_{2k} = \alpha^{-1} * k_{1k} = 0.144*10^{-5}\ \text{s}^{-1}$$

The critical amount of damage will be reached at the moment when, based on the condition (18):

$$CA(t_\psi) + CB(t_\psi) - CC(t_\psi) = 0 \qquad (20)$$

Solving together equations (14), (15), (16), and (20) yields the time to the predicted destruction: $t_{\text{predict }\psi}$ = = 6.6*10^5 s. The factual time to destruction of the control sample is $t_{\text{fact }\psi}$=6.7*10^5 s.

Figure 3 demonstrates a control model diagram, constructed in the coordinates of "concentrations of SE, which are in different states – time", which clearly indicates the process of loss of bearing capacity of the part in time during creep.

The results of basic tests of six groups of samples, as well as the results of calculations of the kinetic basic parameters are presented in Table 3.

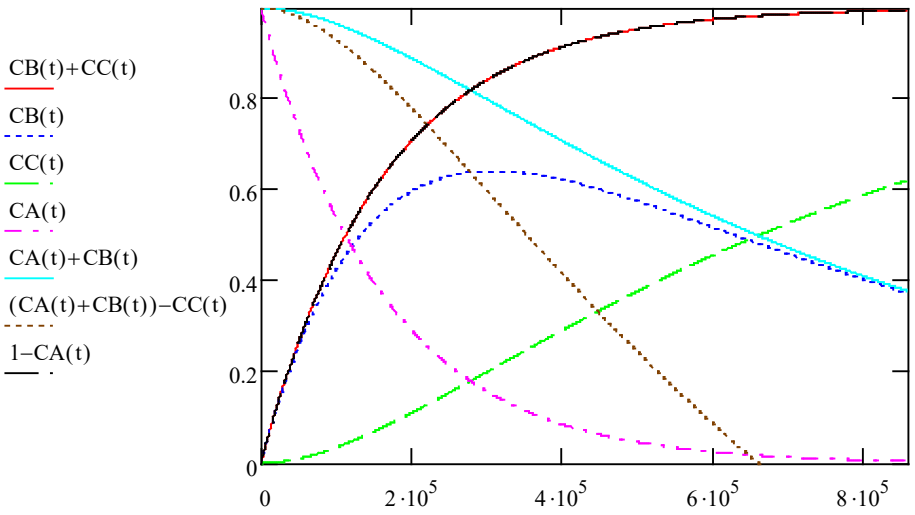

Figure 3. *Control (predicted) creep model diagram: change concentrations of SE in the states: elastic – CA(t), viscoelastic – CB(t), destroyed – CC(t) in time for the deformation control chart*

Table 3. *Basic test results and calculated basic kinetic parameters*

Board type	Test conditions		Test results			
	Stress level (MPa)	Temperature (°C)	Creep life t_{cr} (s)	k_1 (s^{-1})	k_2 (s^{-1})	α
MF PB	12.8	20	457560±7250[a]	1.16E-05	2.69E-06	4.325
		60	302400±3500	1.74E-05	4.08E-06	4.261
VF PB	15.4	20	1717000±9500	3.07E-06	7.19E-07	4.273
		60	686556±5600	7.94E-06	1.78E-06	4.453
P2 PB	12.15	20	283572±850	1.88E-05	4.34E-06	4.331
		60	128700±780	4.53E-05	9.38E-06	4.831

Notes: [a]*The confidence interval is indicated at p=0.05 level*

The results of control tests of six groups of samples, as well as the results of calculations of the control kinetic parameters are presented in Table 4.

Comparing the results of the model time before the destruction of the control samples in each test group (Tab. 4. Creep life predict by Eq. (18)) with the actual time before the destruction of the control samples (Tab. 4. Creep life control diagram), it can be concluded that the convergence of these quantities is quite high. This suggests that the proposed method for predicting long-term creep strength can be used to improve the accuracy of predicting the performance of controlled mechanical systems.

Table 4. *Control test results, calculated control kinetic parameters and predicted time to failure*

Board type	Test conditions		Test results			
	Stress level (MPa)	Temperature (°C)	k_{1k} (s^{-1})	k_{2k} (s^{-1})	Creep life t_{cr} (s)	
					Control diagram	Predict by Eq. (22)
MF PB	14.72	20	1.43E-05	3.30E-06	338933±7500[a]	372827[b]
		60	1.82E-05	4.27E-06	262957±5600	289252
VF PB	17.71	20	7.99E-06	1.87E-06	670000±9800	660000
		60	1.19E-05	2.67E-06	504821±5500	458928
P2 PB	13.97	20	2.50E-05	5.78E-06	234357±6200	213052
		60	5.95E-05	1.23E-05	99000±860	98000

Notes: [a]*The confidence interval is indicated at p=0.05 level;* [b]*Prediction results based on average kinetic coefficients*

A multi-stage description of the kinetics of deformation-fracture allows considering the change in the rheological state of the material during its deformation. Therewith, it becomes possible to mathematically describe not only the process of its destruction, but also the healing process that goes along with it. However, this issue requires separate consideration and will be the subject of further research.

CONCLUSIONS

Based on the analysis of the results of theoretical and experimental studies of the process of deformation-destruction of wood composite materials, the following conclusions can be drawn:

1. For the first time, a two-stage nonlinear kinetic model of resource loss due to the creep of wood-based composites is proposed.

2. The use of formal kinetics methods for modelling the physicochemical processes that occur during deformation-destruction allows designing the multi-stage kinetic models.

3. The use of the method of basic deformation diagrams in combination with the two-stage description of the process of accumulation of damage, allows increasing the accuracy of the prediction of allowable time under different load schemes during creep.

ACKNOWLEDGEMENTS

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Прогнозування тривалої міцності деревних композитів з використанням кінетичних рівнянь

Сергій Миколайович Кульман[1], Людмила Миколаївна Бойко[1], Ян Седлячик[2]

[1]Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна

[2]Технічний університет у Зволені
960 53, вул. Т.Г. Масарика, 24, м. Зволен, Словаччина

Анотація. Існуючі моделі поведінки конструкцій при постійному навантаженні (повзучості) мають досить широкий горизонт прогнозування і низьку точність. Як правило, вони враховують перехід від неруйнованого стану елемента до зруйнованого за одну стадію. Метою цього дослідження було обґрунтування та розробка нового підходу до прогнозування довгострокової міцності на основі кінетичних рівнянь, який, у свою чергу, повинен враховувати багатоступеневий характер процесу поступового руйнування елементів конструкції. Для досягнення цієї мети були вирішені завдання створення багатоступінчастого кінетичного переходу окремих структурних елементів із спочатку пружного стану у в'язкопружний, а потім у тріщинований. Описуючи цей процес, автори статті використовували методи формальної кінетики та теорії механіки пошкоджень континууму, а також метод базових діаграм. В якості матеріалів, що вивчаються, були використані композити на основі деревини. За результатами проведених повномасштабних та обчислювальних експериментів було визначено: математична модель на основі кінетичних рівнянь адекватно описує поведінку досліджуваних матеріалів для довгострокової міцності; запропонована двоетапна модель визначає горизонт прогнозу набагато точніше, ніж існуючі одноетапні моделі. Кінетичні параметри, що визначають швидкість переходу структурного елемента з пружного стану у в'язкопружний, а потім у руйнований, були визначені на основі експериментальних базових діаграм. Час до руйнування визначали при триточковому вигині за навантаження, що дорівнює 70 % міцності на вигин при температурах 20 °C і 60 °C, постійній вологості RH 65 % та вологості MC 8 %. При побудові контрольних карт навантаження збільшилося ще на 15 %. Метод дозволяє звузити горизонт прогнозу та з більшою точністю визначити момент переходу споруди зі стаціонарного стану в режим із загостренням

Ключові слова: кінетична теорія, механіка пошкодження континууму, повзучість, довготривала міцність, параметри пошкоджень, критерій руйнування

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Analytical Study of the Automatic Ventilation System for the Intake of Polluted Air from the Pigsty

Vitalii Yaropud*

Vinnytsia National Agrarian University

21008, 3 Soniachna Str., Vinnytsia, Ukraine

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Abstract. The microclimate of a pigsty is determined by the combination of temperature, relative humidity, chemical and mechanical composition of the air, which have a significant impact on animal productivity and must be maintained within strict limits due to the physiological needs and capabilities of animals. An appropriate ventilation system has been created to ensure the removal of air from the pigsty. The purpose of the study is to establish the dependence of the operating parameters of the automatic ventilation system on the air quality in the pigsty, taking into account the permissible concentrations of gases. The developed automatic ventilation system for polluted air intake is located in the middle of the livestock house under the ceiling and consists of a central air duct, to which air intake pipes are connected. Air intake pipes are placed in the middle above each pen where animals are kept. Intake dampers with servomechanisms, temperature, humidity, and air quality sensors are installed at the inlet of the air intake pipes. The outlet of the central air intake duct is connected to the exhaust fan. Intake dampers with servomechanisms and sensors of temperature, humidity, and air quality are connected to the control unit by electrical wires. As a result of analytical studies of the automatic ventilation system for polluted air intake from a pigsty, the conditions for its effective operation have been mathematically substantiated. The developed technique and the algorithm implemented based on the Mathematica software package allows calculating the area of holes that form intake dampers with servomechanisms in the air intake pipes. The distribution of velocities in the air intake pipes and the distribution diagram of the area of holes that form intake dampers with servomechanisms in the air intake pipes are determined taking into account the design and technological parameters of the ventilation system and the distribution of the gas concentration (carbon dioxide, ammonia, and hydrogen sulphide) over the pens

Keywords: microclimate, pigsty, ventilation, automation, parameters, research, dependencies

*Corresponding author

INTRODUCTION

The microclimate in a pigsty is determined by the combination of temperature, relative humidity, chemical and mechanical composition of the air. Each of these indicators individually has a significant impact on the animal productivity and must be maintained within strict limits due to the physiological needs and capabilities of animals. The microclimate is also affected by the technology of keeping animals, the density of their placement, the quantity and quality of bedding, the type of feeding, the species and age composition of livestock. In other words, a microclimate is a meteorological regime of closed rooms for animals, the concept of which includes temperature, humidity, chemical composition and speed of air movement, dustiness, and illumination. The optimal microclimate helps to increase animal productivity, reduce feed costs for obtaining a unit of production, which has a positive effect on the health of farm animals. The state of the microclimate depends on climatic and weather conditions, the type of pen and its enclosing structures, the level of air exchange, the perfection of the systems of ventilation, heating, sewerage, and manure harvesting [1].

A significant number of research papers are devoted to the study of the influence of microclimate on the productive qualities of pigs [2-4]. M. Kalinin [5], V. F. Lipatnikov and V. P. Stepanov [6] note that the conditions of keeping pigs during rearing significantly affect their productivity. At the same time, a significant number of researchers point out the dependence of microclimate parameters on the technical devices used to provide it [7].

In industrial animal husbandry, the creation of an optimal microclimate depends on many factors and is carried out through a number of compromises. Nowadays, there are data based on which it is possible to accurately determine those environmental factors necessary for the manifestation of genetically determined abilities of animals. However, providing a thermoneutral zone is associated with large capital investments, high energy prices, and recently requires increasing operating costs. As long as there are no significant changes in pricing, instead of forming a thermoneutral zone, it is advisable to create an optimal productive environment, which is a compromise between high production costs and the quality of livestock products. Given that the size of capital investment and operating costs can change significantly in a short time, the microclimatic conditions characteristic of an optimal productive environment also cannot remain unchanged, even taking into account the fact that the requirements of animals for their environment practically do not change for a long time [8].

Modern climate control systems in pig breeding premises include: climate control computers, temperature, humidity and gas sensors, fans, humidifiers. The heart of the microclimate control system is a computer that controls all mechanisms. The computer continuously controls the fans, changing their performance from 0 to 100%, while providing greater resistance of ventilation to changes in atmospheric pressure and less sensitivity to winds. This allows ensuring an optimal indoor microclimate and is cost-effective. At the same time, non-automatic exhaust devices (roof shafts of various configurations; shafts that draw air from manure channels) and supply devices (roof shafts, wall and ceiling vents-valves, windows [9] are also used.

The sex and age of pigs and the configuration of the pig breeding room affect the need to use a particular type of heating. The heating system is selected taking into account the availability of certain energy resources at the farm enterprise. The use of electricity and direct fuel combustion equipment is considered the most common in modern pig breeding complexes. The most economical is the use of blower heat generators. Taking into account the technological features, such systems can be used in pens for keeping boars, mating-gestating sows, and fattening pigs. Due to the generation of intense air flow, they cannot be used in nurseries and rearing pens. To provide heating of rearing pens, a ribbed general heating pipe, water heating registers such as delta tubes and water mats are most often used. In turn, infrared emitters are successfully used in nurseries. Their energy source is electricity or natural gas [10].

The purpose of the study is to establish the dependence of the operating parameters of the automatic ventilation system for the polluted air intake on the air quality in the pigsty, taking into account the permissible gas concentrations.

MATERIALS AND METHODS

Analytical studies of the automatic ventilation system for the intake of polluted air from a pigsty are carried out based on mathematical modelling of the process using the main provisions of aerodynamics and numerical calculation methods.

The Mathematica computer mathematics system was used to simplify the obtained expressions and mathematical modelling. The following provisions were adopted to develop a mathematical model of the operation of the ventilation system for polluted air intake:

– in each section of the air flow through the air ducts, part of the total pressure used to overcome the forces of pneumatic resistances is lost due to the molecular and turbulent viscosity of the moving air, the mechanical work of the resistance forces is converted into heat;

– there are two types of pneumatic resistance in an air duct: friction resistance and local resistance;

– pneumatic friction is caused by the air viscosity (both molecular and turbulent) that occurs during its

movement, and is the result of the exchange of the amount of motion between molecules (in laminar motion), and between individual particles (in turbulent motion) of neighbouring air layers moving at different speeds;

– local resistances occur when a local violation of the normal flow, separation of the flow from the walls, vortex generation, and intense turbulent mixing of the flow in places where the configuration of the air duct changes or when obstacles meet and flow around. These phenomena increase the exchange of motion between moving air particles (i.e., friction), increasing energy dissipation.

The main parameters of the microclimate of pig breeding premises are regulated by the norms of technological design [11]. According to the recommendations of well-known animal technicians and veterinarians [12; 13] and the existing requirements of VNTP-APK-02.05 "Pig breeding enterprises (complexes, farms, small farms)", the technological parameters of the microclimate of premises for keeping pigs can be summarised in Table 1.

***Table 1**. Technological parameters of the microclimate of premises for keeping pigs*

Parameter	Newborn piglets	Piglets up to 8 kg	Growing	Fattening	Closed gilts	Suckling gilts
Air temperature, °C						
Maximum	33	30	20	20	18	22
Minimum	30	24	15	12	13	18
Relative humidity, %						
Maximum	60	70	70	70	70	70
Minimum	55	40	40	40	40	40
Maximum permissible air velocity, m/s						
At the minimum temperature	0.15	0.2	0.2	0.3	0.3	0.15
At maximum temperature	0.4	0.5	0.5	1	1	0.4
Permissible concentrations of gases and dust in the air						
Carbon dioxide (long-term), %	0.2					
Carbon dioxide (short-term), %	0.35					
Ammonia (long-term), mg/m^3	20					
Ammonia (short-term), mg/m^3	30					
Hydrogen sulphide, (long-term), mg/m^3	10					
Hydrogen sulphide, (short-term), mg/m^3	15					

Naturally, such microclimate parameters at ruling energy prices require high costs, but these are the most favourable conditions for the life of suckling piglets.

RESULTS AND DISCUSSION

To ensure the removal of air from the pigsty, an appropriate ventilation system has been created (Fig. 1). To substantiate the design and technological parameters of ventilation system automation, it is necessary to perform analytical studies.

Automatic ventilation system for polluted air intake (Fig. 1) is located in the middle of the livestock room under the ceiling and consists of a central air duct for air intake (1), to which the air intake pipes (2) are connected. Air intake pipes (2) are located in the middle above each pen where animals are kept. Intake dampers with servomechanisms (3) and temperature, humidity, and air quality sensors (4) are installed at the

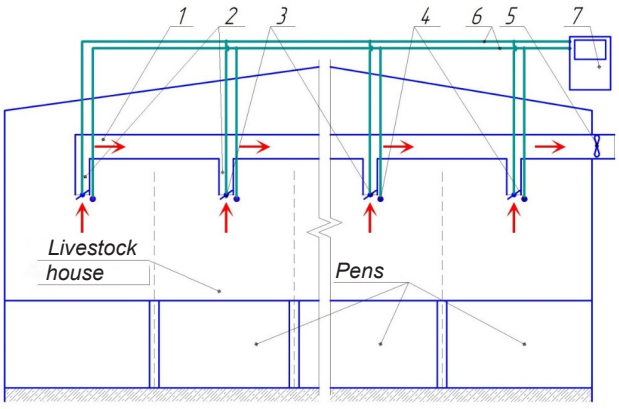

***Figure 1**. Technological scheme of automatic ventilation system for polluted air intake: 1 – central air duct; 2 – branch pipes; 3 – intake dampers with servomechanisms; 4 – temperature, humidity, and air quality sensors; 5 – exhaust fan; 6 – electrical wires; 7 – control unit*

inlet of the air intake pipes (2). The outlet of the central air duct for air intake (1) is connected to the exhaust fan (5). Intake dampers with servomechanisms (3) and temperature, humidity, and air quality sensors (4) are connected to the control unit (7) by means of electrical wires (6).

The automatic ventilation system for polluted air intake works as follows: depending on the air quality above the pens, which is determined using temperature, humidity, and air quality sensors (4) and the limit values set by the operator, the control unit (7) transmits a signal to the intake dampers with servomechanisms (3) by electrical wires (6). If the measured air quality values are less than the limit values set by the operator, the intake flap with servo drive (3) is closed. Otherwise, the intake flap with servo drive (3) opens at an angle that is directly proportional to the corresponding difference between the air quality values and the limit values. Under the action of exhaust fan (5), air is sucked into the air intake pipes (2) and is formed into a stream that moves through the central air intake duct (1) of the polluted air intake system. Then the air flow is removed from the room.

Due to the fact that certain group pens may contain different numbers of animals grouped by age, the gas concentration (carbon dioxide, ammonia, and hydrogen sulphide) located above the pens may differ (Fig. 2) [14-16]. Therefore, the automatic ventilation system for polluted air intake must adjust the air flow rate for each pen individually.

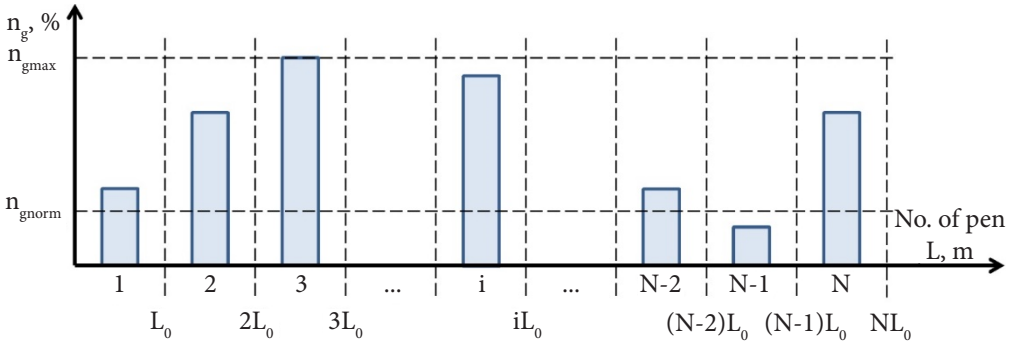

***Figure 2**. Distribution of gas concentrations (carbon dioxide, ammonia, and hydrogen sulphide) ng above the pens: n_g – gas concentration (carbon dioxide, ammonia, and hydrogen sulphide) above the pens, %; n_{gnorm} – limit values of gas concentration in the pigsty, %; n_{gmax} – maximum value value of gas concentration above the pen, %; i – pen number; N – total number of pens; L_0 – width of the pen (provided that the geometric dimensions of all pens are the same), m*

The operation of an automatic ventilation system for polluted air intake can be mathematically represented as follows:

$$\begin{gathered} n_{gi} \le n_{gnorm} \Rightarrow q_i = q_0 \\ n_{gi} = n_{gmax} \Rightarrow q_i = q_{max} = q_0 + \Delta q_{max} \end{gathered} \quad (1)$$

where $q_i = q_0 + \Delta q_i$ – volumetric air flow rates through *i-th* air intake pipe, m³/s; q_0 – volumetric air flow rate through the air intake pipe when the servo-operated intake flap is completely closed, m³/s; Δq_i – volumetric air flow rate through the open i-th intake flap with servo drive at a certain angle, m³/s; q_{max} – volumetric air flow rate through the air intake pipe when the servo-operated intake flap is fully open, m³/s; Δq_{max} – volumetric air flow rate through a fully open *i-th* intake flap with servo drive, m³/s.

The values of air flow through the open *i-th* intake flap with a servo drive must be directly proportional to the gas concentration (carbon dioxide, ammonia, and hydrogen sulphide) over *i-th* pen:

$$\Delta q_i = k\left(n_{gi} - n_{gnorm}\right) \quad (2)$$

$$\Delta q_{max} = k\left(n_{gmax} - n_{gnorm}\right) \quad (3)$$

where *k* – proportionality coefficient, m³/(c·%).

Combining equations (1)-(3), the dependence of air flow through the open *i-th* intake flap with servo drive from the gas concentration (carbon dioxide, ammonia, and hydrogen sulphide) over *i- th* pen is obtained:

$$q_i = \begin{cases} q_0 + \dfrac{\Delta q_{max}}{n_{gmax} - n_{gnorm}}\left(n_{gi} - n_{gnorm}\right), n_{gi} > n_{gnorm}, \\ q_o, n_{gi} \le n_{gnorm} \end{cases} \quad (4)$$

In turn, the volume flow rate of air through the open i-th air intake flap with servo drive at a certain angle directly proportional to the area of the opening σ_i, and air velocity V_i:

$$q_i = q_0 + \sigma_i V_i \quad (5)$$

Expressing from (5) σ_i and substituting in (4):

$$\sigma_i = \begin{cases} \dfrac{1}{V_i}\dfrac{\Delta q_{max}}{n_{gmax} - n_{gnorm}}\left(n_{gi} - n_{gnorm}\right), n_{gi} > n_{gnorm}, \\ 0, n_{gi} \le n_{gnorm} \end{cases} \quad (6)$$

In accordance with previous studies [17-18], it was found that under the condition of uniform placement of air intake pipes and their identical diameter,

the velocity field is deformed, which consists of air velocities from each hole V_i.

The deformation of the velocity field consists in the fact that the air velocity field has a skewed profile: from the axis of the central air duct for air intake in the direction of the opening, an increase in speed is observed, and in the opposite direction (a wall without a hole) – a decrease. The static air pressure changes in the cross-section in the opposite order: it is the smallest in the hole and continuously increases in the direction opposite to the wall of the hole. When moving from one cross-section to another, the average air velocity, dynamic average and average pressure change.

In the direction from the beginning to the end of the central air intake duct (opposite to the air flow), the average speed decreases. Thus, the dynamic pressure will decrease in such a direction that it is opposite to the direction of air flow by a certain amount, which, according to the law of conservation of energy, will turn into static pressure. This value of dynamic pressure is called "released dynamic pressure". Due to the released dynamic pressure, the static air pressure inside the central air intake duct increases in the opposite direction of the flow. However, it will be spent in the same direction on overcoming friction and local resistance. If the released dynamic pressure is greater than the pressure losses on friction and local resistances, then the static pressure will eventually increase, and if it is less than these pressure losses, then the static pressure will decrease. If the released dynamic pressure is equal to the pressure loss, then the static air pressure inside the central air intake duct will remain unchanged. Thus, the nature of the change in static air pressure inside the central air intake duct depends entirely on the ratio of released dynamic pressure and pressure losses. Taking into account the above, equation (6) needs to be clarified taking into account the non-uniformity of the air flow velocity distribution, which occurs due to pressure losses.

Central air duct for air intake of constant cross-section length L (Fig. 3) has a perimeter R and cross-sectional area F. Along the air duct in its side surface, N air intake pipes is evenly distributed. The area of the openings of the air intake pipes is different. The air flow rate at the end of the duct is equal to w_k.

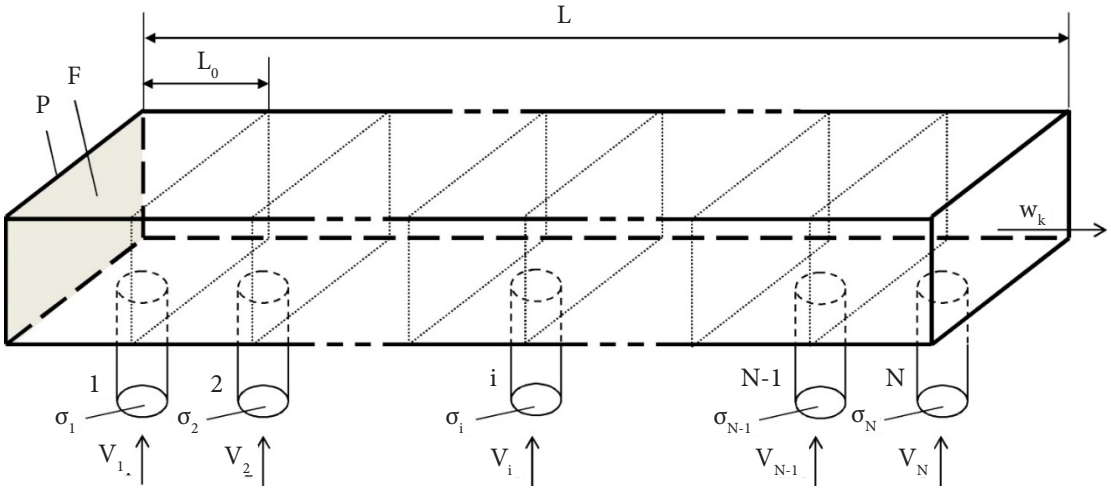

***Figure 3**. Design scheme of the central air duct for air intake*

It is necessary to determine how the areas of the openings of the air intake pipes should change along the length of the central air duct to ensure that air is sucked into the openings in accordance with the equation (4). TIt is necessary to number all the holes in the direction of the air flow and draw cross-sections 1-1, 2-2,…, *i-i*, (*N-1*)-(*N-1*), *N-N* after each hole.

Air intake rate in i-th air intake pipe opening:

$$V_i = \mu\sqrt{\frac{2}{\rho}(p_a - p_i)} \quad (7)$$

where ρ – air density, kg/m^3; p_i – pressure in *i-th* opening of the air intake pipe, Pa; p_a – atmospheric pressure, p_a=101,325 Pa; μ – coefficient of friction of the hole, μ=0.65 [19].

Since the volume is limited by *i-th* and *i-1-th* sections and walls of the central air duct for air intake, the equation of the amount of motion in projections on the axis of the air duct has the form:

$$p_{i-1}F - p_iF - \tau_{i-1}PL_0 = \frac{\rho F w_i^2}{2} - \frac{\rho F w_{i-1}^2}{2} \quad (8)$$

$$\tau_{i-1} = \frac{\lambda}{4}\frac{\rho w_{i-1}^2}{2} \quad (9)$$

where L_0 – distance between the axes of two adjacent holes, m; λ – coefficient of friction resistance, λ=0.01717 [20]; w_i – air velocity through *i-th* cross-section, m/s.

Substituting equation (9) into (8) and dividing all terms of the equation by F, obtain:

$$p_{i-1} - p_i - \frac{\lambda\rho PL_0 w_{i-1}^2}{8F} = \frac{\rho w_i^2}{2} - \frac{\rho w_{i-1}^2}{2} \quad (10)$$

With uniform air distribution:

$$w_i = w_k \frac{i}{N},\ w_{i-1} = w_k \frac{i-1}{N},\ \Delta q \frac{q_k}{N}_{max} \quad (11)$$

Substituting in the last equation w_i and w_{i-1}:

$$p_{i-1} = p_i + \frac{\rho w_k^2}{2}\frac{1}{N^2}\left[\left(\frac{\lambda P L_0}{4F} - 1\right)(i-1)^2 + i^2\right] \quad (12)$$

According to equation (8) for the end of the central air intake duct:

$$p_N = \frac{\rho w_k^2}{2} \quad (13)$$

The air flow rate at the end of the central air intake duct is determined by the equation (14):

$$q_k = w_k F \quad (14)$$

from here:

$$w_k = \frac{q_k}{F} \quad (15)$$

The dependence of (12) and (13), taking into account (15), takes the form:

$$p_{i-1} = p_i + \frac{\rho q_k^2}{2F^2}\frac{1}{N^2}\left[\left(\frac{\lambda P L_0}{4F} - 1\right)(i-1)^2 + i^2\right] \quad (16)$$

$$p_N = \frac{\rho q_k^2}{2F^2} \quad (17)$$

Substituting the pressure value according to equation (16) into (7):

$$V_{i-1} = \mu\sqrt{\frac{2}{\rho}\left(p_a - p_i - \frac{\rho q_k^2}{2F^2}\frac{1}{N^2}\left[\left(\frac{\lambda P L_0}{4F} - 1\right)(i-1)^2 + i^2\right]\right)} \quad (18)$$

Substituting (18) into (6), an equation is finally obtained for calculating the area of the opening formed by the intake flap with a servo drive in the air intake pipe:

$$\sigma_i = \begin{cases} \dfrac{\dfrac{\Delta q_{max}}{n_{gmax} - n_{gnorm}}(n_{gi} - n_{gnorm})}{\mu\sqrt{\dfrac{2}{p}\left(p_a - p_i - \dfrac{pq_k^2}{2F^2}\dfrac{1}{N^2}\left[\left(\dfrac{\lambda P L_0}{4F} - 1\right)(i-1)^2 + i^2\right]\right)}} & n_{gi} > n_{gnorm} \\ 0, n_{gi} \le n_{gnorm} \end{cases} \quad (19)$$

The methodology developed above and the algorithm implemented on its basis are executed in the Mathematica software package.

Taking the structural and technological parameters of the ventilation system for polluted air intake (L=42 m; P=1.25 m; ρ=1.27 kg/m^3; q_k=1.5 m^3/s; F=0.126 m^2; μ=0,025; p_a=101325 Pa; λ=0.01717; n_{gnorm}=10%) and distribution of gas concentrations (carbon dioxide, ammonia, and hydrogen sulphide) ng above the pens (Fig. 4) the speed distribution in the air intake pipes is determined (Fig. 5).

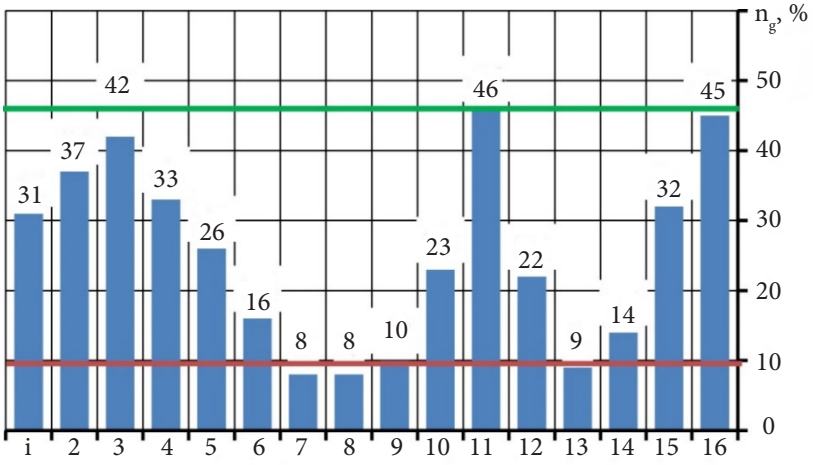

***Figure 4**. Distribution of gas concentration ng above the pens*

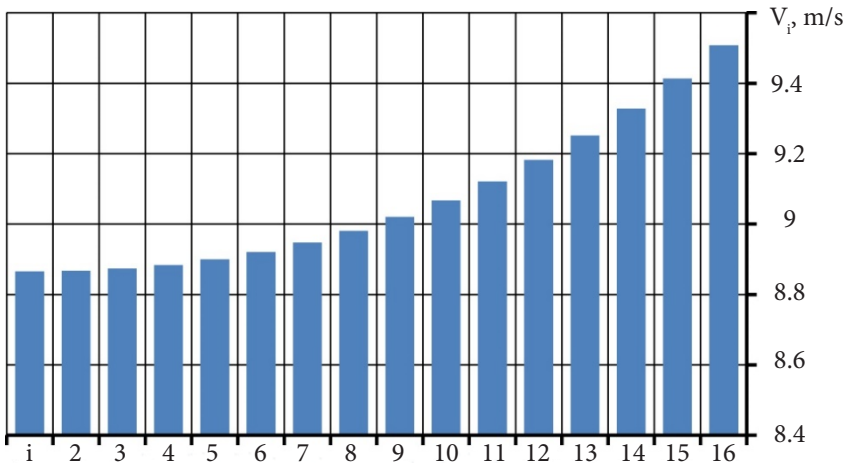

Figure 5. *Velocity distribution V_i in the air intake pipes*

Analysing Figure 5, it can be argued that the speed in the air intake pipes gradually decreases from 9.5 m/s to 8.8 m/s in the direction opposite to the air flow. Given the resulting velocity distribution V_i in the air intake pipes (Fig. 5) and the gas concentration distribution is accepted ng above the pens (Fig. 4) taking into account equation (19), a diagram of the distribution of the area of holes formed by intake dampers with servomechanisms in the air intake pipes is obtained (Fig. 6). For comparison, Figure 6 shows a diagram of the hole area distribution without taking into account the velocity distribution V_i in the air intake pipes.

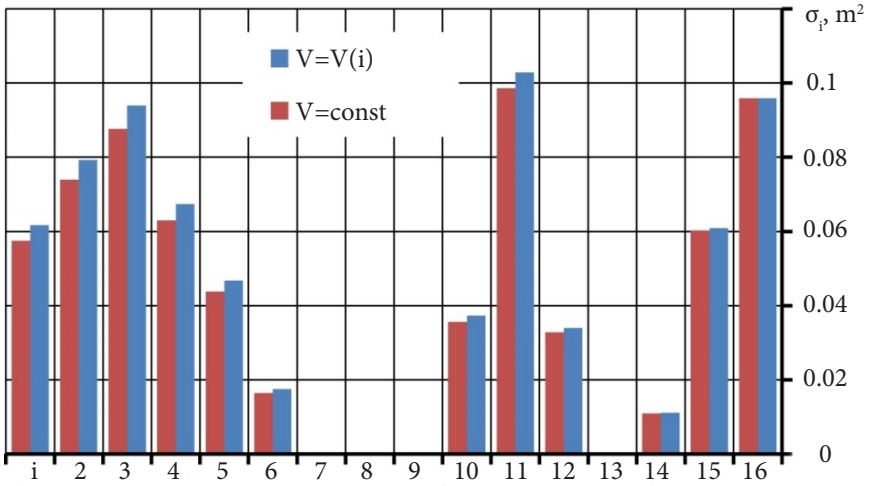

Figure 6. *Velocity distribution V_i in the air intake pipes*

Analysis of Figure 6 shows that given the velocity distribution $V=V_i$ of the control unit of the automatic ventilation system for polluted air intake, it is possible to more accurately adjust the intake dampers with servomechanisms. This allows fulfilling the specified condition (4).

CONCLUSIONS

An increase in pig productivity can be achieved in various ways. The most effective of them is to create a favourable microclimate in the pens where pigs are kept. A favourable microclimate is achieved in various ways, but the simplest is the arrangement of professional ventilation. Proper design of livestock facilities and equipment with ventilation systems prevents cases of dangerous viruses and, as a result, improves the quality and safety of pork.

As a result of analytical studies of the automatic ventilation system for polluted air intake from a pigsty, the conditions for its effective operation have been mathematically substantiated. The developed technique and the algorithm implemented based on the Mathematica software package allows calculating the area of holes that form intake dampers with servomechanisms in the air intake pipes.

Taking the structural and technological parameters of the ventilation system for polluted air intake (L, P, ρ, q_k, F, μ; p_a, λ; n_{gnorm}) and distribution of gas concentrations (carbon dioxide, ammonia, and hydrogen sulphide) n_g the speed distribution in the air intake pipes above the pens V_i is determined and a diagram of the hole area distribution σ_i, which form intake dampers with servomechanisms in the air intake pipes.

Taking into account the speed distribution $V=V_i$

of the control unit of the automatic ventilation system for polluted air intake, it is possible to more accurately adjust the intake dampers with servomechanisms. This allows fulfilling the set condition for the dependence of air flow through the open *i-th* air intake flap with servo drive depending on the gas concentration (carbon dioxide, ammonia, and hydrogen sulphide) over *i-th* pen.

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Аналітичні дослідження автоматичної вентиляційної системи забору забрудненого повітря свинарського приміщення

Віталій Миколайович Яропуд

Вінницький національний аграрний університет
21008, вул. Сонячна, 3, м. Вінниця, Україна

Анотація. Мікроклімат свинарського приміщення визначається сукупністю температури, відносної вологості, хімічного та механічного складу повітря, які мають суттєвий вплив на продуктивність тварин і мають підтримуватися в суворих рамках, обумовлених фізіологічними потребами і можливостями тварин. У рамках зазначеного для забезпечення відведення повітря з приміщення свинарника створена відповідна вентиляційна система. Метою досліджень є встановлення залежності режимних параметрів автоматичної вентиляційної системи забору забрудненого повітря від якості повітря у свинарнику з урахуванням допустимих концентрацій газів. Розроблена автоматична вентиляційна система забору забрудненого повітря розміщена в середині тваринницького приміщення під стелею і складається з центрального повітропроводу для забору повітря, до якого приєднанні патрубки для забору повітря. Патрубки для забору повітря розміщенні посередині над кожним станком, де утримуються тварини. На вході патрубків для забору повітря встановлені забірні заслінки із сервоприводами і датчики температури, вологості та якості повітря. Вихід центрального повітропроводу для забору повітря приєднано до витяжного вентилятора. Забірні заслінки із сервоприводами і датчики температури, вологості та якості повітря по засобах електричних проводів 6 приєднані до блока керування. У результаті аналітичних досліджень автоматичної вентиляційної системи забору забрудненого повітря свинарника математично представлено умову її ефективної роботи. Розроблена методика і реалізований на основі неї алгоритм у програмному пакеті Mathematica дозволяє розраховувати площі отворів, які утворюють забірні заслінки із сервоприводами у патрубках для забору повітря. Приймаючи конструкційно-технологічні параметри вентиляційної системи забору забрудненого повітря і розподіл концентрації газів (вуглекислого газу, аміаку і сірководню) над станками визначено розподіл швидкостей у патрубках для забору повітря і діаграму розподілу площі отворів, які утворюють забірні заслінки із сервоприводами у патрубках для забору повітря

Ключові слова: мікроклімат, свинарник, вентиляція, автоматизація, параметри, дослідження, залежності

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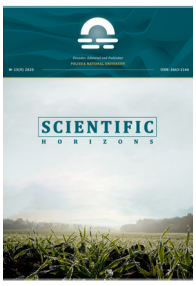

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Epizootological Significance of Rice Weevil as a *Mycobacterium Bovis* Reservoir

Oleksii Tkachenko[1], Kira Alifonova[1*], Olena Gavrylina[1], Amelia Knight[2]

[1]Dnipro State Agrarian and Economic University
49600, 25 Serhii Efremov Str., Dnipro, Ukraine

[2]North South University
1229, Plot 15, Block B, Bashundhara, Dhaka, Bangladesh

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Abstract. This article presents materials on the role of the rice weevil (lat. *Sitophilus oryzae*) in the process of transmission of Mycobacterium of tuberculosis. The relevance of the study is conditioned by the rapid spread of tuberculosis around the world and the need to develop more advanced methods for diagnosing this disease, which, for its part, is impossible without expanding knowledge on all possible reservoirs of the causative agent of infection. Long-term research around the world has proven that insects are carriers of various microflora, including pathogenic ones. Therefore the purpose of study was to establish the epizootological role of the rice weevil as a reservoir for *Mycobacterium bovis* in the process of occurrence and spread of tuberculosis. The study determined the duration of transfer and isolation of Mycobacterium tuberculosis in the external environment by infected beetles. The museum dissociative strain of *Mycobacterium bovis* (118 passage) was used for the study, the subject of the study was rice weevils. For the furtherance of this goal, the culture, microscopic, and statistical studies were conducted, and the viability of mycobacteria was determined after passages through the beetle body by evaluating colony-forming units. The epizootological role of the rice weevil in the development and spread of tuberculosis has been established. It is proved that the beetle can keep mycobacteria in its body for 50 days with a gradual decrease in their number and is then able to secrete the pathogen for another 30 days, contaminating environmental objects. When evaluating colony-forming units of mycobacteria in the dynamics of the experiment, a decrease in their viability after persistence through the body of beetles was revealed from $5.3*10^8$ in 1 g of the original crop up to $1.4*10^8$ in 1 g of crop that grew from beetle homogenisate for 30 days. These study results will allow developing and improving existing measures for the prevention of tuberculosis and prevent the introduction of this infection into safe territory

Keywords: mycobacteria, dissociative strain, infection, beetles-pests of grain stocks, colony-forming units

*Corresponding author

INTRODUCTION

Tuberculosis is one of the most common problems among zooanthroponic diseases, and the issue of improving prevention measures is relevant all over the world, including in Ukraine. This disease poses a high epizootological danger and causes great social and economic damage, which include control measures in the affected area, mass destruction and disposal of animals, health and preventive measures [1]. The ability of mycobacteria to adapt to the environment, their variability and existence in various morphological forms complicate the diagnosis of tuberculosis. Moreover, animal and human organisms can carry the causative agent of infection latently, without showing any clinical signs. In particular, *Mycobacterium bovis* has an extremely large range of susceptible animals, which makes it difficult to eliminate tuberculosis.

Despite many years of fruitful work of researchers around the world, there is still no exhaustive data on all possible ways of introducing the pathogen to the farm. And to completely eradicate the disease, the first priority should be to expand and deepen knowledge on the prevention and elimination of tuberculosis. Special attention, according to the authors of the study, deserves the establishment of all reservoirs of mycobacteria, which are a potential threat of outbreaks of infection in previously safe territories.

Numerous studies from researchers around the world indicate that insects are a reservoir of many types of microorganisms. Foreign researchers managed to isolate mycobacteria from cockroaches, beetles, butterflies, ticks, mosquitoes, and other invertebrates [2-4]. According to many researchers, insects are carriers of potentially pathogenic and pathogenic microorganisms, including the causative agent of tuberculosis. In particular, *Mycobacterium intracellulare, Mycobacterium avium ssp., Mycobacterium fortuitum, Esherichia coli, Klebsiella pneumoniae, Staphylococcus aureus, Salmonella spp., Shigella spp., Pseudomonas aeruginosa* and other types of bacteria were isolated [5-8]. For their part, Fischer et al. have conducted an experimental infection with a suspension of mycobacteria of cockroach nymphs and found that they are able to accumulate and secrete the pathogen into the external environment. Researchers isolated mycobacteria in the excrement of cockroaches after 3 days, and in the homogenisation of infected insects – 10 days after infection [9].

Therefore, existing data indicate the ability of insects to accumulate and secrete mycobacteria into the external environment, that is, to be a potential cause of the active spread of the disease. However, to date, there are no exhaustive data on the duration of the carrier of microorganisms, in particular Mycobacterium of tuberculosis, in the body of insects. And the complete elimination of the disease without perfect knowledge of potential reservoirs and carriers of the causative agent of the disease is impossible.

The objects of research in this study were beetles-pests of grain stocks. In Ukraine, the most common representatives of this group are weevils of the genus *Sitophilus*, namely, the rice weevil. Numerous foreign research papers indicate that beetles of this genus are end carriers of gamma-proteobacteria of the species *Sodalis pierantonos*. These microorganisms are involved in the formation of the beetle's cuticle. Morphologically *S. pierantonos* is a gram-negative rod with a length of 3-4 to 100 μm, a diameter of 1-2 μm, and a microbial cell surrounded by mucopolysaccharide substances. *S. pierantonos* – an intracellular microorganism that is cultivated exclusively in the body of weevils and is not cultivated on a nutrient medium. The number of these bacteria in the beetle's body varies throughout its life cycle: in the larval stages there are many of them, and in adult insects it decreases sharply or disappears altogether after the final cuticle formation [10-12].

The purpose of the study is to investigate the epizootological significance of the rice weevil *Sitophilus oryzae* as a reservoir for *Mycobacterium bovis* in the process of occurrence and spread of tuberculosis.

Research objectives: to establish the duration of the transmission and secretion of *Mycobacterium bovis* into the external environment with infected beetles.

MATERIALS AND METHODS

The research was conducted in the training laboratory of the Department of epizootology and Infectious Diseases of animals of the Dnipro state agrarian and economic University during 2020. The subject of the study were cultures of the dissociative form of *Mycobacterium bovis* (passage 118, microscopy revealed acid-resistant red grains), which were stored in the museum of the department and beetles-pests of grain stocks, in particular the rice weevil (lat. *Sitophilus oryzae*), from the family *Curculionidae* (Fig. 1).

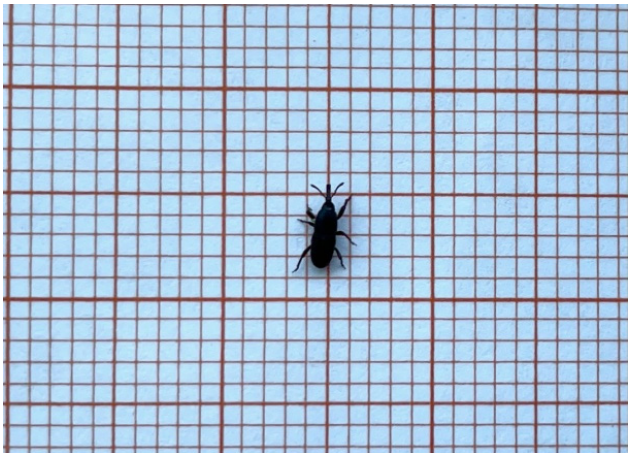

Figure 1. *Rice weevil (lat. Sitophilus oryzae)*

Prior to the start of experimental infection, to exclude the existence of *Mycobacterium bovis* in beetles,

insects were examined by microscopy for the presence of acid-resistant rods. For this purpose, the beetles were washed three times in an isotonic 0.9% sodium chloride solution and smeared on a slide, followed by staining smears according to the Ziehl-Neelsen method.

For the study, an experimental group of beetles was created, which included 50 rice weevils. Experimental beetles were kept in grain treated with a suspension prepared from the culture *Mycobacterium bovis* with subsequent repeated transplantation into sterile grain during the experiment.

For experimental infection of beetles, pre-autoclaved wheat grains were contaminated for 20 minutes at 1.5 atm. For grain contamination with mycobacteria, a suspension from a dissociative strain of *Mycobacterium bovis* (118 passage) was prepared in the proportion of 10 mg of bacterial mass of *Mycobacterium bovis* in 1 cm^3 isotonic 0.9% sodium chloride solution for every 10 g of grain, a total of 20 g of grain and, accordingly, 20 mg of crop per 2 cm^3 solution were used. Adult beetles (50 pieces) were placed in grain contaminated with *M. bovis* for 3 days, on the 4th day the beetles were moved to sterile grain for another 4 days, after which they were again transferred to sterile wheat grain until the 12th day of the experiment, the next transplantation was done on the 20th day of the experiment. Further on, the beetles were moved every 10 days until the experiment was completed to determine the duration of the transfer.

During this time, on days 4, 8, 12, 20 and then every 10 days (up to 90 days inclusive), a microscopic examination of the suspension from grain was carried out after the weevils stayed in it and the beetles themselves were examined directly for the content of mycobacteria. For this purpose, beetles were selected from the experimental group, washed with an isotonic 0.9% sodium chloride solution 3-5 times, depending on the previous results, each time examining the washing samples under an immersion microscope system. After washing, the beetles were smeared on a slide, and the homogenisate was stained according to the Ziehl-Neelsen method.

In addition, on the 30th, 60th, and 90th days of the experiment, beetles pre-washed with sodium chloride solution were pulverised, a suspension was prepared, which was sown on a Mordovsky nutrient medium ("Novaya"). After transplanting the beetles, samples of grain were taken for the study, in which the weevils stayed for a certain time (4-10 days, according to the method). It was added to a mortar with a sterile isotonic 0.9% sodium chloride solution and kept for 30 minutes in a sterile box, after which it was ground. A smear was made from the resulting suspension, stained according to Ziehl-Neelsen method and sown on a Mordovsky nutrient medium ("Novaya"). Grain and beetles that remained after the experiment were decontaminated by autoclaving at 1.5 atm for 3 hours.

The viability of microbial cells was also determined by evaluating colony-forming units (CFU) by serial dilutions [13-15]. For the study, *Eppendorf* microtubes were used, a sterile isotonic 0.9% sodium chloride solution in an amount of 0.5 cm^3 was added in the first test tube and 0.4 cm^3 in the next tubes. The bacterial mass was taken from a test tube using a wire inoculating loop, squeezed between sheets of filter paper, and weighed 50 mg (0.05 g) using a torsion scale. The weighted bacterial mass was placed in micro-tube No. 1 and suspended, thoroughly mixing with an inoculation loop. 0.1 cm^3 of suspension was taken using an insulin syringe, the resulting suspension was transferred to test tube No. 2, thoroughly mixed, and 0.1 cm^3 was taken again and transferred in the next test tube up to the 10th iteration. After that 1 cm^3 of suspension was taken from each microtube using separate insulin syringes, which was introduced into two test tubes with Mordovsky nutrient medium and evenly distributed over the surface. Further on, the test tubes were placed in a thermostat at a temperature of +37 °C

When determining the viability of microbial cells of the initial culture by evaluating CFU, calculations were made in the 8th dilution in the study of the initial culture and in the 7th dilution in the study of the culture that grew from beetle homogenisate on the 30th day of the experiment. These breeding grounds were chosen because the smaller one showed continuous growth, and the larger one showed no colony growth. After the appearance of colony growth, the number of viable microorganisms in 1 g of the experimental culture was mathematically calculated. Statistical analysis of the findings was performed in the Microsoft Office Excel software application.

RESULTS AND DISCUSSION

Microscopic examination of washing samples and homogenisate from beetles before experimental infection revealed non-acid-resistant cocci (Fig. 2). This means that the beetles were carriers of non-acid-resistant microorganisms before the study began. After conducting an experimental infection of beetles, microscopic examination of the latter revealed blue and red grains, which indicates successful infection of insects with the experimental strain *M. bovis*.

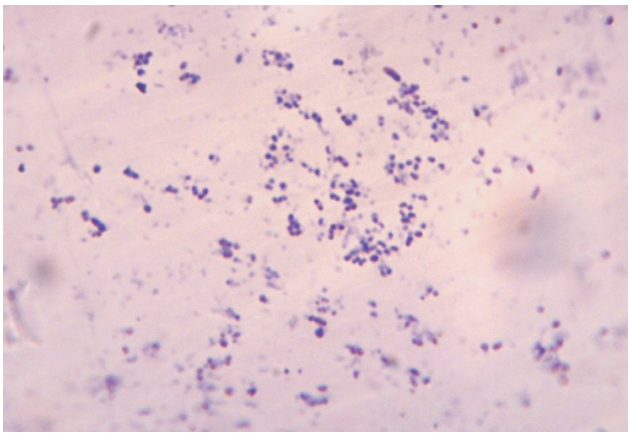

***Figure 2**. Microorganisms from beetle homogenisate before experimental infection*
***Notes**: Ziehl-Neelsen colour scheme*

Washing samples. According to the study results, it was found that during smear microscopy on Days 4 and 8, acid-resistant (red) and non-acid-resistant (blue) cocci were detected up to and including the fourth washing of beetles. On days 12, 20, 30, and 40 up to and including the third wash, microorganisms were detected by the microscopy, and on days 50 and 60 up to the second wash. On day 70, bacteria were detected only in the washing samples after the first rinse. By day 50, acid-resistant and non-acid-resistant cocci were detected, with a gradual decrease in the number of microorganisms, and by day 70, only non-acid-resistant cocci were detected. On days 80 and 90, micro-organisms were absent from the microscope view during the analysis of washing samples (Fig. 3).

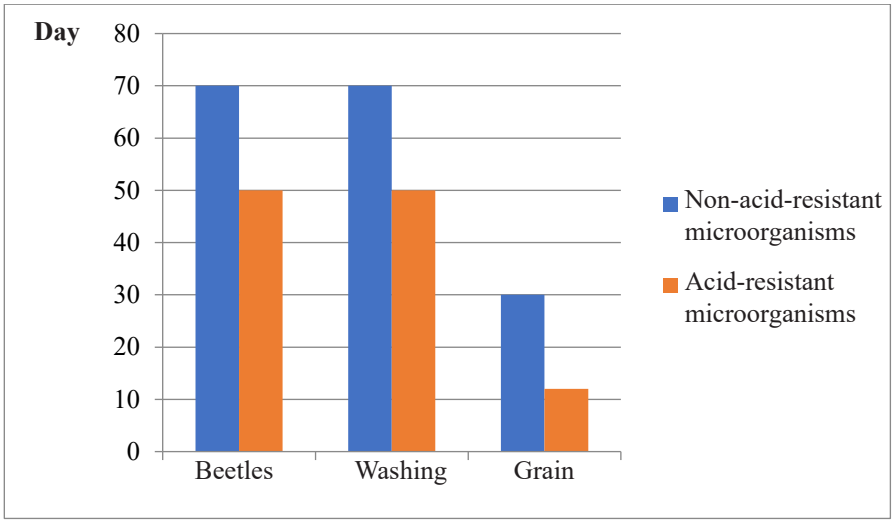

Figure 3. *Duration of isolation of microorganisms from the experimental material (days)*

Bugs. During microscopy of smears of infected beetles, red grains were found in their body up to the 50th day. That is, acid-resistant microorganisms that were contaminated with grain at the beginning of the experiment and blue cocci, non-acid-resistant microorganisms that the beetles were carriers of before infection, also with a gradual decrease in the number of microorganisms, starting from the 20th day of the study (Fig. 4). After the 50th day of the experiment, no bacteria identical to the dissociate Mycobacterium culture that was studied were found in the experimental samples, but by the 70th day, non-acid-resistant cocci were still detected (Fig. 5). On days 80 and 90, no bacteria were present during the microscopic examination.

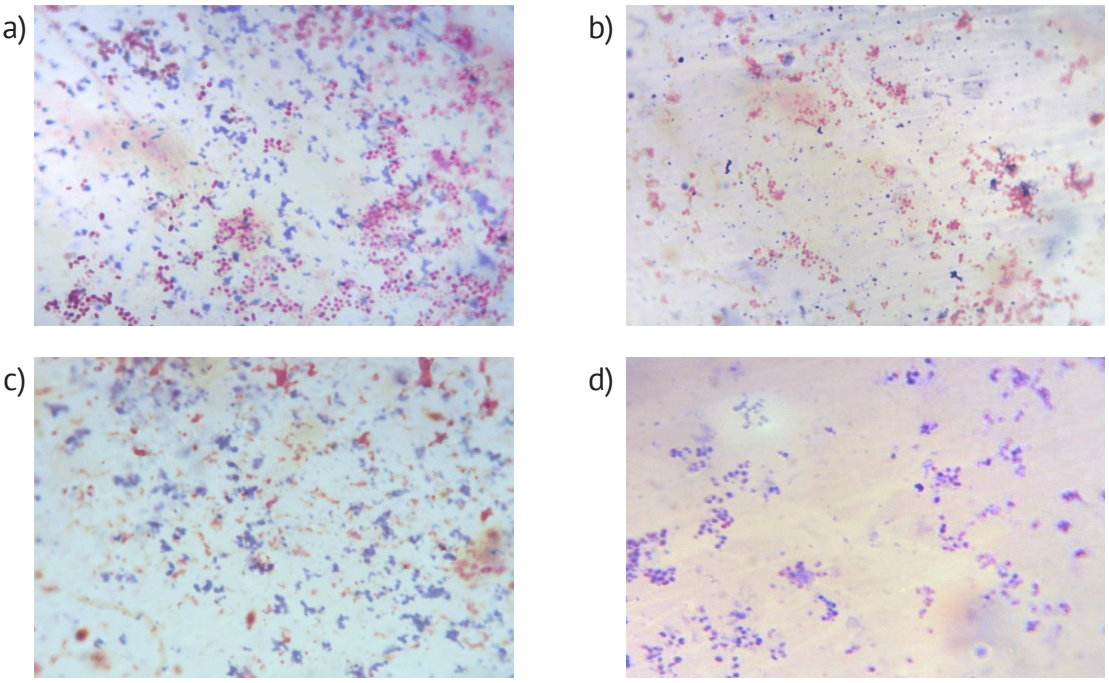

Figure 4. *Microorganisms from beetle homogenisate by day: a) – on the 4th day of the experiment, b) – on the 20th day of the experiment, c) – on the 40th day of the experiment, d) – on the 50th day of the experiment*

Notes: *Ziehl-Neelsen colour scheme*

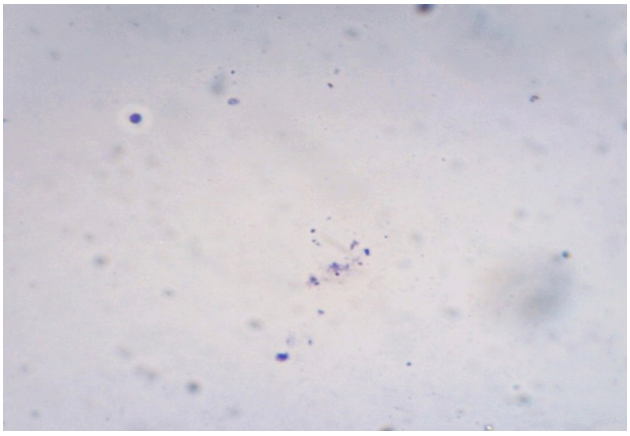

Figure 5. *Microorganisms from beetle homogenisate on the 70th day of the experiment*
Notes: *Ziehl-Neelsen colour scheme*

When sowing homogenisate from beetles on the Mordovsky nutrient medium:

– on day 30 of the experiment: on the nutrient medium (on day 12 after sowing), the growth of single rounded smooth orange colonies with smooth edges was recorded (Fig. 6), identical to the original culture (red grains under microscopy (Fig. 7a)) and the growth (on day 8) of light yellowish rounded S-shaped colonies (blue cocci under microscopy (Fig. 7b));

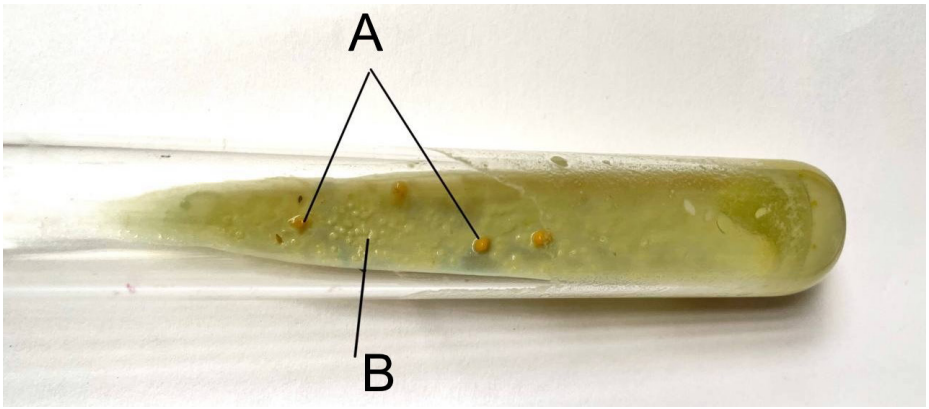

Figure 6. *Colonies of microorganisms from beetle homogenisate on the 30th day of the experiment: A – rounded orange colonies (acid-resistant bacteria); B – yellow rounded colonies (non-acid-resistant bacteria)*

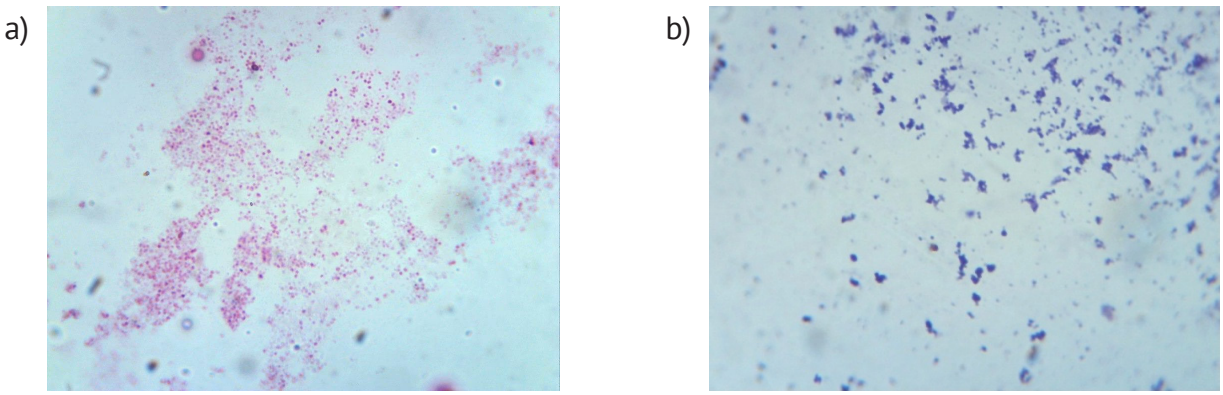

Figure 7. *Microorganisms from colonies from beetle homogenisate on the 30th day of the experiment from the nutrient medium: a) – from orange colonies; b) – from yellow colonies*
Notes: *Ziehl-Neelsen colour scheme*

– on day 60 of the experiment: the growth of light yellowish rounded S-shaped colonies was recorded on the nutrient medium (Fig. 8) on the 13th day of the experiment (blue cocci under microscopy (Fig. 9));

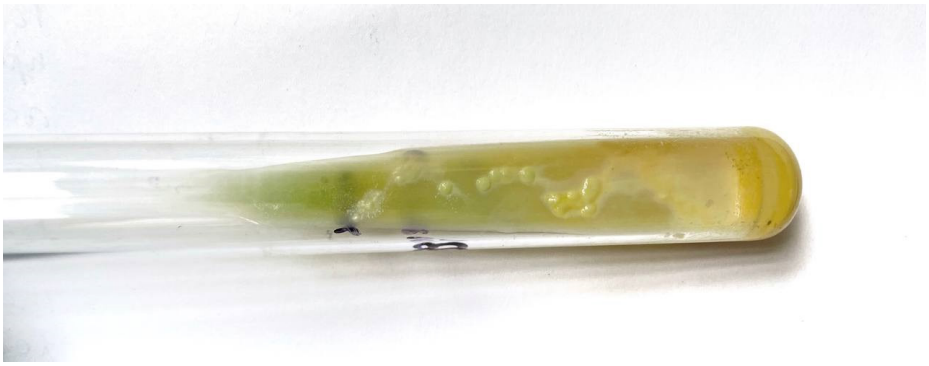

Figure 8. *Colonies of microorganisms from beetle homogenisate on the 60th day of the experiment*

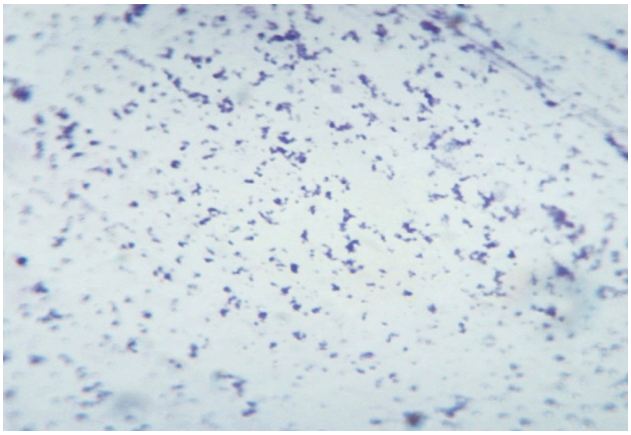

Figure 9. *Microorganisms from beetle homogenisate on the 60th day of the experiment from the nutrient medium*

Notes: *Ziehl-Neelsen colour scheme*

– on day 90 of the experiment: on the medium, the growth of light yellowish rounded S-shaped colonies (Fig. 10) on the 22nd day of the experiment (blue cocci under microscopy) (Fig. 11).

Figure 10. *Colonies of microorganisms from beetle homogenisate on the 90th day of the experiment*

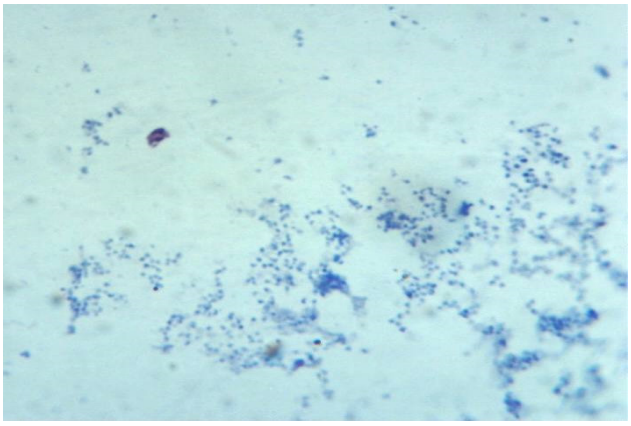

Figure 11. *Microorganisms from colonies from beetle homogenisate on the 90th day of the experiment from the nutrient medium*

Notes: *Ziehl-Neelsen colour scheme*

Thus, the findings indicate the ability of beetles to accumulate microorganisms in their body for quite a long time and be a reservoir of the causative agent of infection.

Grain. Microscopic examination of the grain on which the experimental beetles were kept revealed acid-resistant (red) grains on the 4th day of the experiment, that is, after one beetle transplantation. On days 8 and 12, i.e., after the second and third beetle transplantations, respectively, microscopy of grains revealed acid-resistant (red) and non-acid-resistant (blue) cocci. Further on, no bacteria were found in the grain that would be

identical to the Mycobacterium culture that was studied. However, during microscopic examination of the grain on the 20th and 30th days of the experiment, non-acid-resistant cocci were found. Microscopy on days 40, 50, 60, 70, 80, and 90, i.e., from the sixth to the eleventh beetle transplantation, no microorganisms were detected by the microscope. Consequently, non-acid-resistant microorganisms were detected by the 12th day of the experiment (i.e., by the third beetle transplantation), and acid-resistant microorganisms were detected by the 30th day (i.e., by the fifth transplantation).

When sowing a suspension of grain on a Mordovsky nutrient medium on day 4, that is, after one beetle transplantation, the growth of orange rounded colonies with smooth edges was detected, which have the appearance of red grains (identical to the original culture) on day 12. When sowing a suspension from grain on the 8th, 12th, 20th and 30th days of the experiment (i.e., after the second or fifth beetle transplantation), the growth of light yellowish rounded S-shaped colonies (blue grains under microscopy) and orange rounded colonies (identical to the original culture) was detected on the nutrient medium. When the suspension was sown on days 40 and 50 (i.e., after the sixth or seventh beetle transplantation), only light yellowish S-shaped colonies (non-acid-resistant cocci under microscopy) were found to grow, and no growth of dissociative mycobacteria identical to the experimental cultures was detected. No growth was detected on days 60-90.

The presence of microorganisms in the grain that was sterile before the beetles were transplanted suggests that insects play the role of a mechanical and probably biological carrier of the pathogen. Given that the duration of isolation of blue and red grains was not the same, it can be assumed that the period of isolation of non-acid-resistant bacteria was longer than the isolation of acid-resistant microorganisms due to the fact that initially the density of non-acid-resistant bacteria was higher.

It was found that the number of colonies that grew during the eighth dilution of the initial culture was 317 in test tube No. 1 (sample No. 1) and 359 in test tube No. 2 (sample No. 2) (Table 1). According to the CFU assessment methodology, the average value was determined for further calculations, it is equal to 338 (colonies in 0.00064 mg of culture (eighth dilution)), respectively, in 1 g of the original culture 528125000 or $5.3*10^8$ viable microorganisms. And when determining the CFU of the culture that grew after sowing homogenisate from beetles on the 30th day of the experiment, it was found that during the seventh dilution, 419 colonies grew in test tube No. 1 (sample No. 1) and 465 in test tube No. 2 (sample No. 2), the average value was 442 colonies in 0.0032 mg of culture (seventh dilution), respectively, in 1 g of culture 138125000 or $1.4*10^8$ viable microorganisms.

***Table 1**. Assessment of colony-forming units of dissociative form of Mycobacterium bovis (118 passage) in the dynamics of experiment*

	Source culture	Culture of homogenised experimental beetles on the 30th day of the experiment
Sample No. 1	317*	419**
Sample No. 2	359*	465**
M±m	338±29.7	442±32.5
Number of CFU in 1g of culture	$5.3*10^8$	$1.4*10^8$

***Notes**: * The number of grown colonies on the nutrient medium for the eighth dilution (0.00064 mg of culture); ** the number of grown colonies on the nutrient medium for the seventh dilution (0.0032 mg of culture)*

When determining the CFU, it was found that the number of viable microorganisms in 1 g of the initial culture was higher than in 1 g of the culture isolated from beetles on the 30th day of the experiment, which may indicate a decrease in the viability of microbial cells after mycobacteria pass through the beetle body. A two-sample t-criterion with different variances was used to assess the reliability of the ratio of the initial culture to the culture obtained from homogenised beetles. The value of p=0.04, which indicates high (96%) statistical reliability.

The problem of the widespread and rapid spread of tuberculosis still requires deepening existing knowledge. Thus, science does not have perfect data on all possible reservoirs of Mycobacterium tuberculosis. After analysing the study results, it was found that these data complement the existing findings of other researchers. The study results confirm that beetles, in particular rice weevils, can be a reservoir of mycobacteria and participate in the active spread of tuberculosis and transmission of the causative agent of infection to susceptible animals. Perhaps it is insects that are one of the main causes of tuberculosis in previously safe places.

After experimental infection of beetles with a dissociative strain *M. bovis*, they were kept on pre-sterilised wheat grain, periodically transplanting the insects into a new grain. Microscopic examination of the grain suspension, after transplanting the experimental beetles, revealed acid-resistant bacteria (identical to those that infected the beetles) for up to 12 days, that is, for three transplantations. Culture studies of grain suspensions revealed the growth of rounded orange colonies with

smooth edges (identical to the original culture) on the nutrient medium for up to 30 days, during which time five beetle transplantations were made into a new sterile grain. These data indicate that the beetles isolated mycobacteria from their bodies during this time and contaminated the grain. The results obtained do not contradict the research by O.A. Fischer et al., which found that microorganisms, in particular mycobacteria, are able to remain viable in the intestines of insects for a certain time and release bacteria into the external environment [5]. Similar data can be traced in other researchers, for example, B.W. Allen and J. Guzman & A. Vilcinskas reported that after passing through the intestines of cockroaches, viable mycobacteria can be released with faeces into the external environment [16; 17].

F. Portaels et al. suggested the theory that animals can be infected with mycobacteria through insect bites, and Marsollier et al. reported that *Mycobacterium ulcerans* are transmitted to rodents through the bites of water bugs from the family *Naucoridae* [18; 19]. J. Kazda notes that mycobacteria, due to their cell wall structure, are resistant to the action of insect gastric enzymes, as a result of which they can be excreted in both saliva and faeces [20]. In addition, the study, L. Durnez et al. reports of isolation of mycobacteria from the body of insectivorous animals and rodents [21]. The ingestion of mycobacteria in their body may have occurred as a result of eating infected insects, which is quite a natural phenomenon, analysing our results. Known data suggest that beetles infected with mycobacteria can be captured by animals or birds susceptible to tuberculosis and digested, while acid-resistant mycobacteria, for their part, remain viable and can persist in the body and be released into the external environment.

Thus, summing up this study and the work of many researchers, it can be argued that insects, in particular the rice weevil, can participate in the process of the emergence and spread of tuberculosis.

CONCLUSIONS

According to the study results, it was found that the rice weevil can accumulate pathogenic microorganisms, in particular *Mycobacterium of tuberculosis,* and able to release them into the external environment, contaminating it, and remain a reservoir of the causative agent of infection for quite a long time. Microscopy revealed acid-resistant grains in the beetle's body for up to 50 days, and non-acid-resistant cocci for up to 70 days of the experiment. Microscopic examination of beetle smear samples revealed microorganisms up to 70 days of the experiment (acid-resistant bacteria – up to 50, and non-acid-resistant ones-up to 70 days inclusive). When sowing homogenisate from beetles on a nutrient medium, the growth of orange colonies (identical to the colonies of the original culture) was detected up to 30 days of the experiment, and the growth of yellow S-shaped colonies (blue cocci under a microscope) up to 90 days of the experiment. At the same time, when evaluating the CFU of a dissociative strain M. bovis a decrease in the viability of mycobacteria after passing through the body of beetles on the 30th day of the experiment was established.

Microscopic examination of the grain suspension revealed acid-resistant bacteria up to 12 days of the experiment, that is, after three beetle transplantations, and non-acid-resistant microorganisms were detected up to 30 days of the experiment. When sowing grain suspensions on a nutrient medium, the growth of orange colonies (identical to the original ones) was detected up to 30 days of the experiment, i.e., after five beetle transplantations, and the growth of yellow S-shaped colonies was detected up to 50 days, i.e., after seven beetle transplantations. The data obtained indicate the ability of the rice weevil to accumulate mycobacteria in its body for 50 days and release them into the external environment for 30 days.

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Епізоотологічне значення рисового довгоносика як резервуара *Mycobacterium bovis*

Олексій Андрійович Ткаченко[1], Кіра Володимирівна Аліфонова[1*], Олена Геннадіївна Гавриліна[1], Амелія Найт[2]

[1]Дніпровський державний аграрно-економічний університет
49600, вул. Сергія Єфремова, 25, м. Дніпро, Україна

[2]Північно-Південний університет
1229, Плот 15, Блок Б, Башундхара, м. Дакка, Бангладеш

Анотація. У даній статті наведені матеріали щодо ролі рисового довгоносика (лат. *Sitophilus oryzae*) у процесі передачі мікобактерій туберкульозу. Актуальність проведеного дослідження обумовлена стрімким поширенням туберкульозу по всьому світу та необхідністю розробки більш досконалих методів діагностики даного захворювання, що, зі свого боку, є неможливим без розширення знань з питання всіх можливих резервуарів збудника інфекції. Багаторічними дослідженнями науковців світу доведено, що комахи є переносниками різної мікрофлори, зокрема й патогенної. Тому метою наукового дослідження було встановлення епізоотологічної ролі рисового довгоносика як резервуару *Mycobacterium bovis* у процесі виникнення та поширення туберкульозу. У науковій статті було визначено тривалість носійства та виділення мікобактерій туберкульозу в зовнішнє середовище зараженими жуками. Для проведення дослідження використовували музейний дисоціативний штам *Mycobacterium bovis* (118 пасаж), предметом дослідження були рисові довгоносики. Для досягнення встановленої мети авторами були проведені культуральні, мікроскопічні та статистичні дослідження, а також визначена життєздатність мікобактерій, після пасажів через організм жуків, шляхом оцінки колонієутворюючих одиниць. Встановлена епізоотологічна роль рисового довгоносика в процесі виникнення та поширення туберкульозу. Доведено, що жук може впродовж 50 діб утримувати мікобактерії у своєму організмі з поступовим зменшенням їх кількості й надалі здатний виділяти збудника ще 30 діб, контамінуючи об'єкти зовнішнього середовища. При оцінці колонієутворюючих одиниць мікобактерій у динаміці досліду виявлено зниження їх життєздатності після персистенції через організм жуків з $5,3*10^8$ в 1 г вихідної культури до $1,4*10^8$ в 1 г культури, яка виросла з гомогенізату жуків на 30 добу. Наведені результати дослідження дозволять розробити та удосконалити вже існуючі правила профілактики туберкульозу та недопустити занесення даної інфекції на благополучну територію

Ключові слова: мікобактерії, дисоціативний штам, інфекція, жуки-шкідники зернових запасів, колонієутворюючі одиниці

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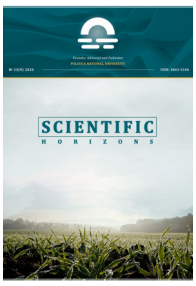

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Conditions for the Development of Phase Components $K_2CaP_2O_7$, $KCaP_3O_9$ in Toxic Dust

Anar K. Zhumadilova*, Elmira B. Madaliyeva, Saule Z. Zhigitova

M.Kh. Dulaty Taraz Regional University
080012, 7 Suleymenov Str., Taraz, Republic of Kazakhstan

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Abstract. The present study analyses the composition and main components of toxic dust. To develop and understand the methods of controlling the dust generation process, it is necessary to study the data that provide detailed information about the reaction mechanism. The results of studies of the phase composition of dust conducted in the laboratory and their comparison with the data obtained earlier by other authors allowed establishing a fairly reliable diagnosis of the phase composition of dust. The analysis revealed that the dust of various phosphorus plants comprises the same basic components, yet the chemical bonds between them differ. The purpose of this study, conducted in the research laboratory of the Zhambyl Branch of LLP "Kazphosphate" (NDFZ) is to investigate the possibility of using new toxic dust, as well as the toxic dust from storage tanks to obtain NPK fertilisers. The study comprises three stages of investigating the oxidation of elementary phosphorus with nitric acid, since elementary yellow phosphorus is dangerous for the environment. As a result of the 1st stage of the study, it was found that toxic dust oxidised with nitric acid cannot be used as a fertiliser, since a non-technological mass is generated, such as acid resin, which is not suitable for drying and granulation. To neutralise the acid reaction mass, it was decided to use an aqueous solution of ammonia, thereby increasing the nutrient content and obtaining a complex NPK fertiliser. In the course of the study, the authors found in the 2nd and 3nd stages of the experiment that to obtain a productsuitable for fertilisation, it is necessary to strictly control the content of elemental phosphorus in the initial toxic dust and adjust the consumption of nitric acid based on its results

Keywords: nitric acid, carbon, phosphorus, sample, temperature, experiment

*Corresponding author

INTRODUCTION

The development of methods for controlling the dust generation process is impossible without information about the reaction mechanism. In general, it leads to the generation of individual dust components. Information about this is not found in the literature. Until recently, the scientific literature contained only scattered and incomplete data on the composition of dust [1]. The results of studies of the phase composition of dust conducted in the laboratory and their comparison with the data obtained earlier by other authors allowed establishing a fairly reliable diagnosis of the phase composition of dust. It was found that the dust of various phosphorus plants comprises the same basic components, and only the chemical bonds between them change. Such components are as follows: silicon dioxide, double calcium and potassium pyrophosphate, double calcium and potassium metaphosphate. The mass of the total content of these components in dust often reaches 30%. The average phase composition of the dust of various phosphorus plants is presented in Table 1 [5; 6].

***Table 1**. The average phase composition of the dust of various phosphorus plants*

Phase	Composition (% of weight)
SiO_2 (amorphous)	
$K_2CaP_2O_7$	
$KCaP_3O_9$	31
C	20
CaF_2	38
K_2SiF_6	
KCl	
$Ca_2P_2O_7$	11
$KCaPO_4$	

To investigate the conditions for the development of double pyro-, meta-, potassium-, calcium phosphates, the authors of this study calculated the thermodynamic probability of the development of these salts from compounds K_2O, KPO_3, CaO, P_2O_5, which are the furnace gas components. The calculation results are presented in Table 2 [7].

***Table 2**. Thermodynamic characteristics of reactions between furnace gas components*

Seq. No.	Reaction	ΔN 298°C kcal/mol	ΔG -298°C kcal/mol	ΔG 1773°C kcal/mol
1	$K_2O + CaO + P_2O_5 \rightarrow K_2CaP_2O_7$	-187.0	-185.0	-159
2	$2KPO_3 + CaO \rightarrow K_2CaP_2O_7$	-45.0	-44.7	43.0
3	$K_2O + 2CaO + 3P_2O_5 \rightarrow 2KCa(PO_3)_3$	-294.0	X*	–
4	$3KPO_3 + CaO \rightarrow KCa(PO_3)_3 + K_2O$	+66.0	+67.0	–
5	$KPO_3 + CaO + P_2O_5 \rightarrow KCa\ (PO_3)_3$	-76.0	-73.6	–

***Note**: X* – for compounds involved in the reaction, the calculation was not performed due to the lack of thermodynamic constants in the literature*

Thus, from a thermodynamic standpoint, the reaction (reactions 1 and 3) of formation of double pyrophosphate and double metaphosphate from K_2O, CaO, P_2O_5 is possible in the furnace process. Reactions involving HPO_3 are less probable, and in the absence of P_2O_5 are not realised. According to the results of thermodynamic calculations, the study revealed the synthesis of these double compounds. Potassium metaphosphate KH_2PO_4 was pre-formed by heating according to a two-stage method: at t= 100°C, the water is evaporated, then the crucible is slowly cooled, and then heated to 325°C for 1 hour. The diagnosis of obtaining pure KPO_3 by infrared spectroscopy and X-ray phase was made.

The purpose of this study, conducted in the research laboratory of the Zhambyl Branch of LLP "Kazphosphate" (NDFZ) is to investigate the possibility of using freshly yielded toxic dust, as well as the toxic dust from storage tanks to obtain water-soluble complex (NPK) fertilisers.

THE REASONS FOR THE EMERGENCE OF RED PHOSPHORUS IN THE TOXIC DUST OF THE NDFZ (NEW ZHAMBYL PHOSPHORUS PLANT)

The special composition of the dry residue of the toxic dust was observed at the NDFZ since the launch of the plant into operation. If the phosphorus content is expressed through P_2O_5, then the sum of the constituent elements exceeded 100%. The studies performed in the laboratory of the Physico-Chemical Research Methods and Analyses (PCRMA) on several samples of elemental phosphorus Py (from benzene extract) and the total (distillation) type amount to 5%. Toxic dust from the NDFZ showed the difference between the definitions. Since it was assumed that the elements in toxic dust are represented by red phosphorus, the derivatograms of the dry residue of the dust and the red phosphorus sold were removed [8; 9].

According to the derivatogram in Figure 1, the oxidation process of red technical phosphorus proceeds in several stages:

1. The onset of oxidation is observed at 240°C, which is manifested on the thermogram in the form of an exoeffect accompanied by an increase in the sample mass.
2. The second stage of oxidation begins at 350-360°C and is accompanied by an intensive increase in the sample mass.
3. The third stage of oxidation begins at 450-470°C and is accompanied by an intense increase in the sample mass.

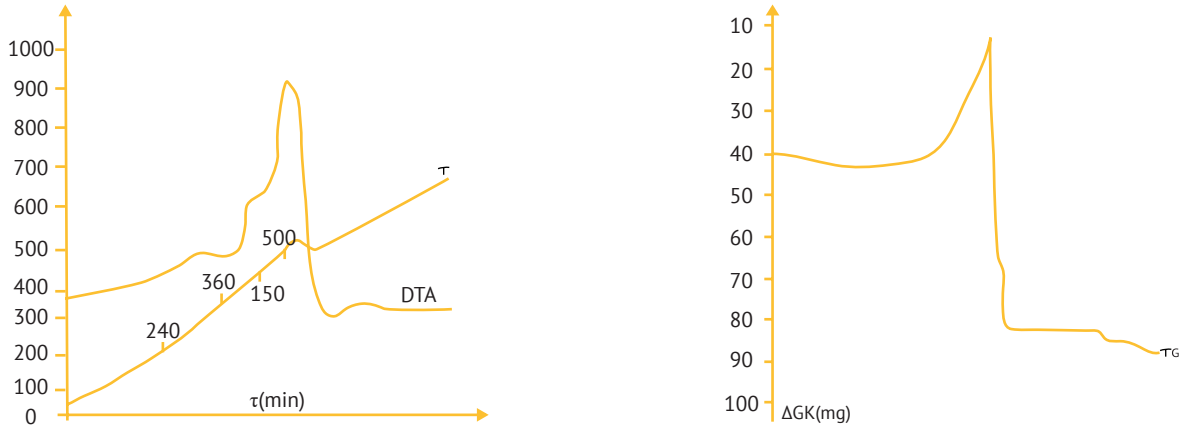

***Figure 1**. Derivatogram of technical red phosphorus*

At temperatures above 500°C (after the end of the exoeffect), a sharp decrease in the mass of the sample begins, which corresponds to the generation of volatile forms of P_2O_5 (white vapour can be visually observed).

On the thermograms of the studied samples of toxic dust (Fig. 2), the oxidation process begins at 200-230°C and is accompanied by an intensive increase in the sample mass to a temperature of 400-420 °C.

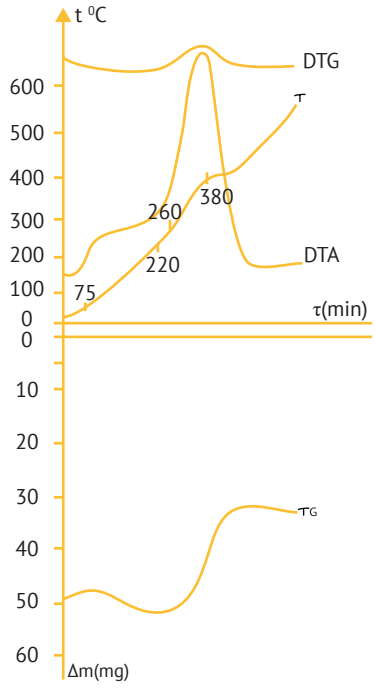

***Figure 2**. Dervitogram of the solid phase of toxic dust*

During the experiments in the electrothermy laboratory in an inert medium, a light brown condensate was yielded, heated by the dry residue of the toxic dust to 280-350 °C. Like red phosphorus, it is stable in air and does not dissolve in organic solvents, but ignites at a temperature lower compared to red phosphorus and instantly discolours a weakly coloured solution of $KMnO_4$ (red phosphorus discolours when left to stand undisturbed). Upon combustion it gives off white smoke P_2O_5, like red phosphorus. This suggests that the elementary phosphorus in the test sample has the form of a polymer with a less ordered structure than commercial red phosphorus (when the structure is regulated, the inertia of phosphorus increases) [10].

The study analysed the samples of Sholaktau phosphorite, Zhanatas shale, NDFZ agglomerate in pure form and with a mixture of coke. The light-brown plate on the first gas filter was found only in the agglomerate, while the coke mixture did not increase the yield. Spectral analysis of the coated part of the filter confirmed that the main composition of the light-brown sublimation is phosphorus. When heated up to 8000°C, the filters remained clean, the polymer form transforms into P4 and re-mains in the gas phase [11].

Upon developing a method for determining various forms of carbon in the agglomerate with the preservation of samples in nitrogen, in some cases, a decrease in carbon was detected at 5000°C. Conventionally, it was called "active carbon". It has been suggested that the agglomerate takes part in the low-temperature reduction of certain secondary phosphates generated upon the decomposition of phosphorites during carbon agglomeration. 3 samples with a relatively high total carbon content were tested (Table 3), but various carbon losses were observed at 5000°C, various carbon losses were observed in nitrogen, the third sample was selected in the absence of P0 in the factory dust. Perhaps P0 is not a consequence of low-temperature reduction of phosphites, for example, heavy metals, but a product of the decay of low-temperature phosphates, an intermediate form of reduction of ortho-, pyro-, metaforms.

Table 3. *Comparative analysis of carbon losses in nitrogen at 5000°C*

Sample No.	Amount of carbon		The increase in the mass of the filter compared to a blank, (g)
	Total	$N_{2\ at}$ 500°C	
1	1.13	0.62	0.0005
2	1.06	0.36	0.0011
3	1.47	1.24	n/a

However, upon processing the agglomerate, it is inevitable that polymer phosphorus can be released into the toxic dust, and this is conditioned upon the action of residual carbon. Since P0 is oxidised in the liquid phase, oxidants must be introduced upon dust processing [12].

INVESTIGATION OF THE OXIDATION OF ELEMENTAL PHOSPHORUS BY NITRIC ACID IN LABORATORY CONDITIONS

The study comprised three stages of investigating the oxidation of elementary phosphorus with nitric acid, since elementary yellow phosphorus is dangerous for the environment:

– investigation of the possibility of yielding NPK fertilisers from freshly generated toxic dust and dust mixture from components stored for a long time (up to 20 years);

– study of the possibility of yielding NPK fertilisers from fresh toxic dust [13].

The method of investigation of the oxidation of simple phosphorus was as follows. The content of simple yellow and red phosphorus in toxic dust prepared with the ratio S:L=1:1 (S — solid, L — liquid phase) was identified according to the following methods. Upon constant stirring with a laboratory mixer at a speed of 600 rpm, 56% nitric acid was poured into the dust placed in a porcelain glass in a thin stream and kept at a temperature of 65-700°C for 2 hours. By changing the ratio of toxic dust and nitric acid, complete oxidation of yellow phosphorus in the test sample (99.7%) was achieved (Table 4). The oxidation process of red phosphorus occurring under the action of nitric acid was observed mainly throughout the entire period of research until the emergence of lower phosphate forms [14].

As a result of the 1st stage of the study, it was found that toxic dust oxidised with nitric acid cannot be used as a fertiliser, since a non-technological mass is generated, such as acid resin, which is not suitable for drying and granulation. To neutralise the acid reaction mass, it was decided to use an aqueous solution of ammonia, thereby increasing the nutrient content and obtaining a complex NPK fertiliser. The method of conducting experiments to obtain NPK fertiliser from a mix of toxic dust and a new mixture of toxic dust was as follows. The authors of the study analysed the preformed, average, and sufficient amount of dust yielded from a disk from a depth of 1 m, and fresh dust with a ratio of S:L=1:1. The results of the analysis are presented in Table 5, columns 4, 5. 0.8 weight part of the toxic dust in the current formation and 1.1 weight part of 56% nitric acid were added to one weight part of the

toxic dust from the mixer, while stirring constantly at a temperature of 60-70°C for 2 hours at a speed of 600 rpm in a laboratory mixer. Cellulose was neutralised with a concentrated ammonia solution to pH 6-7, dried, ground, sieved through a 0.5 mm sieve, analysed to prevent nitrogen loss at 600°C. The results of the analysis are presented in Table 5, Figure 1.

***Table 4**. The results of the analysis of toxic dust*

Seq. No.	Analysed dust	The ratio of toxic dust and HNO_3	Analysis of toxic dust after oxidation with HNO_3						
			P yellow %	ortho-, poly-phosphate (P_2O_3), %	ortho-, poly-, lower phosphates (P 2O 5), %	P_2O_3, %	phospho-rus (P_2O_5), %	P red, %	The degree of oxidation of yellow P, %
1	Basic	–	0.3	9.8	11.2	1.1	12.3	0.5	–
2	After oxidation	1:0.5	0.04	10.2	12.3	1.6	13.0	0.3	86.7
3	-//-	1:0.8	0.01	10.3	12.5	1.7	13.0	0.2	96.7
4	-//-	1:1.1	0.001	10.4	14.0	2.8	14.1	n/a	99.7
5	-//-	1:1.3	0.001	10.4	13.7	2.6	13.5	n/a	99.7

***Table 5**. The empirical data on yielding NPK fertilisers*

Scheme No.	Analysis of the product on dry basis											
	H_2O, %	P yellow, ppm	ortho-, poly-phosph. P_2O_5, %	Σ ortho-, poly-, lower. P_2O_5, %	P_2O_3, %	P_2O_5 total, %	P red, %	P_2O_5 absorb., %	P_2O_5 water-soluble., %	CaO water-soluble, %	CaO total, %	N total, %
Scheme 1	11.1	170	22.5	25.1	2.0	25.2	0.04	20.0	9.9	0.4	7.1	8.5
Scheme 2	11.5	70	23.7	24.1	0.2	24.3	0.04	18.8	10.0	1.1	9.1	7.2
Scheme 3	12.6	50	21.3	21.7	0.3	22.1	0.17	16.5	8.6	0.2	10.2	7.5
Scheme 4	13.0	70	22.4	22.6	0.2	22.9	0.13	16.3	8.4	0.2	12.4	7.0
Scheme 5	12.2	40	22.4	22.8	0.3	23.2	0.17	16.2	7.9	0.4	12.5	6.8

To reduce the drying time and minimise the consumption of the ammonia solution, first 0.15 weight part, and then 0.3; 0.4; 0.6 weight parts of the phosphor are introduced into the mixture oxidised with nitric acid, while constantly stirred and heated to 60-700°C for 2 hours. The process was accompanied by intense, active gas generation. Then the cellulose was neutralised with an ammonia solution to pH 6-7 and dried at a temperature of 600°C. From the standpoint of the effectiveness of the neutralised reaction mass, the most optimal was the product obtained according to Scheme 4. It served as the basis for a set of statistical data with samples of toxic dust taken from the surface of the disk from different depths: 5 cm, 15 cm, 30 cm, 50 cm, 100 cm. The analysis results for toxic dust samples are presented in Table 4, columns 6-10, based on which the results of experiments on yielding NPK fertilisers are presented in Table 6.

Analysis of the data in Table 6 suggests that in this series of experiments, the oxidation process of elemental phosphorus turned out to be unsatisfactory. All samples had a characteristic smell of yellow phosphorus, the content of which in the samples was in the range of 150-840 ppm. Apparently, the samples taken from the samples were heterogeneous (the toxic dust in the storage was poorly averaged), and part of the nitric acid was spent on the oxidation of red phosphorus and lower phosphates in the lower layers of the storage [15].

Adjustment of nitric acid consumption was required. The basis for this series of experiments was again Scheme 4 of Table 5. The content of nitric acid – 1,7; 1,6; 1,4; 1,3, from the mass of toxic dust obtained from the storage. The experimental results are summarised in Table 7, diagrams 1-4. The analysis of the empirical data suggests that based on a toxic dust mixture and fresh toxic dust, it is possible to obtain a technological

product with the characteristics provided in Table 7. The purpose of the next stage of the study was to investigate the composition of the resulting product without the addition of toxic dust in the storage of NPK fertilisers obtained from toxic dust generated at that time. For the experiment, average samples of toxic dust were prepared, the analysis results for which are presented in Table 4, column 11. The previous method served as the basis for this series of experiments, but all the toxic dust was preformed and the required amount of nitric acid was selected empirically, factoring in the large amount of red phosphorus in the source dust.

***Table 6**. The analysis results for samples of toxic dust taken from the storage surface at different depths*

	Analysis of products on dry basis														
Level	H_2O, %	P yellow, ppm	ortho-, poly- phosphate (P_2O_5), %	Σ ortho-, poly-, lower. P_2O_5, %	P_2O_3, %	P_2O_5 total, %	P red, %	P_2O_5 absorb., %	P_2O_5 water-soluble, %	CaO water-soluble, %	CaO total, %	N total, %	N ammon., %	K_2O, % acid-degradable	Na_2O, % acid degradable
5 cm	10.0	230	11.6	25.5	10.8	25.2	-0.15	18.8	11.0	1.6	11.7	6.7	4.0	19.6	1.7
15 cm	9.0	220	23.7	25.0	1.0	25.4	0.15	18.0	11.3	1.7	10.9	6.7	3.0		
30 cm	5.0	840	23.5	27.0	2.7	31.6	2.0	19.2	12.1	1.9	11.0	7.6	3.1		
50 cm	8.8	150	25.4	27.9	1.9	30.9	1.3	18.0	11.1	1.6	11.0	7.2	3.2		
100 cm	14.6	360	25.4	27.0	1.2	29.6	1.1	19.0	10.3	1.4	10.9	7.5	3.4	19.4	1.7

***Table 7**. Study results*

	Analysis of products on dry basis												
Scheme No.	H_2O, %	P yellow, ppm	ortho-, poly-phosphate (P_2O_5), %	Σ ortho-, poly-, lower, (P_2O_5), %	P_2O_3, %	P_2O_5 total, %	P red, %	P_2O_5 absorb., %	P_2O_5 soluble, %	CaO soluble, %	CaO total, %	N total, %	N ammon., %
1	2.0	40	21.9	23.2	1.0	23.2	n/a	17.1	11.0	1.5	9.8	10.0	4.6
2	2.6	40	20.0	20.8	0.6	20.8	n/a	16.1	9.0	1.1	9.9	12.3	4.1
3	4.0	40	19.9	20.8	0.7	20.5	n/a	16.2	9.1	1.3	10.2	11.2	4.6
4	3.7	40	21.0	21.8	0.6	21.9	n/a	16.9	8.7	1.2	10.3	11.2	4.3

CONCLUSIONS

For a complex fertiliser, a product with acceptable characteristics has been successfully obtained. According to the content of absorbing and water-soluble P_2O_5, total and ammonium nitrogen, it is similar to the product currently obtained from a mixture of storage dust and freshly generated toxic dust, but due to the considerable content of elemental red phosphorus in the initial toxic dust, the content of total and incomplete oxidised phosphates P_2O_5 is much higher. The general conclusion based on the empirical data found at stages II and III: to obtain a product suitable for fertilisation, it is necessary to strictly control the content of elemental phosphorus in the initial toxic dust and adjust the consumption of nitric acid based on its results.

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Дослідження умов утворення фазових компонентів $K_2CaP_2O_7$, $KCaP_3O_9$ котрельного пилу та «молока»

Анар Каратаєвна Жумаділова, Ельмира Бегалієвна Мадалієва, Сауле Затибековна Жигітова

Хортицька національна навчально-реабілітаційна академія
69017, вул. Наукового Містечка, 59, м. Запоріжжя, Україна

Анотація. У статті проведено аналіз складу та основних компонентів котрельного пилу. Для розробки та розуміння методики управління процесом пилоутворення необхідно вивчити дані, що надають детальну інформацію про механізм реакції. Результати досліджень фазового складу пилу, проведених у лабораторії, і їх зіставлення з даними, отриманими раніше іншими авторами, дозволили встановити досить достовірний діагноз фазового складу пилу. Під час аналізу було встановлено, що пил різних фосфорних заводів складається з одних і тих же основних компонентів, тільки з'ясовується, що хімічні зв'язки між ними різні. Метою даної роботи, проведеної в дослідницькій лабораторії ДФ ТОВ «Казфосфат» (НДФЗ), є вивчення можливості використання нового котрельного молока і котрельного молока з накопичувачів для отримання NPK добрив. Дослідницька робота складалася з трьох етапів вивчення процесу окислення елементарного фосфору азотною кислотою, оскільки елементарний жовтий фосфор небезпечний для екології. У результаті 1-го етапу дослідження було встановлено, що котрельне молоко, окислене азотною кислотою, не може бути використано в якості добрива, оскільки утворюється нетехнологічна маса, така як кисла смола, яка не підходить для сушки і грануляції. Для нейтралізації кислотної реакційної маси вирішили використовувати водний розчин аміаку, тим самим збільшивши вміст поживних речовин і отримавши комплексне NPK добриво. У процесі дослідження авторами було встановлено на 2-му і 3-му етапах експерименту, що для отримання продукту, придатного для використання в якості добрива, необхідно строго контролювати вміст елементарного фосфору у вихідному котрельном молоці і за його результатами коригувати витрати азотної кислоти

Ключові слова: азотна кислота, вуглець, фосфор, зразок, температура, експеримент

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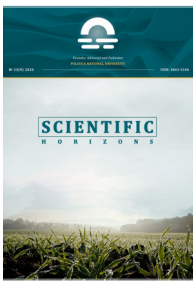

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Total and Fractional Composition of Water in Pear Leaves Depending on the Optimised Fertiliser

Roman Yakovenko*

Uman National University of Horticulture

20305, 1 Instytutska Str., Uman, Ukraine

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Abstract. The water content in tissues is an important indicator of the physiological state of the plant and is of great importance in the comparative assessment of their cultivation measures that increase productivity. One of such measures is rational fertilisation of plantings, which determines the relevance of the study. The purpose of the study was to establish the effect of optimised fertiliser on the water content in pear tree leaves and the fractional composition of water during stressful growing periods. One of the critical problems is drought, which negatively affects the growth and productivity of plantings. Under such conditions, the turgor of plant cells decreases and the passage of biochemical and physiological processes in the plant slows down. The paper considers the results of studying the water regime of leaves (the content of total, available, and inaccessible moisture) of pear varieties Konferentsia and Osnovianska on vegetative rootstock Quince A grown using optimised fertiliser in nonirrigated plantations. The study was conducted in 2011 and 2018 in a certified educational and research laboratory of the Uman National University of Horticulture. It was found that during the age periods of growth and fruiting, there was a change in the total water content in the pear leaves of the studied varieties. Leaves from pear trees of the Konferentsia variety had a higher water content compared to the Osnovianska variety. Fertiliser options increased the total water content in the leaves, which had a positive effect on the condition of the trees. It was found that at the beginning of the growing season, the free water content in the leaves of pear varieties Konferentsia and Osnovianska was higher, while it significantly decreased in the middle of the season. The bound water content was higher in all studied options. Under stressful situations (drought, temperature increase), fertiliser application had a positive effect on the water content in the leaves of both studied pear varieties. The practical significance of the study is to recommend the production of a rational fertiliser system for nonirrigated pear plantations in different age periods of growth and fruiting, which positively affected the water content in leaves and the fractional composition of water during stressful periods of cultivation

Keywords: pear leaves, Konferentsia, Osnovianska, leaves, free water, bound water, soil fertility

*Corresponding author

INTRODUCTION

The water content in the plant tissues indicates their moisture supply. It is an important indicator of the physiological state of the plant and is of great importance in the comparative assessment of their cultivation measures that increase productivity. One of these measures is rational fertilisation of plantings, which determines the relevance of the study. The water in the leaf tissues is in a free and bound state. This characterises the water balance of the leaves and determines its corresponding physiological significance. Free water determines the physiological activity of fruit plants and determines the level of viability. Bound water, which plays a structure-forming role, is of great importance at critical (drought, high temperatures) moments of growing plantings [1-3].

The ratio of bound water to free water can be one of the physiological features indicating the degree of activity of physiological processes in the plant: the predominance of bound water slows down growth processes, and the content of free water, on the contrary, accelerates them [4; 5]. The amount of bound water and its ratio to free water varies depending on the age of the tree, water supply, air and soil temperature [6]. The leaf cover of fruit trees is the main structural element of photosynthesis. The level of productivity of plantings depends on its features of life activity in the future [4-7].

In recent years, there has been a change in climatic conditions, in particular, the air temperature rises and the amount of precipitation decreases during the main periods of plant vegetation. Climate change factors are mainly biotic processes, fluctuations in solar radiation, and certain types of human activity [8]. One of the most pressing problems is the drought. Air drought limits the normal growth and high productivity of cultivated plants. It also negatively affects photosynthesis, reducing the generation of chlorophyll grains in leaves and the assimilation of nutrients [9-11]. Stressful phenomena reduce the turgor of plant cells, which negatively affects the passage of biochemical and physiological processes in the plant [12; 13]. Under such conditions, one of the most effective ways to reduce stress is to use a rational system of fertilising plants, especially in nonirrigated plantations [14-16].

The purpose of the study is to establish the effect of optimised fertilisation of pear trees on leaf water content and fractional composition (free, bound) of water during stressful growing periods.

MATERIALS AND METHODS

Studies were conducted in 2011 and 2018 in a certified educational and research laboratory for optimising soil fertility in fruit and vegetable plantations with the status of a research laboratory for mass analysis of the Uman National University of Horticulture. An experiment included variants of optimised fertilisation of a pear garden with Konferentsia and Osnovianska varieties on a vegetative rootstock Quince A planted according to the 5x3 m scheme. Experimental plantings were not irrigated.

The experimental design included the following options: 1. Without fertiliser (absolute control); 2. $N_{90}P_{60}K_{90}$ (production control); 3. calculated fertiliser rates (background); 4. Background + N_{30}; 5. Background + $N_{30}K_{30}$; 6. Background + $N_{30}P_{30}K_{30}$. The options were laid down in three repetitions with a randomised placement of plots, each of which grows five accounting trees. When laying the experiment, the level of soil supply with nitrate nitrogen (by nitrification ability) was insufficient ($N\text{-}NO_3$ content in the 0-40 cm layer was 16.5 mg/kg of soil, which is less than the optimal level (23.5 mg/kg) by 7 mg/kg). The soil supply with mobile phosphorus compounds was higher, and potassium forms were within the optimal level in the layer of 0-60 cm (P_2Oh_5 content was 166 mg/kg at an optimal rate of 70-100 mg/kg and K_2O – 250 mg/kg with an optimal 230-280 mg/kg of soil). To create an optimal background of nitrogen nutrition, according to the indicators of agrochemical analyses, the norm of only nitrogen fertiliser was calculated to bring the $N\text{-}NO_3$ content in the soil to the optimal level. Further, the soil in the experiment was analysed annually and based on the results of the analyses, the norms of nitrogen fertiliser were calculated to maintain the optimal $N\text{-}NO_3$ content in the root layer of the soil (0-40 cm). The amount of K_2O, which was applied with potash fertiliser, was designed to maintain its optimal content in the soil for a 3-4-year period.

The total moisture in the leaf was determined by the thermogravimetric method [17] by drying it in a drying cabinet at a temperature of 100-105°C to a constant weight. Washed glass weighing cups with an open lid were pre-dried in a drying cabinet at a temperature of 105°C, cooled and weighed on an analytical scale with an accuracy of 0.01 g. Then 15-20 g of fresh leaf clippings were added into the weighing cup and weighed. Weighing cups with an open lid were placed in a drying cabinet and the leaves were dried first at a temperature of 50-60°C (4-5 hours), and then at 100-105°C (4-6 hours). After drying, the weighting cup was covered with a lid, cooled, and weighed. This procedure was repeated to a constant weight (the difference between the two weighings should not exceed 0.02 g). The moisture content (Y), as a percentage of dry weight, was calculated by the equation (1):

$$Y = \frac{(a - b) * 100}{\mathrm{m}} \quad (1)$$

where a – weight of the weighting cup with leaves before drying, G; b – weight of the weighting cup with leaves after drying, G; m – weight of the weighing batch after drying, g; 100 – for conversion to percentages.

Determination of bound water was carried out by the refractometric method [18], placing a weighing

batch of leaves in a sucrose solution of a known concentration. After the weighing batch stayed in such a solution, its concentration decreased due to the release of free water from the leaves. Bound water is firmly held in the cell and was calculated from the difference between the total amount of water and free water that passed into the sucrose solution. The 10 g weighing batch of leaf clippings was filled into 100 cm^3 flasks, in which 25 cm^3 of sucrose solution were added (25% concentration). Flasks with the solution were pre-weighed on analytical scales, and after adding the leaves, they were weighed again for the reliability of weighing batch and solution. Next, the material with the filled solution was kept in flasks for two hours. At the end of the prescribed time, the contents of the flask were mixed with a glass stick and several drops were taken to determine the sucrose concentration on a refractometer.

The amount of free water as a percentage (x) was determined by the equation (2):

$$x = \frac{100 * (a - b) * v}{b * n} \quad (2)$$

where a – percentage of sucrose in solution (before determination); b – percentage of sucrose in the experimental solution after holding the weighing batch in it; v – weight of the solution before analysis (G); m – weighing batch of the studied material.

Describing the weather conditions that prevailed during the surveys, it is worth noting that in 2011, the amount of precipitation in June exceeded the long-term data by 42.2 mm, while in August it was 8.6 mm less (Fig. 1). In 2018, there was a lack of moisture in the study months, respectively, by 4.6 and 56.4 mm, which further affected the fractional composition of pear leaves. The temperature regime in 2011 in June and August was higher than the annual average. The excess temperature in June and August was 2.1 and 0.7°C, respectively (Fig. 2). The summer months in 2018 were hotter. The excess of the average annual temperature in June was 2.6, while in August – 3.9°C. Fluctuations in climatic indicators over the years of study have had different effects on the total water content and its fractional composition in pear leaves due to different fertilisation of plantings.

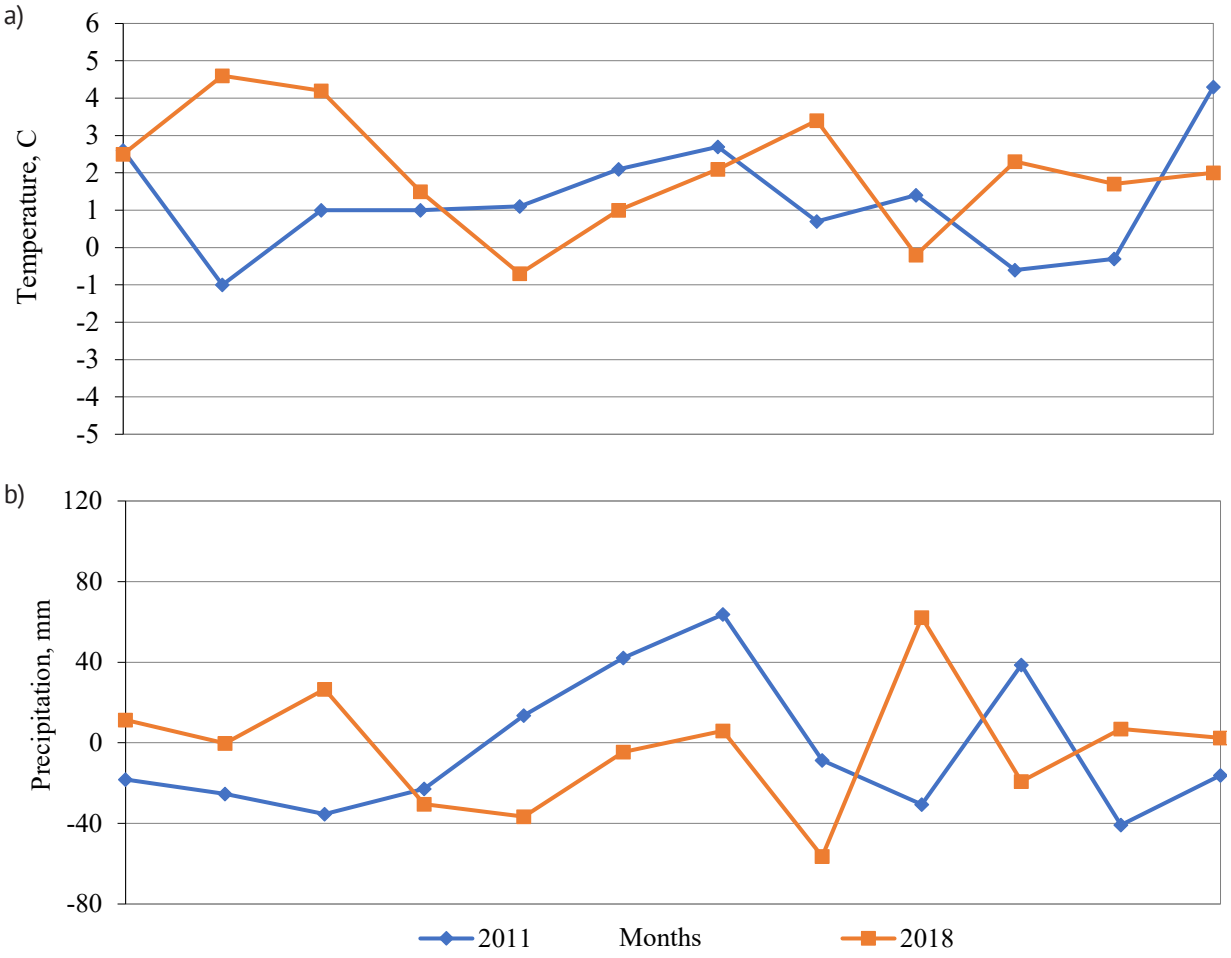

Figure 1. *Deviation of average monthly temperatures (a) and precipitation (b) from long-term data in 2011 and 2018 (data from the Uman weather station)*

RESULTS AND DISCUSSION

Studies have established that the total moisture content in pear leaves differed by age periods of cultivation and experimental varieties. There was also a decrease in the total water content in the leaves of experimental pear varieties during the growing season (Table 1). During the period of growth and fruiting (2011) in June, under excellent climatic conditions and active growth of biomass by young trees, the leaves of the Konferentsia variety were characterised by a significantly higher water content compared to Osnovianska variety. Among the fertiliser options, more moisture in the leaves was in the option with an additional application of $N_{30}K_{30}$ against the background of optimised fertiliser, where the excess of control options for the Konferentsia variety was 2.2 and 0.6%, respectively, while for the Osnovianska variety – 1.8 and 0.4%. No significant differences in fertiliser options were found, which was obviously conditioned by the equally active increase in biomass.

Table 1. *Total water content in pear leaves depending on the optimised fertiliser, %*

Variety	Fertiliser option	Periods			
		Growth and fructification 2011		Fructification and growth 2018	
		VI*	VIII	VI	VIII
Konferentsia	Without fertiliser (control)	58.9	57.1	57.7	51.0
	$N_{90}P_{60}K_{90}$ (production control)	60.5	59.4	58.9	52.6
	Calculated fertiliser rates (background)	60.0	59.0	58.3	51.4
	Background + N_{30}	59.7	59.1	56.8	51.7
	Background + $N_{30}K_{30}$	61.1	60.0	59.1	53.0
	Background + $N_{30}P_{30}K_{30}$	60.7	59.5	58.9	52.3
Osnovianska	Without fertiliser (control)	57.5	56.0	54.0	50.8
	$N_{90}P_{60}K_{90}$ (production control)	58.9	57.8	55.8	51.2
	Calculated fertiliser rates (background)	58.7	57.1	55.8	52.0
	Background + N_{30}	58.9	58.0	55.6	52.4
	Background + $N_{30}K_{30}$	59.3	58.2	56.0	52.4
	Background + $N_{30}P_{30}K_{30}$	58.9	57.9	55.6	51.6
LSD_{05}		*1.3*	*1.3*	*1.1*	*0.8*

Notes: **Sampling time (months)*

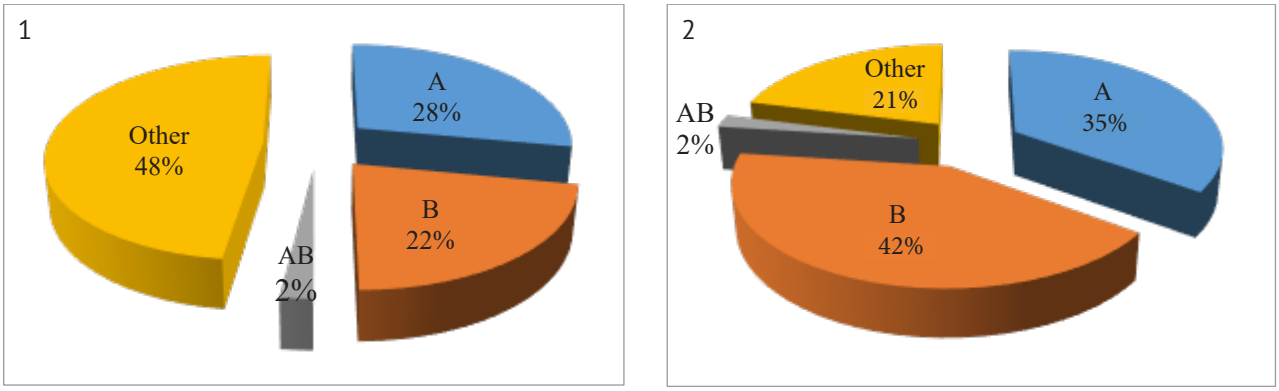

Figure 2. *Influence of factors and their interaction on the water content in pear leaves depending on the variety and fertiliser in 2011*

Notes: *A – rootstock; B – fertiliser; AB – interaction; 1 – June; 2 – August*

In August, there was a decrease in moisture in all fertiliser options of the studied varieties. All fertiliser options had a significantly higher moisture content compared to the control, with the exception of the option with the calculated application of fertilisers in Osnovianska variety. The leaves of the Konferentsia variety had a higher moisture content compared to Osnovianska, although this increase was not significant.

According to the data of the variance analysis (Fig. 2) on the moisture content in the leaves in June,

the influence of factors was almost at the same level – factor A – 28%, factor B – 22%. In August, there was a noticeable effect of fertiliser (factor B) – 42% and a decrease in the influence of the variety (factor A) to 35%.

During the growth and fruiting period (2018), a similar trend was observed regarding changes in leaf moisture during the growing season. The June was characterised by close to the average annual climate data and the moisture content in pear leaves in the studied fertiliser options ranged from 54.0-59.1%. Describing the varieties among themselves, the leaf moisture content in Konferentsia trees was significantly higher by 3.7% with LSD_{05}=1.1. There is also the highest leaf humidity in both varieties in the background + $N_{30}K_{30}$ option.

In August, due to the drought, the moisture content in the leaves of the studied pear trees significantly decreased compared to June. Among the studied fertiliser options in trees of the Konferentsia variety, the moisture content in leaves in the background + $N_{30}K_{30}$, $N_{90}P_{60}K_{90}$ and background + $N_{30}P_{30}K_{30}$ options was significantly higher compared to the control, where the excess of control was 2.0, 1.6, and 1.3%. Leaves of the Osnovianska variety were characterised by a significantly higher moisture content in the areas of options where calculated fertiliser rates were applied and additionally – N_{30} and $N_{30}K_{30}$. Excess in control (without fertilisers) was 1.2 and 1.6%, while in production control – 0.8 and 1.2%.

According to the data of the variance analysis (Fig. 3) the moisture content in the leaves was highly influenced by the variety (factor A) – 71%, the fertiliser effect (factor B) was 14%, and their interaction – 11%. In August, there was a noticeable effect of fertiliser (factor B) – 48% and a decrease in the influence of the variety (factor A) to 4%. The interaction of factors was 23%.

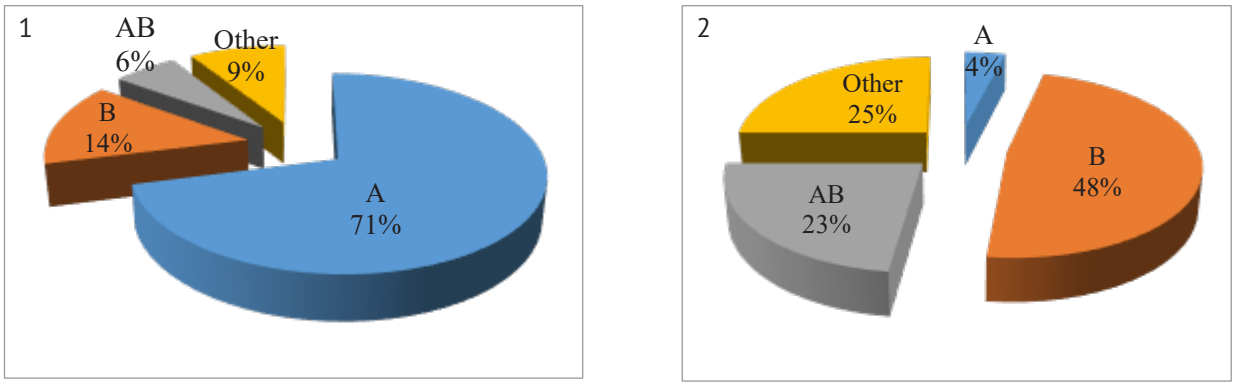

***Figure 3**. Influence of factors and their interaction on the water content in pear leaves depending on the variety and fertiliser in 2018*

***Notes**: A – rootstock; B – fertiliser; AB – interaction; 1 – June; 2 – August*

During two age periods of pear trees of the Konferentsia and Osnovianska varieties (Table 2) when using the studied fertiliser options in leaves with changes in soil moisture and age of plantings, water forms were redistributed within the options, in particular, there was an increase in free and a decrease in bound water. This is confirmed by other researchers [1; 2; 6].

***Table 1**. Influence of the variety and optimised fertiliser on the state (fractional composition) of water in the leaves of pear trees, %*

Variety	Fertiliser option	Periods							
		Growth and fructification 2011				Fructification and growth 2018			
		Free		Bound		Free		Bound	
		VI*	VIII	VI*	VIII	VI*	VIII	VI*	VIII
Konferentsia	Without fertiliser (control)	23.6	18.2	35.3	38.9	19.3	10.7	38.4	40.3
	$N_{90}P_{60}K_{90}$ (production control)	22.7	17.7	37.8	41.7	21.3	10.7	37.6	41.9
	Calculated fertiliser rates (background)	22.2	16.8	37.8	42.2	20.5	10.7	37.8	40.7
	Background + N_{30}	22.0	16.9	37.7	42.2	21.0	10.1	35.8	41.6
	Background + $N_{30}K_{30}$	22.4	17.4	38.7	42.6	21.3	10.7	37.8	42.3
	Background + $N_{30}P_{30}K_{30}$	22.6	17.7	38.1	41.8	21.2	10.8	37.7	41.5

Table 1, Continued

Variety	Fertiliser option	Periods							
		Free		Bound		Free		Bound	
		VI*	VIII	VI*	VIII	VI*	VIII	VI*	VIII
Osnovianska	Without fertiliser (control)	22.1	17.1	35.4	38.9	20.8	10.7	33.2	40.1
	$N_{90}P_{60}K_{90}$ (production control)	22.1	17.3	36.8	40.5	21.2	10.6	34.6	40.6
	Calculated fertiliser rates (background)	22.6	17.7	36.1	39.4	21.4	10.7	34.4	41.3
	Background + N_{30}	22.2	17.4	36.7	40.6	21.2	10.8	34.4	41.6
	Background + $N_{30}K_{30}$	22.0	16.9	37.3	41.3	21.6	10.1	34.4	42.3
	Background + $N_{30}P_{30}K_{30}$	22.3	17.5	36.6	40.4	21.6	10.9	34.0	40.7
	LSD_{05}	*0.5*	*0.3*	*0.7*	*0.8*	*0.4*	*0.2*	*0.7*	*0.8*

***Notes**: *Sampling time (months)*

During the period of growth and fruiting (2011) in June, when the amount of precipitation exceeded the annual average by 48.3%, young leaves retained moisture and a higher content of free water, which positively affected the growth and development of trees. At the same time, a higher content of free water was observed in trees of the Konferentsia variety in the areas of absolute and production control and when applying full mineral fertiliser against the background of optimised nutrition of 58.9%. In August, there was some lack of moisture (15% less precipitation), which affected a decrease in free water and an increase in bound water. For trees of the Konferentsia variety, it was most significant in control at 18.2, and for the Osnovianska variety – in the option with estimated fertiliser rates of 17.7%. The background + $N_{30}K_{30}$ option was characterised by the largest amount of bound water. During the period of fruiting and growth (2018) in June, when the amount of precipitation and air temperature of free water in the leaves of both varieties were close to optimal, according to the studied options, it was in the range of 19.3-21.6%. A significant increase was noted in the Osnovianska variety compared to the Konferentsia. In August, when precipitation was 23 times less than the annual average and the air temperature increased by 3.9°C, there was a significant decrease in the free water content and an increase in bound water in all fertilised options of both experimental varieties, which positively affected the water content in the leaves, and among the fertiliser options, the best result was obtained in the background + $N_{30}K_{30}$ option – 42.3%.

CONCLUSIONS

During the age periods of growth and fruiting, the total water content in pear leaves in nonirrigated plantings changed. Leaves from pear trees of the Konferentsia variety had a higher water content compared to the Osnovianska variety. At the young age of trees (the period of growth and fruiting) in the month of June, additional application of $N_{30}K_{30}$ against the background of optimised fertiliser, it contributed to an increase in moisture in the leaves, compared to the control, in the Konferentsia variety by 2.2% and 0.6%, while in the Osnovianska variety – 1.8% and 0.4%. In August, all fertiliser options had a significantly higher moisture content compared to the control, with the exception of the option with the calculated application of fertilisers in Osnovianska varieties.

During the growth and fruiting period in August, due to the drought, the moisture content in the leaves of the studied pear trees significantly decreased. Under such conditions, the Konferentsia variety had a significant increase in leaf moisture in the background + $N_{30}K_{30}$, $N_{90}P_{60}K_{90}$ and background + $N_{30}P_{30}K_{30}$ options, where the excess of control was 2.0, 1.6% and 1.3%. Leaves of the Osnovianska variety had a significantly higher content in the options where the calculated fertiliser rates were applied + additional N_{30} and $N_{30}K_{30}$. It was found that at the beginning of the growing season, the free water content in the leaves of pear varieties Konferentsia and Osnovianska was higher, while in the middle it significantly decreased. The bound water content was higher in all studied options. Under stressful situations (drought, rising temperatures), fertiliser application had a positive effect on the water content in the leaves of both studied pear varieties.

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Загальний і фракційний склад води в листі груші залежно від оптимізованого удобрення

Роман Володимирович Яковенко

Уманський національний університет садівництва
20305. вул. Інститутська, 1, м. Умань, Україна

Анотація. Вміст води у тканинах є важливим показником фізіологічного стану рослини та має велике значення при порівняльній оцінці заходів їх вирощування, які підвищують врожайність. Одним із таких заходів є раціональне удобрення насаджень, що й визначає актуальність досліджень. Метою наукової роботи було встановлення впливу оптимізованого удобрення дерев груші на обводненість листя та фракційний склад води у стресові періоди вирощування. Однією з критичних проблем є посуха, що негативно впливає на ріст і продуктивність насаджень. За таких умов зменшується тургор рослинних клітин і уповільнюється проходження біохімічних та фізіологічних процесів у рослині. У статті розглядаються результати вивчення водного режиму листя (вміст загальної, доступної та недоступної вологи) груші сортів Конференція та Основ'янська на вегетативній Айва А підщепі, вирощуваної на фонах оптимізованого удобрення в незрошуваних насадженнях. Дослідження проводились у 2011 і 2018 рр. у сертифікованій навчально-дослідній лабораторії з оптимізації родючості ґрунту в плодоягідних насадженнях зі статусом наукової лабораторії масових аналізів Уманського НУС. Встановлено, що протягом вікових періодів росту і плодоношення відбувалася зміна вмісту загальної води в листі груші досліджуваних сортів. Листя з дерев груші сорту Конференція мало вищий вміст води, як порівняти з сортом Основ'янська. Варіанти удобрення підвищували загальний вміст води в листі, що позитивно впливало на стан дерев. З'ясовано, що на початку вегетації вміст вільної води в листі груші сортів Конференція і Основ'янська був більший, тоді як у середині значно зменшується. Вміст зв'язаної води був вищим у всіх досліджуваних варіантах. За стресових ситуацій (посуха, підвищення температури) внесення добрив позитивно вплинуло на обводненість листя обох досліджуваних сортів груші. Практична цінність наукової роботи полягає у рекомендації виробництву раціональної системи удобрення незрошуваних насаджень груші в різні вікові періоди росту і плодоношення, яка позитивно впливала на обводненість листя та фракційний склад води у стресові періоди вирощування

Ключові слова: листя груші, Конференція, Основ'янська, листя, вільна вода, зв'язана вода, родючість ґрунту

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Intensity of Soil Pollution by Toxic Substances Depending on the Degree of Its Washout

Oleksandr Tkachuk*, Victoria Verhelis

Vinnytsia National Agrarian University

21008, 3 Soniachna Str., Vinnytsia, Ukraine

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Abstract. A significant degree of ploughness of agricultural lands of Ukraine has led to increased erosion and the creation of soils of varying degrees of washout, which leads to dehumification and contamination of soils with toxic substances. Therefore, the purpose of the study was to establish the features of horizontal migration and accumulation of heavy metals of lead, cadmium, copper, and zinc, trace elements of boron and manganese, radionuclides of caesium and strontium on podzolic heavy loamy chernozems with varying degrees of washout: non-eroded, weak and medium washout, conditioned by the development of erosion processes. During the study, spectrophotometric, colorimetric, gamma-spectrometric, and radiochemical methods were used to determine the content of toxic substances in the soil. The study results showed that on slightly washed soils, the content of humus is 12.9% less, easily hydrolysed nitrogen – 13.3%, mobile forms of phosphorus – 51.1%, mobile potassium – 34.9% less than on slightly washed soils. The humus content on medium-washed soil was 8.8% less than on lightly washed soil, easily hydrolysed nitrogen – 14.3% less, mobile phosphorus – 15.3% more, mobile potassium – 42.9% more. A strong horizontal migration of mobile lead forms in washed podzolic heavy loamy chernozem was established, which increases with increasing degree of soil washout with the content of mobile lead forms on medium-washed soil by 24% more than on non-eroded soil. The same dependence was established on the content of mobile forms of zinc in the soil, with their predominance on medium-washed soil by 17 %, compared to non-washed. The content of mobile forms of copper is lower on slightly washed soil, compared to non – washed soil by 5%, boron – 18.8% less on non-washed soil, compared to medium-washed, and the content of mobile forms of manganese increases by 3.3% from slightly to medium-washed soil. It was also found that the concentration of caesium decreased by 25.6% on medium-washed soils, compared to non-washed ones

Keywords: heavy metals, trace elements, radionuclides, horizontal migration, soil erosion

*Corresponding author

INTRODUCTION

The modern use of land resources in Ukraine is characterised by intensity and does not meet the requirements of rational use of natural resources. Land resources lose their fertility and degrade due to crop rotation irregularity, ploughing soils on slopes, applying high rates of mineral fertilisers and pesticides, and over-compaction with machinery [1]. One of the defining agroecological problems of agriculture in Ukraine is the high degree of ploughness of agricultural soils. The ploughness of soils in Ukraine is one of the largest in the world and accounts for 57% of the country's territory, and the ploughness of agricultural land reaches 80%. Intensive ploughing of lands, including inclined ones, leads to a decrease in soil fertility due to their over-compaction, deterioration of the structural condition, reduction of water permeability, aeration, and contamination with toxic substances [2].

In Ukraine, the following degradation processes in soils are most widespread: dehumidification and reduction of the content of nutrients, physical degradation (over-compaction), erosion, pollution, etc. [2]. Especially dangerous for soils is erosion, which has significantly accelerated with the introduction of intensive farming technologies and significant ploughing of protected land on the slopes. Due to the development of erosion processes caused by anthropogenic activity, the soil is washed away, which leads to a decrease in its fertility and contamination with toxic substances [2].

Accelerated erosion is estimated by the volume of soil washout per year: weakly washed soils – 0.5-1.0 t/ha; medium-washed soils – 1.0-5.0 t/ha; heavily washed soils – 5-10 t/ha; very strongly washed soils – more than 10 t/ha [3]. In Ukraine, the area of eroded and erosive soils is approximately 17 million hectares. Most of the washed-off soils were found in Luhanska, Vinnytska, Dnipropetrovska, and Odeska oblasts, where the share of washed-off soils reaches 53-66% of the total arable land area [4]. The number of polluted and unproductive soils on the territory of Ukraine reaches 15 million hectares, while over the past 130 years their number has increased significantly, which is also affected by a decrease in the humus content in the soil. On such soils, along with the problem of acidification, pollution with heavy metals, radionuclides, pesticide residues, and salts is growing. Data from the Institute of Soil Science and Agrochemistry show that 20% of the soil area in Ukraine is contaminated with heavy metals [4], which requires their constant agroecological monitoring.

Studies by E.Ya. Zhovinsky, A.I. Samchuk [5], and A.I. Fateev [6] are devoted to the issues of heavy metal contamination of the soil cover. Considerable attention of researchers is focused on the study of issues of landscape ecogeochemistry in agrogenesis zones: T.M. Myslyva [7], O.I. Trunova [8]. Part of the research concerns the features of migration and accumulation of certain chemicals in the soil. Study by Yu.M. Dmytruk [9] is aimed at investigating the features of the movement of copper and zinc in the soil thickness of the Carpathian region, A.I. Melnyk [10] – migration and accumulation of heavy metals in the soils of the Chernihivska Oblast, S.S. Rudenko and S.S. Kostyshin – in the soils of agricultural land of the Chernivetska Oblast [11; 12]. Features of distribution of Zn in agricultural soils of the Kharkivska Oblast are considered by M.M. Miroshnichenko and A.I. Fateev [13], the nature of migration and accumulation of heavy metals in the soils of protected areas – by A.I. Samchuk and E.Ya. Zhovinsky [5], agro-cultural landscapes – T.M. Myslyva [7]. A small amount of research papers concerns the study of the horizontal movement of toxic substances and their accumulation in the soil. There are almost no data on the horizontal redistribution of toxicants in soils undergoing erosion.

Considering the above, *the purpose of the study* is to establish the features of horizontal migration and accumulation of heavy metals, some trace elements and radionuclides under conditions of varying degrees of washout of soils due to the development of erosion processes.

THEORETICAL OVERVIEW

According to the degree of mobility, all heavy metal compounds in the soil are divided into stationary, potentially mobile, and mobile components. Among them, heavy metals in mobile form have the most negative effect on living organisms, including humans. Agrochemical properties of soils significantly affect the mobility of heavy metals: in soils with low buffering, the number of mobile forms of heavy metals will be significantly higher than in soils with high buffering with the same other characteristics: the background content of heavy metals, the level of anthropogenic pollution, and others. Based on this, "the buffer capacity directly determines the protective properties of soils, so to determine the actual danger of heavy metals, it is necessary to monitor the content of their mobile forms. The value of the gross content of heavy metals should be used only to establish the general characteristics of soil contamination and identify their potential danger" [14].

It was found that the transfer of heavy metals from landscapes located above the landform leads to an increase in the content of Pb in the lowlands by 4.5 times, Sr – by 1.7, Ag – by 2.2, Cu – by 1.7, Zn – by 2.5, Ga – by 1.5, Sn – by 1.6 and Yb – by 1.5 times [15]. Admittedly, the reaction of the soil environment also directly affects the mobility of chemical elements. In an acidic environment, most cationic elements (Cd, Hg, Pb, Ni, Co, Mn, Zn, Cu, etc.) easily migrate, and an increase in PH leads to a sharp decrease in the intensity of migration processes due to the generation of poorly soluble compounds of these substances.

An important factor in the intensity of movement of heavy metals in the soil is its redox properties. Heavy

metals are the least mobile in the soil under highly reducing conditions (50-150 mV), and Co, Cd, Mn, Fe, Ni, and Zn are the most mobile at the reducing properties of soils of 400 mV, and Cu – at 700-800 mV [16]. However, since the redox potential of soils is a very dynamic Value, its study is rarely conducted.

A significant part of heavy metals is bound in the soil by the organic matter of humus – humic and fulvic acids. Fertile soils with a high humus content are able to retain high concentrations of heavy metals compared to sandy or humus-poor soils [17]. At the same time, the long-term supply of heavy metals to the soil, even in low concentrations, causes their significant accumulation in the soil [18]. The toxic effect of heavy metals in heavy soils with a high humus content is less than in light and humus-poor soils. This can be explained by the property of clay particles and organic matter of humus to transfer heavy metals to a bound and sedentary state.

When pollutants enter the soil, its structure is destroyed, which leads to preconsolidation of the soil. The consequences of this are a decrease in water permeability, the generation of a soil crust, and the deterioration of the water-air regime. When heavy metals accumulate in the soil, its physical and chemical properties deteriorate: the mobility of the clay fraction increases, the acid reaction of the soil environment changes, the concentration of calcium and magnesium exchange compounds decreases, compounds of carbonates and iron hydroxides are destroyed, the quantitative composition of humus decreases, and the mobility of humic acids of humus increases [19].

MATERIALS AND METHODS

The study was conducted during 2017-2020 based on processing materials for monitoring and ecological and agrochemical certification of agricultural land of the farm "Avgust VA" in the village of Markovka, Tomashpol district, Vinnytska Oblast, which were developed by the Vinnytsia branch of the state institution "Institute of soil protection of Ukraine" [20]. The soil of the experimental site is podzolic heavy loamy chernozem with varying degrees of washout: non-eroded, slightly washed, medium washed. The following ecological and agrochemical parameters of the soil were analyzed: the content of mobile forms of heavy metals: lead (Pb), cadmium (Cd), copper (Cu) and zinc (Zn) – by spectrophotometric method; the content of trace elements: boron (B) – by colorimetric method, manganese (Mn) – by spectrophotometric method; the density of radioactive contamination: Caesium – 137 (Cs) – by gamma spectrometer, strontium-90 (Sr) – by radiochemical method [20].

Agrochemical survey of the soils was carried out on a total area of 740.5 hectares. Sampling was carried out in accordance with the guidelines for large-scale agrochemical survey of soils in the agrochemical service of Ukraine. The study was conducted on two adjacent soil areas with different degrees of washout: non-eroded and slightly washed soil and slightly washed and medium-washed soil. On the experimental non-eroded podzolic heavy loamy chernozems by mechanical composition, the humus content was 2.94%. On slightly washed soils, the humus content was 12.9% lower. The content of easily hydrolysed nitrogen on non-eroded soils was 113 mg/kg, and on slightly washed soils – 13.3% less. The content of mobile forms of phosphorus on non-eroded soils was 137 mg/kg, and on slightly washed soils – decreased by 51.1%. The content of mobile potassium on non-eroded podzolic heavy loamy chernozems was 152 mg/kg. This was 34.9% more than on lightly washed soil.

Observation of a section of podzolic heavy loamy chernozem with a weak and medium-washed degree showed that the humus content on slightly washed soil was 2.94%, and on medium-washed soil it decreased by 8.8%. The content of lightly hydrolysed nitrogen on lightly washed podzolic heavy loamy chernozem was 112 mg/kg, and on medium-washed – decreased by 14.3%. The content of mobile forms of phosphorus on lightly washed soil was 50 mg/kg, and on medium-washed soil – increased by 15.3%. The content of mobile forms of potassium on lightly washed podzolic heavy loamy chernozems was 89 mg/kg, and on heavily washed – increased by 42.9%.

The hydrolytic acidity of non-eroded soil was 2.34 mg-eq/100 g, and slightly washed – increased by 4.9%. The reaction of the soil solution on unwashed soil was 5.5 pH, and on slightly washed soil – increased by 1.8%. The sum of the absorbed bases of non-eroded podzolic heavy loamy chernozem was 25.6 mg-eq/100 g, and slightly washed – increased by 11.4%.

Observations of the acidity indicators of another soil area, where the degree of washout was higher, revealed the hydrolytic acidity of slightly washed soil of 1.72 mg-eq/100 g. Medium-washed podzolic heavy loamy chernozem had a hydrolytic acidity of 11.3% higher. The reaction of the soil solution of slightly washed soil was 5.8 pH, and the reaction of medium-washed soil was 1.7% less. The sum of the absorbed bases of weakly and medium-washed soils was the same and amounted to 29.2 mg – eq/100 g.

RESULTS AND DISCUSSION

The main toxic substances in soils that can negatively affect plant growth and development are heavy metals, radionuclides, pesticide residues, salts and acids. At high concentrations in soils, trace elements can also be toxic to plants.

Among the group of heavy metals, lead and cadmium are the most dangerous. At the same time, copper and zinc can act in soils, depending on their concentration, as heavy metals, and microelements useful for plants. In this study, the influence of the degree of washout of podzolic heavy loamy chernozem on the concentration of mobile forms of heavy metals in it was revealed. In particular, on non-eroded soil, the content of mobile forms of lead was 1.13 mg/kg, and on lightly washed soil, it increased by 6.6% and amounted to 1.21 mg/kg (Table 1).

***Table 1**. Intensity of soil contamination with heavy metals depending on the degree of its washout, mg/kg*

Soil type	Mechanical composition	Degree of washout	Heavy metals							
			Pb		Cd		Cu		Zn	
			Content	MPC	Content	MPC	Content	MPC	Content	MPC
Podzolic chernozem	Heavy loam	Non-eroded	1.13	6.00	0.07	0.70	0.20	3.00	0.47	23.0
		Slightly washed	1.21	6.00	0.07	0.70	0.19	3.00	0.49	23.0
Podzolic chernozem	Heavy loam	Slightly washed	0.85	6.00	0.06	0.70	0.24	3.00	0.41	23.0
		Medium washed	1.03	6.00	0.06	0.70	0.24	3.00	0.47	23.0

***Notes**: MPC – maximum permissible concentrations*
***Source**: compiled based on [20]*

The content of mobile forms of cadmium in the soil did not depend on the degree of its washout and amounted to 0.07 mg/kg on unwashed and slightly washed soil. The concentration of mobile forms of copper on unleaded podzolic chernozem was 0.20 mg/kg, and on slightly washed chernozem it was 5% less and amounted to 0.19 mg/kg. The content of mobile forms of zinc on unwashed soil was 0.47 mg/kg, and on lightly washed soil – increased by 4.1% and amounted to 0.49 mg/kg.

Comparison of indicators of the content of mobile forms of heavy metals between lightly and medium-washed podzolic heavy loamy chernozem revealed an increase in lead concentration by 17.5% on medium-washed soil: from 0.85 mg/kg on slightly washed – to 1.03 mg/kg on medium washed. The concentration of mobile cadmium forms did not depend on the degree of soil washout and was 0.06 mg/kg. In addition, there was no effect of the degree of soil washout on the content of mobile forms of copper in it – 0.24 mg/kg. At the same time, the content of mobile forms of zinc on slightly washed soil was 0.41 mg/kg, and on medium-washed soil it increased by 12.8% and amounted to 0.47 mg/kg.

Analysis of indicators of the content of heavy metals in soils of various degrees of washout showed that the concentration of mobile forms of lead and zinc increases from unwashed to medium-washed soil, and the concentration of mobile forms of cadmium and copper does not depend on the degree of its washout. At the same time, the concentration of mobile forms of lead and zinc in the soil increases three times more intensively during the transition from slightly washed to medium-washed than from unwashed to slightly washed. This indicates a horizontal migration of lead and zinc along the slope. Lead has a greater horizontal migration in the soil compared to zinc. At the same time, cadmium and copper migrate in a horizontal plane along soil slopes less intensively. In particular, only copper migration was detected in slightly washed soil compared to non-eroded soil, while such migration between slightly and medium-washed soil was not detected.

Assessment of the content of heavy metals in experimental soils in comparison with maximum permissible concentrations (MPC) did not detect that the permissible limits were exceeded. In particular, the content of mobile forms of lead was 0.14-0.20 MPC, cadmium – 0.09-0.10 MPC, copper – 0.06-0.08 MPC, zinc – 0.02 MPC. The study analysed changes in the concentration of trace elements in the soil depending on the degree of its washout. In particular, the content of mobile forms of boron on unwashed soil was 0.84 mg/kg, and on lightly washed soil – decreased by 9.5% and amounted to 0.76 mg/kg. The manganese content on non-eroded soil was 35.80 mg/kg, and on lightly washed soil it decreased by 0.2% and amounted to 35.74 mg/kg (Table 2).

***Table 2**. Content of trace elements boron and manganese in the soil depending on the degree of its washout, mg/kg*

Soil type	Mechanical composition	Degree of washout	Trace elements			
			B		Mn	
			Content	Background	Content	MPC
Podzolic chernozem	Heavy loam	Non-eroded	0.84	6.0	35.80	700
		Slightly washed	0.76	6.0	35.74	700
Podzolic chernozem	Heavy loam	Slightly washed	0.86	6.0	35.64	700
		Medium-washed	0.78	6.0	36.84	700

***Source**: compiled based on [20]*

During the transition of soil from slightly to medium washed, the content of mobile forms of boron decreased by 9.3% (from 0.86 to 0.78 mg/kg), and manganese – increased by 3.3% (from 35.64 to 36.84 mg/kg). The results of the conducted studies indicate that with an increase in the degree of soil washout, the boron content in it decreases – evenly between weakly and medium-washed soil, but the manganese content increases, especially in medium-washed soils. The background content of boron in the soils of the forest-steppe of Right-Bank Ukraine is 6.0 mg/kg, which is significantly higher than the actual content of boron in the soil of experimental sites. The maximum permissible concentration of mobile forms of manganese in the soil is 700 mg/kg, and the actual content is 0.05 maximum permissible concentration.

The influence of varying degrees of soil washout on the content of radionuclides in it is revealed. In particular, the caesium content in the undisturbed soil was 0.37 Ki/km^2. On slightly washed soil, the caesium content decreased by 18.9% and amounted to 0.30 Ki/km^2. On medium-washed podzolic chernozem, the caesium content also decreased by 16.7% (0.25 Ki/km^2 against 0.30 Ki/km^2). The content of strontium in the studied soils did not depend on the degree of its washout (Table 3).

***Table 3**. Intensity of changes in soil contamination with radionuclides depending on the degree of its washout, Ki/km^2*

Soil type	Mechanical com-position	Degree of washout	Trace elements			
			Cs		Sr	
			content	MPC	content	MPC
Podzolic chernozem	Heavy loam	Non-eroded	0.37	1.0	0.02	0.15
		Slightly washed	0.30	1.0	0.02	0.15
Podzolic chernozem	Heavy loam	Slightly washed	0.30	1.0	–	0.15
		Medium-washed	0.25	1.0	–	0.15

***Source**: compiled based on [20]*

At the maximum permissible concentration of caesium in the soil of 1.0 Ki/km^2, its actual content at the experimental sites was 0.3-0.4 MPC, and strontium – 0.1 MPC.

CONCLUSIONS

According to the study results, the migration ability of toxic substances in the soil was revealed, depending on the degree of its washout. A strong horizontal migration of mobile forms of lead in the soil was established, which grows from non-eroded to medium-washed soil with the highest lead content on medium-washed podzolic heavy loamy chernozems, which is 24% more than on non-eroded soil. A similar relationship was found in the content of mobile forms of zinc in the soil, where its concentration on medium-washed soil was 17% higher than on non-eroded soil. The content of mobile forms of copper decreases on slightly washed soils by 5% compared to non-eroded ones, boron – by 18.8% from non-eroded to medium-washed soils, and the content of manganese increases from slightly to medium-washed soil by 3.3%. A decrease in the concentration of caesium was revealed on medium-washed soils compared to non-eroded soils by 25.6%.

Prospects for further research are to investigate the features of accumulation of toxic substances: heavy metals, radionuclides, salts and acids in crop products grown on soils with varying degrees of washout and develop measures to reduce the horizontal migration of such toxicants along soil slopes.

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Інтенсивність забруднення ґрунту токсичними речовинами залежно від ступеня його змитості

Олександр Петрович Ткачук, Вікторія Ігорівна Вергеліс

Вінницький національний аграрний університет
21008, вул. Сонячна, 3, м. Вінниця, Україна

Анотація. Значний ступінь розораності сільськогосподарських ґрунтів України призвів до посилення ерозійних процесів та утворення ґрунтів різного ступеня змитості, що призводить не тільки до дегуміфікації, але й до забруднення ґрунтів токсичними речовинами. Тому метою дослідження було встановити особливості горизонтальної міграції та накопичення важких металів свинцю, кадмію, міді та цинку, мікроелементів бору та марганцю, радіонуклідів цезію і стронцію на чорноземах опідзолених важкосуглинкових із різним ступенем змитості: незмиті, слабо- та середньозмиті, зумовленої розвитком ерозійних процесів. Під час дослідження було використано спектрофотометричні, колориметричні, гамма-спектрометричні та радіохімічні методи визначення вмісту токсичних речовин у ґрунті. Результатами досліджень виявлено, що на слабозмитих ґрунтах вміст гумусу на 12,9 % менший, азоту легкогідролізованого – на 13,3 %, рухомих форм фосфору – на 51,1 %, рухомого калію – на 34,9 % менший, ніж на слабозмитих ґрунтах. Вміст гумусу на середньозмитому ґрунті був на 8,8 % меншим, ніж на слабозмитому, азоту легкогідролізованого – на 14,3 % меншим, рухомого фосфору – на 15,3 % більшим, рухомого калію – на 42,9 % більшим. Встановлено сильну горизонтальну міграцію рухомих форм свинцю у чорноземі опідзоленому важкосуглинковому змитому, що зростає із збільшенням ступеня змитості ґрунту із вмістом рухомих форм свинцю на середньозмитому ґрунті на 24 % більшому, ніж на незмитому ґрунті. Така ж залежність встановлена за вмістом у ґрунті рухомих форм цинку, з їх переважанням на середньозмитому ґрунті на 17 %, порівняно із незмитим. Вміст рухомих форм міді менший на слабозмитому ґрунті, порівняно із незмитим на 5 %, бору – на 18,8 % менший на незмитому ґрунті, порівняно із середньозмитим, а вміст рухомих форм марганцю збільшується на 3,3 % від слабо- до середньозмитого ґрунту. Також встановлено зниження концентрації цезію на 25,6 % на середньозмитих ґрунтах, порівняно із незмитими

Ключові слова: важкі метали, мікроелементи, радіонукліди, горизонтальна міграція, ерозія ґрунту

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The Effect of Neutralising Materials on the Reaction of the Peat Substrate Medium when Growing Ball-Rooted Seedlings

Siarhei Rabko[1], Ivan Kimeichuk[2,3*], Siarhei Surauyou[1], Vasyl Khryk[2], Svitlana Levandovska[2]

[1]Belarusian State Technological University
220006, 13a Sverdlova Str., Minsk, Republic of Belarus

[2]Bila Tserkva National Agrarian University
09117, 8/1 Soborna Sq., Bila Tserkva, Ukraine

[3]National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine

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Abstract. The use of various types of neutralising materials in the cultivation of standard planting material of high-quality forest wood species has a significant effect on substrate acidity. Therefore, the study sets a goal to select peat substrates with different dosages of the neutralising component and determine their effect on the reaction of the peat substrate medium. The paper presents the results of the influence of neutralising materials of dolomitic meal and chalk of various doses with the use of mineral fertilisers. Dolomitic meal was used as a neutralising component, the pH of the peat substrate was 6.6 and chalk was 7.5. It was found that when neutralising a peat substrate created based on high-moor milled peat (pH 2.5) with the introduction of dolomitic meal in doses of 2-4 kg/m^3 (European spruce), 3-4. 5 kg/m^3 (Scots pine), optimal acidity can be achieved in a month. An increase in the concentration of lime material was recorded, which leads to an increase in the neutralisation of the substrate at a dose of 2.5 g and 3.0 g per 125 g of peat. The best indicators were demonstrated by options of doses of 1.5-2.5 g per 125 g of peat for 7-8 days of use and a dose of 3.0 g per 125 g of peat for 5-6 days compared with the control. An increase in the concentration of chalk in the neutralising material from 30% to 70% leads to a faster deoxidation of the substrate (pH 3.2), and an increase in the dosage of chalk increases substrate neutralisation. The electrical conductivity of the substrate at a dosage of 6-8 kg/m^3 when applying chalk and dolomitic meal increases by 1.6-2.0 and 1.2-1.4 times, respectively. At the rate of application of 6-10 kg/m^3, it has a lesser effect on the change in the electrical conductivity of the high-moor peat, and the introduction of dolomitic meal 2-4.5 kg/m^3 into the milled peat during neutralisation does not lead to a change in the electrical conductivity of the peat. This data allows choosing neutralising materials of a certain concentration that will enable the cultivation of standard planting material of European quality and thereby ensure the proper quality of future stands

Keywords: acidity of the medium, planting material, dolomitic meal, chalk, peat, substrate

*Corresponding author

INTRODUCTION

In the 21st century in the Republic of Belarus, high-moor peat, enriched with the necessary nutrients and pre-neutralised, is used in containers for preparing the substrate for the cultivation of standard seedlings [1-3]. The success of growing planting material is influenced by technical and technological aspects. Technical problems are associated with the use of lines for filling cassettes and sowing seeds, and with technical means of observing the elements of growing technology. These problems can be solved at the level of the equipment manufacturer, provided that the entire line of equipment is assembled by one manufacturer, or there is a risk of the inconsistency of individual components, which can be expressed in a decrease in the quality of filling cassettes or sowing seeds, violation of growing regimes. Technological problems can be caused by regional features that affect individual elements of the technology, for example, the choice of substrate, the microclimate of the substrate, mineral nutrition, water regime, etc. [4-7].

When using peat as a substrate for growing seedlings, it is necessary to take into account the influence of the entire organic complex of peat mass as a carrier of a wide variety of physiologically active substances, which manifests itself mainly in stimulating the growth processes of vegetative organs, intensifying protein metabolism and in the relative inhibition of the synthesis of a complex of carbohydrate substances [8; 9].

There is no unambiguous opinion on the preparation of peat substrates for the cultivation of ball-rooted planting stock (BRPS) among the producers of planting material. Each breed has its own optimal characteristics, which requires mandatory preliminary testing before preparing the substrate. As a result of conducting detailed studies on the chemical properties of the substrate suitable for growing BRPS, it is necessary to establish its best indicators [10]. The formulation of the substrate varies not only between manufacturers, but also in the case of self-preparation of a nutrient substrate – within each centre for growing BRPS [10]. Sometimes certain target additives are added to the substrate, which allow changing the chemical or water-physical properties of peat. The main goal, in this case, is the enrichment of the substrate with nutrients to ensure an optimal nutrition regime for young plants immediately after transplanting to the forest-cultivated area. Another possible option is to ensure a favourable water regime of the substrate by creating moisture reserves in it, which allows for rational use of it on the forest-cultivated area when there is a shortage of atmospheric or soil moisture [6]. Therefore, the cultivation of BRPS of the main forest-forming species with an optimal reaction of the environment would allow obtaining a high yield of standard seedlings for creating forest crops on the territory of the Republic of Belarus.

Since there are quite large areas of swamps on the territory of Belarus – about 2.5 million hectares (14.1% of the total area), the reserves of raw peat are about 30.4 billion m^3 [8], which is used in greenhouses when growing seedlings of forest tree species in the closed ground. The peat of high moors contains an insignificant amount of macronutrients (about 0.56-2.0% nitrogen, 0.03-0.26% phosphorus and 0.01-0.1% potassium), but such a substrate has a high water-retaining and absorbing capacity (moisture capacity 600-1200% by volume, 56-84% by weight), and valuable bactericidal properties that block the spread of fungal microflora. The acidity of the high-moor peat (pH 3.2) is negative, which prevents the development of good seedlings. Therefore, the study selected the most common neutralising materials and their doses in a certain ratio relative to the control to grow a standard planting material with improved planting properties.

The purpose of this study is to determine the effect of neutralising materials on the reaction of the peat substrate medium for their use in growing ball-rooted seedlings.

The object of study is a substrate for growing ball-rooted planting stock. *The subject of study* is the selection of peat substrates with different dosages of the neutralising component.

MATERIALS AND METHODS

Dolomitic meal with a mass fraction of magnesium and calcium carbonate and chalk with a mass fraction of calcium carbonate of at least 85% were used as a lime material. Experimental studies were conducted in March-April 2020-2021 in laboratory conditions at a temperature of 17-20^{0}C and relative humidity of 50-60%. For the integrity of the experiment, 2-litre containers of polyethylene were used. The active experiment was based on two coniferous wood species (pine and spruce) in 2 or 5-fold repetition for each study option with a certain ratio of doses of dolomitic meal and chalk, which is designed for 500 cm^3 (125 g) of separated high-moor milled peat (fraction 0-7 mm).

To optimise the acidity, mixtures of dolomitic meal and chalk were used in different ratios and different dosages in 3 repetitions:

Option 1: with an excess of dolomitic meal in the composition, the ratio was in the total weight of dolomitic meal (70%) and chalk (30%), respectively, and the dosage of mixed lime substance in the experimental options was: 1.5 g; 2.0 g; 2.5 g; and 3.0 g of mixed lime substance per 125 g of peat;

Option 2: in the composition, the ratio was in the total weight of dolomitic meal (50%) and chalk (50%), respectively, and the dosage of mixed lime substance in the experimental options was: 1.5 g; 2.0 g; 2.5 g; and 3.0 g of mixed lime substance per 125 g of peat;

Option 3: with an excess of chalk in the composition, the ratio was in the total weight of dolomitic meal (30%) and chalk (70%), respectively, and the dosage of the mixed lime substance in the experimental variants

was: 1.5 g; 2.0 g; 2.5 g; and 3.0 g of mixed lime substance per 125 g of peat.

The pH value of the deoxidised peat was analysed for 8 days in accordance with GOST 11623-89 [11] until the onset of constant acidity. A characteristic feature of peat is the high water content in it. The ratio of the weight of moisture in peat to the weight of wet peat or to the weight of its dry matter, expressed as a percentage, is called peat moisture. The moisture content of peat was determined in accordance with GOST 11305-2013 [12].

The moisture content in peat as a percentage of the weight of wet or dry peat substrate is calculated according to the equations (1-2):

$$W_{rel} = \frac{m_b - m_c}{m_c - m_p} \cdot 100$$

$$W_{abs} = \frac{m_b - m_c}{m_c - m_p} \cdot 100$$

The humidity result is recalculated according to the equations (3-4):

$$W_{rel} = \frac{100 \cdot W_{abs}}{100 + W_{abs}}$$

$$W_{abs} = \frac{100 \cdot W_{rel}}{100 - W_{rel}}$$

where W_{rel}, W_{abs} – relative and absolute humidity of the substrate, %; m_b – the weight of aluminium weighing cups with the substrate before drying, g; m_c – the weight of aluminium weighing cups with the substrate after drying, g; m_p – the weight of aluminium weighing cups, g.

The total acidity of peat includes active (pH) and potential acidity, the latter is divided into the exchange and hydrolytic. Since peat has a large moisture capacity and its acidity is mainly conditioned by the presence of a large amount of free humic acids in it, it is necessary to take a wider (1:25) ratio of peat to the solution when determining the acidity (1:2.5) compared to mineral soils (1: 2.5).

The particle size distribution was determined using a Fritsch GmbH laser microanalyser Analytte 22. The X-ray phase analysis was performed using a Bruker X-ray diffractometer "D8 Advance", which includes an X-ray tube with a copper cathode. Table 5 shows the technical characteristics of dolomitic meal GOST 14050-93 (data from the manufacturer of JSC "Dolomit") [13].

RESULTS AND DISCUSSION

The negative property of high-moor peat – excessively high acidity. According to L.P. Smoliak [14], the acidity of peat in the high moors of Belarus is at the pH_{KCl} level of 3.2-4.2, and according to V.A. Ipatiev – pH_{H2O} 2.6-4.2 [7]. The studies of N.I. Piavchenko [15] established that the acidity of the high-moor peat of the northern regions of Europe is pH_{KCl} 2.8-3.7 [15].

To determine the acidity in this experiment, milled and spade-cut peat of PU "Vitsebsktorf" (Vitebsk region, Dokshitsky district) was used. Peat samples were selected from big bales in the Republican Forest Selection and Seed Centre, followed by mixing and forming an average sample (Table 1).

Table 1. *Options of peat samples and its acidity for analysis*

Sample option	Sample characteristics	pH in KCl	Repetition of the determination
1	Milled peat	2.63	5
2	Spade-cut peat	2.58	5

Under laboratory conditions, peat samples were dried to an air-dry mass, then their analysis was carried out according to modern methods used in the study of peat and substrate [15]. The pH value of peat was determined using a pH meter in a KCl salt extract [11], which is similar in its values in peat of various types of preparation. This acidity is characteristic of peat bogs. When using lime material with an excess of dolomitic meal in the composition and ratio of the dolomitic meal (70%) and chalk (30%), the following results were obtained (Fig. 1).

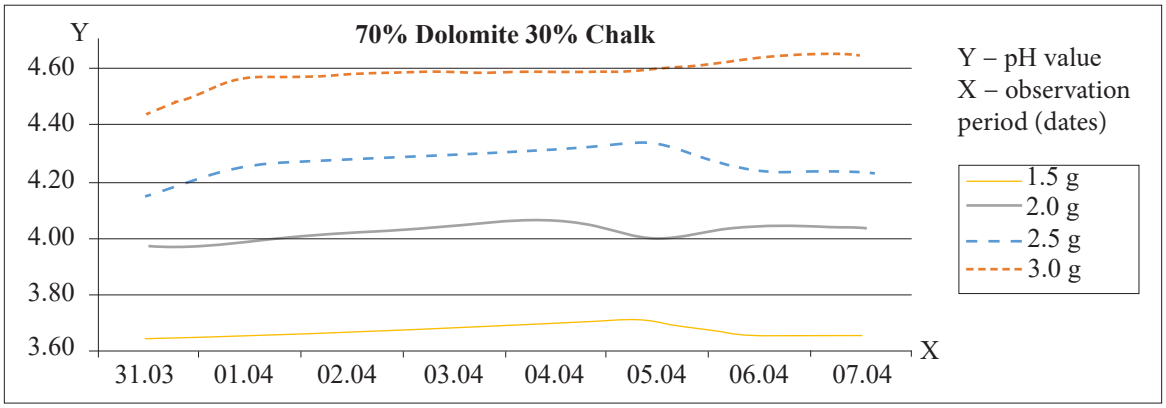

Figure 1. *Change in the pH value with the predominance of dolomitic meal in the mixture (70%) over chalk (30%) as a neutralising component*

Increasing the dosage of the mixed lime material increases substrate neutralisation. However, the growth of deoxidation process does not occur quite evenly. At a dosage of 1.5 g of lime material, the final pH value was 3.66, and at dosages of 2.0 and 2.5 g – 4.04 and 4.22, respectively. At a dosage of 3.0 g, the pH value was significantly higher and amounted to 4.64.

The use of an equal ratio of dolomitic meal and chalk in the composition (50% each) indicates that an increase in the dosage of the mixed lime material increases the neutralisation of the substrate, while the growth of the deoxidation process occurs more evenly (Fig. 2).

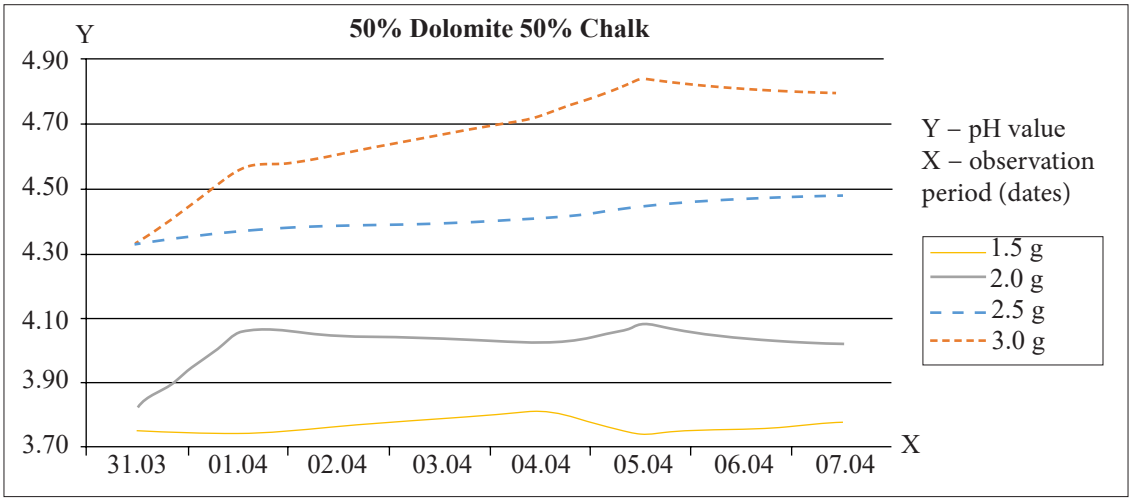

Figure 2. *Change in the pH value at an equal ratio in a mixture of dolomitic meal (50%) and chalk (50%) as a neutralising component*

At a dosage of 1.5 g of lime material, the final pH value was 3.77; 2.0 g – 4.03; 2.5 g – 4.48; 3.0 g – 4.80, respectively.

The use of lime material with an excess of chalk in the composition with a ratio of dolomitic meal of 30% and chalk of 70% indicates that an increase in its dosage increases the neutralisation of the substrate (Fig. 3), while the growth of the deoxidation process also occurs more evenly. At a dosage of 1.5 g of lime material, the final pH value was 3.70, at a dosage of 2.0 g – 4.03, at a dosage of 2.5 g – 4.34, at a dosage of 3.0 g – 4.81.

The process of neutralising the substrate using different dosages of mixed lime material is shown in Figure 4.

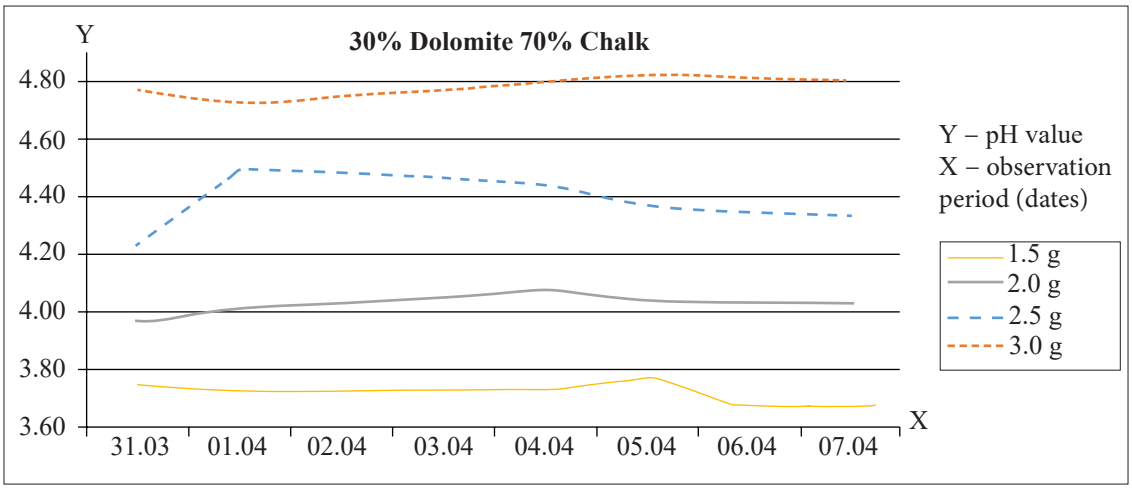

Figure 3. *Change in the pH value when chalk (70%) prevails in the mixture over dolomitic meal (30%) as a neutralising component*

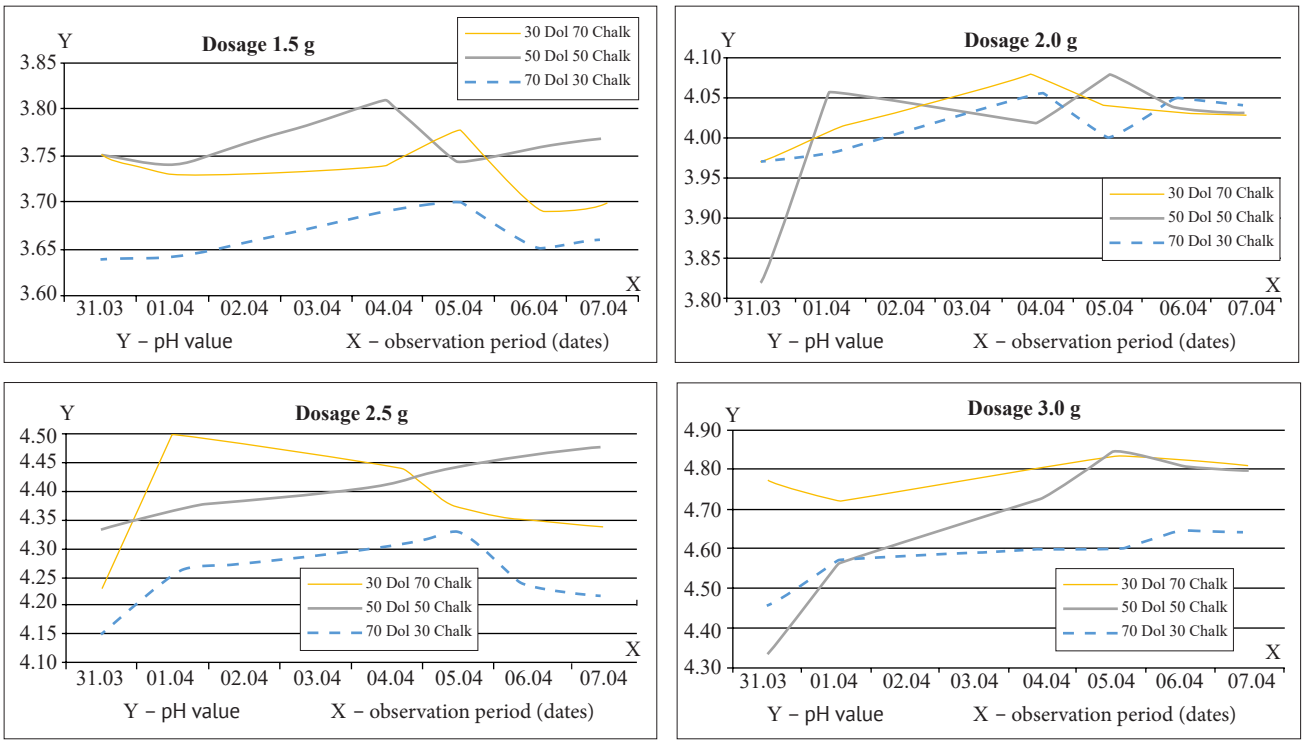

***Figure 4**. Dynamics of the change of substrate neutralisation with the use of different dosages of mixed lime material in different study periods*

An increase in the concentration of chalk in the neutralising material leads to a faster deoxidation of the substrate prepared based on separated cottongrass-sphagnous high-moor milled peat with a pH of 3.2 before neutralisation begins.

Chalk was used as a lime material. The peat under study is characterised as cottongrass-sphagnous, pH 3.2, humidity 50-60% per wet weighing batch (relative humidity). The results of the conducted analyses are shown in Table 2.

***Table 2**. The results of determining the actual acidity (pH_{KCl}) of high-moor peat at different rates of chalk application and duration of experiment*

The norm of chalk, kg/m³	Duration of experiment, days					
	1	3	5	7	9	14
2	4.1	4.1	4.2	4.3	4.4	4.4
4	4.4	4.5	4.7	4.9	4.7	4.7
6	5.1	5.2	5.3	5.4	5.1	5.4
8	5.3	5.8	6.1	6.8	6.7	6.6

***Source**: [6]*

According to the results of the conducted studies [6], it follows that the norms of its application from 2 to 8 kg/m³ were selected for the neutralisation of the peat substrate with chalk. With an increase in the chalk norm, the actual acidity of the peat substrate increases from pH_{KCl} 4.1 to pH_{KCl} 4.3-6.8. The dose of chalk application is calculated for 1 m³ of the substrate (Table 3).

***Table 3**. The required amount of chalk to be applied to the substrate*

Indicator name	Tree species			
	Spruce	Pine	Larch	Oak
Relative humidity of the peat substrate, Wh, %	50-60			
Acidity of the peat substrate, pH_{KCl}	4.0-5.0	4.5-5.5	5.5-6.0	5.5-6.5
Introduction of chalk into the peat substrate, kg/m³	2.5-4.5	3.5-5.5	5.5-7.5	5.5-8.0
Introduction of chalk into the peat substrate, kg/t	10-18	14-22	22-30	22-32

With humidity of 50-60% and natural addition, the specified volume of peat has a weight of about 250 kg. This calculation is given according to the recommendations [11] for the volume and weight of peat. According to the literature data [16] and the study by S.V. Suravyov [6], the amount of chalk applied should be more than dolomitic meal. The reaction of the medium in the peat substrate was established on day 7 when the substrate interacted with chalk. When applying chalk, the reaction of the medium in the substrate changes depending on the dose and the period of interaction of the substrate with the chalk.

Dolomitic meal of JSC "Dolomit" of various deposits (GOST 14050-93 [17]) and/or finely granulated chalk of JSC "Krasnoselskstroymaterialy" (TU RB 590118065.007-2004 [18]), ground separated chalk of JSC "Shebekinsky Melovoy Zavod" (GOST 12085-88 [19]), ground chalk for the production of compound feeds of JSC "Belarusskiy Cementnyy Zavod" (TU BY 700002051.001-2009 [20]) can be used as an additive in the neutralisation of peat substrate.

Table 4 shows the chemical composition of the dolomites of the Gralevo deposit (data from the manufacturer of JSC Dolomit). Raw materials from this deposit are used for the production of limestone (dolomite) meal GOST 14050-93, which is used for the production of substrates by the branch of the production republican unitary enterprise "Vitebskoblgaz" of the production department "Vitebsktorf".

***Table 4**. Chemical composition of dolomites from "Gralevo" deposit of JSC "Dolomite"*

Oxides	Fluctuations, %		The most typical values, %	Average value, %
	From	To		
SiO_2	0.39	13.37	1.0-2.0	1.65
Al_2O_3	0.10	1.79	0.2-0.5	0.37
Fe_2O_3	0.11	1.27	0.2-0.5	0.35
TiO_2	0.01	0.14	0-0.05	0.05
CaO	23.84	34.54	29.00-31.00	30.02
MgO	14.75	22.36	20.00-21.00	20.50
K_2O	0.02	0.64	0.05-0.20	0.13
Na_2O	0.03	0.24	0.03-0.10	0.05
SO_3	–	1.02	0-0.62	0.26
P_2O_5	–	0.17	0-0.03	0.03
MnO	–	0.11	0-0.05	0.02
Total	–	–	–	46.39
$CaCO_3$	47.0	58.0	50.0-52.0	51.0
$MgCO_3$	38.0	47.0	43.0-45.0	42.0
$CaCO_3$+ $MgCO_3$	85.0	99.8	93.0-96.0	95.0

It was found that when neutralised with dolomitic meal, the maximum pH value in the KCl of the peat substrate reaches 6.6, while when neutralised with chalk – 7.5. To determine the cause of this phenomenon, it is necessary to determine the qualitative and quantitative compositions of the neutralising additives used. The content of magnesium, calcium, water, and the amount of the residue insoluble in hydrochloric acid were determined in the starting substances. In the chalk, the sum of sesquioxides (Fe_2O_3) was additionally determined + Al_2O_3). In addition, the dolomites used and the insoluble residues obtained from them were studied by granulometric and X-ray phase analysis.

***Table 5**. Technical characteristics of limestone meal (dolomite) GOST 14050-93*

Indicator	Value
Total mass fraction of calcium and magnesium carbonates, %, not less	85.0
Mass fraction of moisture, %, not more	1.5
Grain composition, total residue on the sieve, %	–
5 mm, not more	–
3 mm, not more	1.0
1 mm, not more	3.0
The index of active ingredient, not less	81.0

The results of the analysis of samples of dolomitic meal from the PU Vitsebsktorf Oktyabrsky (sample 1), (PU Vitsebsktorf) Krulevschina (sample 2), (PU Vitsebsktorf) Obol (sample 3) are presented in Table 6 and Table 7.

***Table 6**. Results of the analysis of dolomitic meal of JSC "Dolomit"*

Component	Deposit		Sample 1	Sample 2	Sample 3
	Gralevo	Ruba			
$MgCO_3$, %	43.1	42.9	43.0	39.2	36.5
per MgO, %	20.5	20.5	20.5	18, 7	17.4
$CaCO_3$, %	53.6	53.4	43.7	55.4	48.4
per CaO, %	30.0	29.9	24.5	31.0	27.1
H_2O, %	0.3	0.1	0.26	0.42	0.15
Insoluble residue, %	3.2	3.0	2.7	3.5	2.1

***Table 7**. The results of the analysis of the chalk deposits Gralevo, Ruba, PU Vitsebsktorf*

Component	Chalk		
	Small-pelleted	Ground	
		For the production of feed compounds	Separated
$CaCO_3 + MgCO_3$ in terms of $CaCO_3$	95.57	91.87	98.00
$CaCO_3$, %	94.5	91.31	96.00
$Fe_2O_3 + Al_2O_3$	0.21	0.65	0.2
H_2O, %	0.48	0.6	0.42
Insoluble residue, %	1.98	5.11	1.3

Samples of dolomite from the Gralevo and Ruba deposits and three samples presented by the PU Vitebsktorf were used for the analysis. As can be seen from the analysis, dolomitic meal consists of a class of carbonates of the chemical composition $CaCO_3 \times MgCO_3$, while in accordance with regulatory documents, the total residue on the sieve of 1 mm or more is 25%, which indicates the size of dolomite particles of 0.1-1.5 mm. In turn, the basis of chalk is calcium carbonate with a small amount of magnesium carbonate and a slight admixture of the smallest quartz grains, while the residue on the 0.045 mm sieve does not exceed 5%, i.e., chalk is a finely dispersed material.

The particle size of the neutralising material affects the speed of the process: the smaller the particle size of the material, the larger the interaction surface of the phases (liquid–solid). Therefore, when adding chalk in the preparation of a peat substrate, the neutralisation process proceeds faster than when adding dolomitic meal. This can also explain the impossibility of obtaining a peat substrate with a pH_{KCl}=7 when using dolomitic meal. Organic acids entering the pores of a granular material (dolomitic meal) are blocked in the pores after a certain period of time due to the generation of products of the interaction of acids with calcium and magnesium carbonates. And they do not have access to the original neutralising additive. When selecting the consumption rate of a neutralising additive, it is necessary to rely not on the mass of limestone flour (dolomitic meal) GOST 14050-93, but on the total content of calcium and magnesium carbonates in terms of $CaCO_3$.

During the experiment on neutralising the peat substrate with chalk, 3 options were delivered in 3-fold repetition with a rate of application from 8 to 10 kg/m^3 using the PNT 3000 combi device. The use of chalk led to a gradual change in the acidity of the peat substrate from pH_{KCl} 2.5, EC – 0.05 mS/cm (milled peat from field 2A) to pH_{KCl} 6.4-7.5 and the establishment of a medium reaction on 6-7 days (Table 8). When conducting an experiment on the neutralisation of a peat substrate with dolomite, 3 options were delivered in 3-fold repetition with a rate of application from 8 to 10 kg/m^3.

***Table 8**. Actual acidity (pHKCl) and electrical conductivity of high-moor peat during neutralisation, taking into account the rate of application of chalk and dolomitic meal*

The norm of chalk, kg/m^3	pH_{KCl}		EC, mS/cm	
	Chalk	Dolomitic meal	Chalk	Dolomitic meal
6	6.4	5.9	0.08	0.06
8	7.5	6.4	0.09	0.06
10	7.5	6.6	0.10	0.07

The use of chalk led to a gradual change in the acidity of the peat substrate from pH_{KCl} 2.5, EC – 0.05 mS/cm (milled peat from field 2A) to pHKCl 5.9-6.6 and the establishment of the reaction of the medium on day 14. For an active experiment, milling peat (fraction from 0 to 7 mm) was taken. These data show that the change in the electrical conductivity of peat depends on the dose and type of neutralising material introduced (Table 9).

***Table 9**. Changes in the acidity and electrical conductivity of top separated peat when applying dolomitic meal*

Experiment option	Tree species	pH_{KCl}	EC, mS/cm
22.02 (the day of experiment)			
Milling peat + dolomitic meal 2 kg/m³	European spruce	3.47	0.05
Milling peat + dolomitic meal 4 kg/m³		4.04	0.05
Milling peat + dolomitic meal 3 kg/m³	Scots pine	3.82	0.05
Milling peat + dolomitic meal 4.5 kg/m³		4.34	0.05
27.02			
Milling peat + dolomitic meal 2 kg/m³	European spruce	3.61	0.05
Milling peat + dolomitic meal 4 kg/m³		4.48	0.05
Milling peat + dolomitic meal 3 kg/m³	Scots pine	4.11	0.05
Milling peat + dolomitic meal 4.5 kg/m³		4.79	0.05
13.03			
Milling peat + dolomitic meal 2 kg/m³	European spruce	3.67	0.05
Milling peat + dolomitic meal 4 kg/m³		4.68	0.05
Milling peat + dolomitic meal 3 kg/m³	Scots pine	4.18	0.05
Milling peat + dolomitic meal 4.5 kg/m³		5.07	0.05

Initially, the milled peat from field 2A had an electrical conductivity of 0.05 mS/cm. When applying chalk: 6 kg/m³, the electrical conductivity increases by 1.6 times (0.08 mS/cm), 8 kg/m³ – increases by 1.8 times (0.09 mS/cm), 10 kg/m³ – increases by 2.0 times (0.10 mSm/cm). The introduction of dolomitic meal in a dosage of 6-8 kg/m³ changes the electrical conductivity by 1.2 times (0.06 mS/cm), and 10 kg/m³ – by 1.4 times (0.07 mS/cm).

Compared with chalk, dolomitic meal at a rate of application of 6-10 kg/m³ has a lesser effect on the change in the electrical conductivity of the high-moor peat. To conduct an experiment on neutralising the peat substrate with dolomite and changing the electrical conductivity, 4 options were studied in 3-fold repetition with a rate of application from 2 to 4.5 kg/m³. The milled peat from field 2A was taken (bulk density at relative humidity (Wrel) 60% – 238 kg/m³, actual acidity (pH_{KCl}) – 2.5, electrical conductivity (EC) – 0.05 mS/cm The experimental data show that the introduction of dolomitic meal from 2 to 4.5 kg/m³ into the milled peat during neutralisation does not lead to a change in the electrical conductivity of the peat.

CONCLUSIONS

Thus, according to the study results, it was found that with an increase in the dosage of mixed lime material (2.5 g and 3.0 g per 125 g of peat), the neutralisation of the substrate naturally increases. The equalisation of the neutralising ability of the mixed lime material occurs approximately on day 7-8 at a dosage of 1.5-2.5 g per 125 g of peat and on day 5-6 at a dosage of 3.0 g per 125 g of peat. Moreover, at a lower dosage, after an increase in the pH value, a certain decline occurs at the end of neutralisation.

An increase in the concentration of chalk in the neutralising material from 30% to 70% leads to a faster deoxidation of the substrate, which is conditioned by the fact that the reaction of the medium in the peat substrate is established after a 10-day interaction with dolomitic meal and a 7-day interaction with chalk.

It was found that when neutralised with dolomitic meal, the maximum pH value in the KCl of the peat substrate reaches 6.6, while when neutralised with chalk – 7.5. These studies have shown that the change in the electrical conductivity of peat during the cultivation of Scots pine depends on the dose and type of neutralising material introduced. Initially, the milling peat had a conductivity of 0.05 mS/cm, but with the introduction of chalk at 6-8 kg/m³, its electrical conductivity increases 1.6-2.0 times (0.08-0.10 mS/cm, and the introduction of dolomite in a dosage of 6-10 kg/m³ changes the conductivity of 1.2-1.4 times (0.06-0.07 mS/cm). Compared with chalk, dolomitic meal with a rate of

application of 6-10 kg/m^3 has a lesser effect on the change in the electrical conductivity of high-moor peat. The introduction of dolomitic meal in a dosage from 2 to 4.5 kg/m^3 into the milled peat (acidity (pH_{KCl}) – 2.5, electrical conductivity (EC) – 0.05 mS/cm) during neutralisation does not lead to a change in the electrical conductivity of the peat substrate (when growing European spruce).

When carrying out the neutralisation of milling peat (pH in KCl – 2.5), the introduction of the dolomite in dosages of 2-4 kg/m3 (European spruce), 3-4.5 kg/m^3 (Scots pine) allows achieving optimal acidity within a month of finding the substrate in the greenhouse and before the emergence of woody plants. According to TU BY 100061961.001-2015, the optimal acidity of the substrate for growth of European spruce is pH in KCl 4.0-5.0; for Scots pine – pH in KCl 4.5-5.5. As a result of experiments, it was possible to achieve neutralisation of the peat substrate when applying dolomitic meal at a dosage of 5.8-10 kg/m^3 only up to a pH in KCl of 4.9-5.4. Increasing the dose of application of dolomitic meal to 11-14 kg/m^3 allows reaching a pH of 6.0-6.1 in KCl after a month in the greenhouse. The use of large doses of dolomite does not significantly or practically affect the change in the acidity of the peat substrate.

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Вплив нейтралізуючих матеріалів на реакцію середовища торф'яного субстрату при вирощуванні сіянців із закритою кореневою системою

Сергій Володимирович Ребко[1], Іван Васильович Кімейчук[2,3*], Сергій Валерійович Сурав'єв[1], Василь Михайлович Хрик[2], Світлана Миколаївна Левандовська[2]

[1]Білоруський державний технологічний університет
22006, вул. Свердлова, 13а, м. Мінськ, Республіка Білорусь

[2]Білоцерківський національний аграрний університет
09117, вул. Соборна площа, 8/1, м. Біла Церква, Україна

[3]Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна

Анотація. Використання різних видів нейтралізуючих матеріалів при вирощуванні стандартного посадкового матеріалу лісових деревних видів високої якості істотно впливає на кислотність субстрату. Тому авторами статті було поставлено за мету підібрати торф'яні субстрати з різним дозуванням нейтралізуючої складової і визначити вплив їх на реакцію середовища торф'яного субстрату. У представленій статті наведені результати впливу нейтралізуючих матеріалів доломітового борошна і крейди різних доз із застосуванням мінеральних добрив. Як нейтралізуючий компонент використовувалося доломітове борошно pH торф'яного субстрату – 6,6 і крейди – 7,5. Встановлено, що при нейтралізації торф'яного субстрату, створеного на основі верхового торфу фрезерної заготівлі (pH 2,5) із внесенням доломітового борошна дозами 2–4 кг/м^3 (ялина європейська), 3–4,5 кг/м^3 (сосна звичайна), оптимальної кислотності можна досягти через місяць. Авторами статті було зафіксовано збільшення концентрації вапняного матеріалу, що призводить до збільшення нейтралізації субстрату при дозі 2,5 г і 3,0 г на 125 г торфу. Кращі показники продемонстрували варіанти доз 1,5–2,5 г на 125 г торфу при 7–8-денному використанні і дозуванні 3,0 г на 125 г торфу на 5–6 день у порівнянні з контролем. Збільшення концентрації крейди в нейтралізуючому матеріалі від 30 % до 70 % призводить до більш швидкому розкисленню субстрату (pH 3,2), а при підвищенні дозування крейди збільшує нейтралізацію субстрату. Електропровідність субстрату в дозуванні 6–8 кг/м^3 при внесенні крейди і доломітового борошна збільшується в 1,6–2,0 і 1,2–1,4 рази відповідно. При нормі внесення 6–10 кг/м^3 чинить менший вплив на зміну електропровідності верхового торфу, а внесення доломітового борошна 2–4,5 кг/м^3 в торф фрезерної заготівлі в процесі нейтралізації не призводить до зміни електропровідності торфу. Зазначені наукові знання дозволяють підібрати нейтралізуючі матеріали певної концентрації, які дозволять вирощувати стандартний посадковий матеріал європейської якості і тим самим забезпечать належну якість майбутніх деревостанів

Ключові слова: кислотність середовища, посадковий матеріал, доломітове борошно, крейда, торф, субстрат

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Landscaping Project for a Private Garden Plot in the City of Zaporizhzhia

Leonid Khoroshkov, Nataliia Derevianko*

Khortytsya National Training and Rehabilitation Academy
69017, 59 Naukove Mistechko Str., Zaporizhzhia, Ukraine

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Abstract. Landscaped areas provide individual, distinctive features and play an important role in shaping the environment of a private garden plot. The authors of the present study developed a landscaping project for a private garden plot at 80 Izmailivska Street, city of Zaporizhzhia. One of the main points of the works was to conduct an inventory of the available plantings. The authors identified the species composition of trees and shrubs located on the landscaping territory. In the project territory, the largest area is occupied by herbaceous cover and is 32.5%, while the smallest area is allocated for tree plantations – only 1.9%. The area under paving and flower beds will be increased at the expense of the territory that is not occupied in the reconstruction project. In the project area, most woody plants require only pruning and are in good condition. Pruning is planned for 10 black mulberry trees (*Mórus nígra L.*), remnants of a privet hedge (*Ligústrum vulgáre*), one bush of Vanhoutt Spiraea (*Spiraea* × *vanhouttei* (*Briot*) *Zabel.*) and one bush of rosehip corymbose (*Rosa corymbifera*), which have lost their decorative appeal. The formation of plantings in this study aims to create an orderly shape of the crowns of trees and shrubs, which will give them a geometric shape. For decorative purposes, it is also planned to plant the following plants: boxwood tree (*Buxus sempervirens var.*), iris brazenberry (*Iris L. brazenberry*), moss phlox (*Phlox subulata L.*). On the site located to the east of the outbuilding, it is proposed to set up a flower garden from groundcover and flowering plants in a peculiar geometric shape that would follow the shape of the path. On the north-western side of the plot, it is planned to replace the fence with a modular gabion wall covered with rambling vine. The colour of elements of this style should be made in cool, grey tones, white, blue and purple colours are well combined. As a result, it is planned to set up a decorative pond near the arbour, the contour of which will be decorated with smooth stones. The rest of the area is to be covered with a rolled lawn. As a result, an individual and beautiful style of landscape design will be selected for the project area

Keywords: Art Nouveau, gardening, private territory, paths, bench, landscaping

*Corresponding author

INTRODUCTION

Art Nouveau gardens replaced the then-popular luxurious gardens with a riot of colours and plants at the turn of the 19th-20th centuries and became a worthy alternative. It was an attempt to escape from a style that copied historical forms and set a new development vector. The main inspiration for the creators of this period was nature, its asymmetry, variety of textures, elegant colours or smooth and wavy lines. Artistic motifs were drawn from the richness of the local flora and fauna. Flowering shrubs, perennials and lianas were particularly inseparable decorative and compositional elements of the garden. A variety of shrubs – especially roses and perennials such as lilies, irises, and phlox – gave the impression of architecture immersing itself in the surrounding garden. [1] Art Nouveau appeared at the junction between the aesthetically beautiful and the pragmatically functional, between the idealised natural world and the industrialised society [2]. Nowadays, it is widely used in landscape design, which is expressed through a special interpretation of the basic rules and compositional techniques, the colour scheme of a small garden, the choice of plants and their combinations, types of decorative paving, small architectural forms and garden equipment [3].

When choosing the style of landscape design of the territory, it is worth paying attention to the style of the house and choose the style of landscape design accordingly. For the design of the territory, this style of landscape, described by aesthetics and simplicity, is combined with the plants existing on the territory [4-7]. Previously, all that could be attributed to professional landscaping in the city was large objects: squares, parks, boulevards, alleys, etc. But over the past few decades, the situation has radically changed. At present, the demand for the services of a landscape designer has increased, precisely if it concerns the landscaping of private garden plots. Modern trends in the design of such objects are becoming an integral part of creating a homely, aesthetically attractive object [8-10].

Efforts to design gardens and preserve and develop green open spaces in and around cities are efforts to maintain contact with the original rural landscape. Filling open areas in cities, gardens and design landscapes create integrity in the space between structural urban landscapes and open rural landscapes outside them [11; 12]. Key aspects of green plantings are their contribution to habitat suitability. A key feature of the home garden is that it is considered as an external extension to the residence, providing a unurged rest [13; 14].

An important key to successful landscaping is to think about the people who use the space. An important element of any project is the seats and they should be placed where the hosts and guests will feel comfortable. Many successful locations currently have movable chairs so that people can find the most comfortable location and feel a sense of ownership in this territory [13; 15]. The scientific originality of the obtained research results lies in the development of new proposals for landscaping of private territory.

The purpose of the study – development of a landscaping project of a private garden plot in the conditions of the city of Zaporizhzhia.

To achieve this purpose, *the main objectives of this study* are determined as follows: conduct a comprehensive assessment of the territory to be reconstructed; create a reconstruction project for the object; give recommendations on the maintenance after the project is implemented.

MATERIALS AND METHODS

One of the main points of the works was to conduct an inventory of the available plantings. Based on the data obtained, drawings were compiled. The survey data was used to develop a project on improvement of the existing condition of plantings and decorative design of the object. Inventory of existing plantings was performed in accordance with the Instructions for Inventory of Green Plantings in Localities of Ukraine [16]. Plant names are given according to the guide to plants [17], Latin names are specified according to the international classification of The Plant Database.

The design site is located in the private sector "Zelenyi Yar" of the Shevchenkivskyi District in the city of Zaporizhzhia, at 80 Izmailvska Street. The territory has a rectangular shape, bounded on three sides by other private estates and partitioned off from them by a fence. The entrance to the property is on the west side.

At the pre-project stage, a survey of the proposed site was carried out, considering the terrain features. The landscape type is open. The terrain of the site is flat. The object area is 520 m^2. Length is 46.9 m; width is 11.1 m. Survey of soil conditions: the mechanical composition of the soil was determined according to the N.A. Kachynskyi's "wet" method. The reaction of the soil solution was determined using the Alyamovsky's device. The structure and colour of the soil were determined visually [15]. The authors investigated the state and proper condition of stationary engineering and architectural structures and gardening equipment, underground and ground engineering networks and communications. On the project territory, engineering networks are in satisfactory condition: air electric network, underground water supply, sewerage. In the course of the study, the authors developed a calendar plan for landscaping works on the object, indicating all types of works according to seasons.

As a result, all project work, namely the key plan and the landscaping plan, were created using the CorelDraw 2018 software.

RESULTS AND DISCUSSION

Territory inventory at the 80 Izmailivska Street, city of Zaporizhzhia

After the inventory, the following indicators were identified:

1. Land use distribution (total area under green plantings, in particular under trees, shrubs, lawns, flower beds; paths, buildings, and structures, etc. – Table 1).

On the project territory, the largest area is occupied by herbaceous vegetation. It is 32.5%. And the smallest area allocated for tree stands is only 1.9%. The reconstruction project will be increased the area under paving and flower beds at the expense of the territory that is not occupied.

***Table 1**. Land use distribution at the 80 Izmailivska Street, city of Zaporizhzhia*

Seq. No.	Structure elements	Current state		Under project	
		m^2	%	m^2	%
1.	Path coverage	131.4	25.3	135.0	25.9
2.	Plantings:	197.7	38.0	120.1	23.1
	Namely: trees	10.0	1.9	10.0	1.9
	shrubs	18.9	3.6	19.8	3.8
	lawns	169.0	32.5	103.3	19.9
	flower beds	–	–	9.0	1.7
TOTAL		520	100	520	100

2. Species composition of trees and shrubs. Most woody plants are in good condition and only require pruning. The vast majority of plantings are about 5 years old, some were planted in sanitary areas of engineering networks, and according to the rules must be removed. However, according to their indicators, they do not cause damage to engineering networks; therefore, it is recommended to leave them in the reconstruction project (Table 2).

***Table 2**. Species composition of trees and shrubs in the landscaping territory at the 80 Izmailivska Street, city of Zaporizhzhia*

Seq. No.	Plant names, species	Quantity	Share of the species in the totality of plantings, %	Decorative features	Condition
1	Boxwood tree *Buxus sempervirens L.*	9	33.3	Crown shape, evergreen	Good
2	Red raspberry *Rúbus idáeus L.*	6	22.2	Crown shape, decorative fruits	Good
3	Grape vine *Vitis vinifera*	4	14.8	Liana, decorative fruits	Good
4	Domesticated apple *Malus domestica (Borkh.)*	2	7.4	Crown shape, decorative fruits	Good
5	Common juniper *Juniperus communis L.*	2	7.4	Evergreen, crown shape	Good
6	Peach tree *Prunus persica L.*	1	3.7	Crown shape, well-flowering, decorative fruits	Good
7	Common lilac *Syringa vulgaris*	1	3.7	Crown shape, flowering	Good
8	Common plum *Prunus domestica L.*	1	3.7	Well-flowering, decorative fruits	Good
9	Sweet cherry *Prunus avium L.*	1	3.7	Crown shape, decorative fruits	Good
TOTAL:	***27***				

3. State and proper condition of stationary engineering and architectural structures and gardening equipment, underground and ground engineering networks and communications (Table 3).

***Table 3**. Explication of aboveground and underground engineering networks and communications*

Seq. No.	Type of utility networks	Length, m	Area of the protected territory, m²	Placement	Note
1.	Sewerage	14. 5	72.5	Underground	Planting trees is forbidden in a zone of 5 m
2.	Water supply system	44.6	223.0	Underground	
3.	Power grid	32.2	161.0	Air	
4.	Inspection wells of eng. networks	–	5	Overland	

The project territory contains an inspection well of the drainage network. According to the Construction Standards and Regulations (SNiP), it is prohibited to plant woody plants that fall under the five-metre sanitary zone of engineering networks [5]. Currently, there are six architectural elements on the site.

During the preliminary survey of the site and work on the inventory of plantings, it was established that the territory of the design object, in general, is in good condition (Fig. 1).

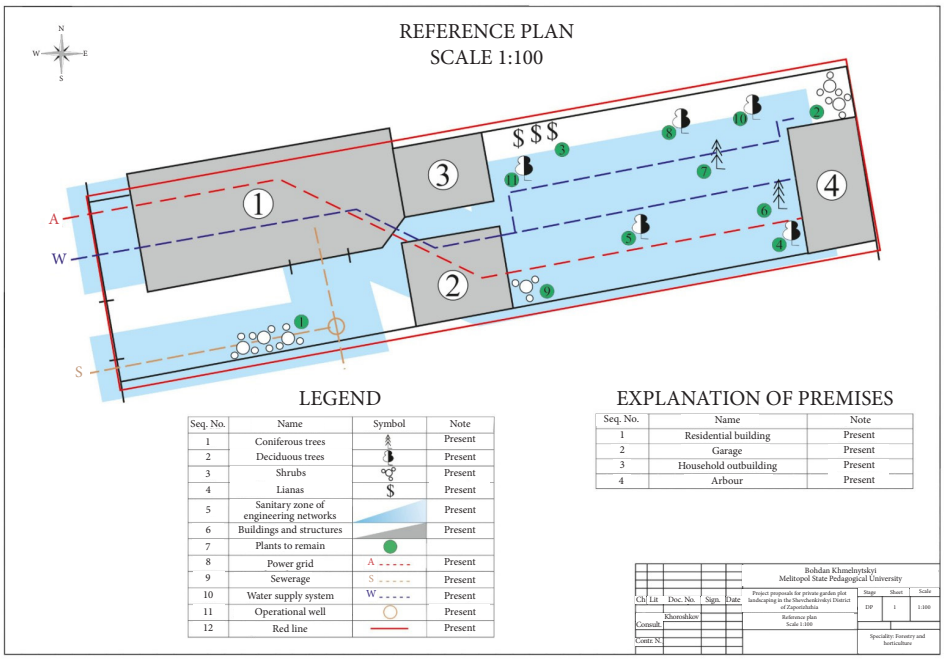

***Figure 1**. Reference plan based on the inventory of plantings*

Pre-project survey of the soil allowed identifying the characteristics of the soil as follows: mechanical composition – sandy loam; soil structure – pulverescent and granulated; pH of water extraction – 7.2; soil colour – grey. With this colour, soils usually contain about 3-4% humus.

General planning composition and landscape organisation of the territory

The choice of plot design was influenced by its small size, rectangular shape of the garden plot, including buildings and structures available on the territory. Art Nouveau was chosen as the best and appropriate style, through which it is proposed to create a unique place for recreation and embody original and bold landscaping ideas. The design of a private garden plot in the Art Nouveau style is an opportunity to create maximum beauty with a minimum of space. The main principle of organising a plot in this style is geometric shapes and natural decorative materials.

The bulk of plantings on the territory of the garden plot were laid recently, but without considering any rules and styles. Since the plants are arranged randomly, it was necessary to pay attention to their harmonious combination with the style of the future garden. It is proposed to leave the entire western half of the plot unchanged. On the site located to the east of the outbuilding, it is proposed to set up a flower garden from

groundcover and flowering plants in a peculiar geometric shape that would follow the contour of the path. On the left, near the arbour, it is planned to set up a decorative pond of square shape, decorated with smooth stones (pebbles) along the contour, stretching it directly to the arbour. The path leading to the arbour is proposed to be made step-by-step, slightly wavy in shape. In addition, on the north-western side of the plot, it is planned to replace the fence with a modular gabion wall covered with rambling vine. The rest of the area is to be covered with a rolled lawn.

The formation of plantings in this study aims to create an orderly shape of the crowns of trees and shrubs, which will give them a geometric shape. In this case, it includes 10 black mulberry trees, remnants of a privet hedge, one bush of Vanhoutt Spiraea and one bush of rosehip corymbosem which have lost their decorative appeal. According to the landscaping plan (Fig. 2), the following plants are to be planted: boxwood tree (*Buxus sempervirens var.*), iris brazenberry (*Iris L. brazenberry*), moss phlox (*Phlox subulata L.*).

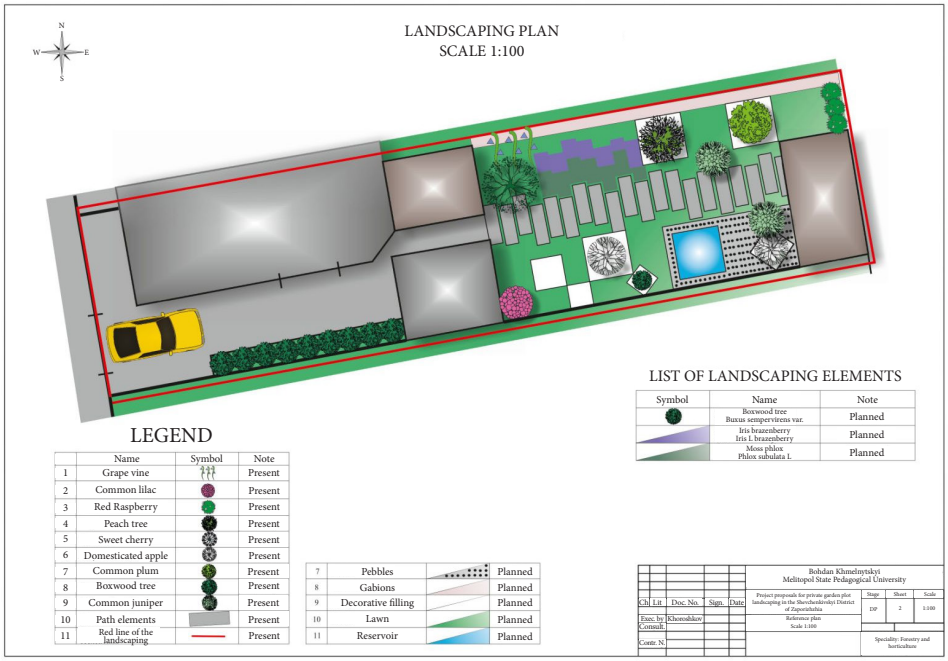

***Figure 2**. Landscaping plan for the territory at the 80 Izmailivska Street, city of Zaporizhzhia*

Garden and park equipment for landscaping and calendar plan of landscaping works

To improve the territory, it is proposed to create conditions for comfortable rest using the following elements: a step-by-step path; decorative filling; a reservoir; gabions. The future pathway will cross the eastern part of the garden from west to east. The shape and surface of the paths are designed according to the style of the reconstruction project. Material – white granite. Using decorative filling, it is proposed to make squares of different sizes on the surface of the soil, which are inherent in the Art Nouveau. Material – white granite chips. Due to their shape, ornaments made of coloured filling form a single composition with other landscaping elements, reproducing the contrast against the background of a green lawn.

Gabions are three-dimensional factory-build structures, made of galvanised metal gauze. Gabion structures perfectly fit into the environment, often almost completely merging with it. Not only do they not alter the aesthetic value of nature (unlike, for example, reinforced concrete structures), but even complement it. For a rational organisation of the construction of an object, it is necessary to establish the order of execution of certain types of work. When establishing such a priority, it is necessary to consider the following factors: the performance of one type of work should not complicate and affect the quality of another type of work; natural conditions and weather features; real opportunities for obtaining the necessary materials.

The calendar plan for works at the landscaping object was developed in accordance with the design decisions and is presented in Table 4.

***Table 4**. Calendar plan of works for the construction of a landscape architecture object*

Seq. No.	Name of works	Schedule											
		January	February	March	April	May	June	July	August	September	October	November	December
1	Engineering preparation of the territory										■		
2	Dismantling the path											■	
3	Laying the lawn						■						
4	Path arrangement				■								
5	Construction of a water body					■							
6	Planting flower beds					■							
7	Sanitary care of plants	■				■	■	■	■				

The calendar plan of reconstruction works on the territory of a private estate is designed for 1 year. According to the calendar plan, all types of work can be divided into seasons as follows:

1. **Autumn**. Starting from October, one can start engineering preparation of the object's territory; collection and removal of garbage; laying of engineering networks; dismantling of the old road surface, planting seedlings of woody plants.

2. **Winter**. Starting from January, sanitary care is to be carried out for the available tree plantings.

3. **Spring**. Starting from April, one can start the reconstruction of the path; installation works on the arrangement of a gabion fence, including the setup of a water body; breakdown and arrangement of flower beds and decorative filling; pruning of woody plants; laying of lawn cover.

4. **Summer**. Plant maintenance: watering, fertilising plants, pest and weed control, lawn mowing.

CONCLUSIONS

The authors developed a landscaping project for a private garden plot at 80 Izmailivska Street, city of Zaporizhzhia:

• a comprehensive assessment of the territory to be reconstructed was carried out. An inventory was carried out and the land use distribution was identified. The species composition of trees and shrubs was studied.

• According to the project, the main landscaping features of the site will be in the Art Nouveau style, which will fit harmoniously into the project.

• A project for the reconstruction of landscaping of the garden plot has been created, tackling the urgent problems of the given territory and considering the intended functionality of the object.

• Recommendations for the maintenance of plantings after the project implementation are presented.

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Проект благоустрою та озеленення приватної присадибної ділянки у місті Запоріжжя

Леонід Михайлович Хорошков, Наталія Петрівна Дерев'янко

Хортицька національна навчально-реабілітаційна академія
69017, вул. Наукового Містечка, 59, м. Запоріжжя, Україна

Анотація. Зелені насадження надають індивідуальні, своєрідні риси та відіграють важливу роль у формуванні середовища приватної присадибної ділянки. Авторами статті було розроблено проект благоустрою та озеленення приватної присадибної ділянки за адресою вул. Ізмайлівська, 80, м. Запоріжжя. Одним із основних пунктів робіт було проведення інвентаризації існуючих насаджень. Визначено видовий склад дерев і кущів, які знаходяться на території озеленення та благоустрою. На території проектування найбільшу площу займає трав'яний покрив і становить 32,5 %, а найменша площа відведена під деревні насадження – всього 1,9 %. Буде збільшено площі під мощенням і квітниками за рахунок території, що не є зайнятою у проекті реконструкції. На території проектування більшість деревних рослин потребують тільки заходів з формуючої обрізки та є у доброму стані. Заплановано обрізку 10 дерев шовковиці чорної (*Mórus nígra L.*), залишки живоплоту із Бирючини звичайної (лат. *Ligústrum vulgáre*) та по одному чагарнику Таволги Вангутта (*Spiraea × vanhouttei* (*Briot*) *Zabel.*) і Шипшини щитконосній (*Rosa corymbifera*), які втратили свою декоративну привабливість. Формування насаджень у даному дослідженні має на меті створення акуратної форми крон дерев і чагарників, що надасть їм геометричної форми. Для декоративності заплановано також висадка таких рослин: Самшит вічнозелений (*Buxus sempervirens var.*), Півники блазенбері (*Iris L. brazenberry*), Флокс Шиловидний (*Phlox subulata L.*). На ділянці, що розташована на схід від господарської споруди, пропонується розбити квітник цікавої геометричної форми, яка повторює вигляд доріжки, з ґрунтопокровних і гарноквітучих рослин. З північно-західної сторони ділянки передбачається змінити існуючий паркан на модульну стінку з габіонів, прикривши її в'юнким виноградом. Колір елементів такого стилю має бути виконано в холодних, сірих тонах, добре поєднується білий, синій і фіолетовий кольори. У результаті біля альтанки планується облаштувати декоративну водойму, контур якої буде задекоровано гладким камінням. Усю іншу площу запропоновано вкрити рулонним газоном. В результаті буде підібраний індивідуальний та красивий стиль ландшафтного дизайну для території проектування

Ключові слова: стиль модерн, озеленення території, приватна територія, доріжки, лавка, благоустрій

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Prerequisites for the Creation of a Mechatronic System of Indented Cylinders for the Separation of Fine Seeds

Elchyn Aliiev[1*], Krystyna Lupko[2]

[1]Institute of Oilseed Crops NAAS
69093, 1 Instytutska Str., v. Soniachne, Zaporizhzhia District, Zaporizhzhia Region, Ukraine

[2]Dnipro State Agrarian and Economic University
49600, 25 Serhii Efremov Str., Dnipro, Ukraine

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Abstract. Nowadays, an important aspect for achieving a high level of seed production is the expansion of the range of high-quality seed material, which disrupts the technological process of separation and increases its costs. The purpose of the study is to analyse indented separator cylinders for cleaning small-seed crops and develop an appropriate mechatronic system for their control, the use of which would allow performing the technological process of separation with lower specific operating costs and higher productivity. The presented analysis of the technical support of the process of separation of seed material of small-seeded crops indicates the need to improve indented separator cylinders based on automated control of their parameters using photo or video recording of the seed separation with subsequent processing. It has been established that the determination of formal performance indicators of an indented separator cylinder is not trivial. Based on the results of the analysis, a design and technological scheme of the mechatronic system of an indented separator cylinder has been developed. The difference between the proposed system and the conventional one is that the camera captures the trajectory of seeds. This information is processed in the control unit, which in turn changes the speed of rotation of the gear motor and, as a result, the drum with cells, the angle of inclination of the tray, the angle of rotation of the flap with the stepper motor of the hopper dispenser. These manipulations with the operating parameters of the indented separator allow adjusting it to changes in the seed mixture composition, thereby improving the quality and productivity of separation. In addition, due to the automatic adjustment of the operating parameters of the indented separator, the participation of the operator in the separation process is practically not required, which reduces labour costs

Keywords: seed, grain separator, control, automation, parameters, modes

*Corresponding author

INTRODUCTION

An important task of agro-industrial production remains to increase the range of seed material to meet the growing needs of farms of various forms of ownership. When the level of seed production is reached, the load on seed cleaning equipment increases, which leads to a violation of the technology of its in-line post-harvest processing [1].

The quality of seed material after processing is largely determined by the compliance of technical means of volume and rational technology of post-harvest seed treatment [2]. Therefore, seed treatment in existing production lines does not allow selecting high-quality seeds without cost and ensure the efficiency of their cleaning from impurities in length. In Ukrainian institutions engaged in selection and seed work, grain separators made more than 20 years ago are used as basic machines for cleaning seeds of various agricultural crops collected from research sites. Physically, the machines are worn out and need to be upgraded.

There are a large number of technologies and technical means of post-harvest seed processing and preparation of seed material of small-seeded crops. The most famous manufacturers of seed cleaning equipment are Bühler Schmidt-Seeger, Denis Prive, NEUERO Farm- und Fördertechnik GmbH, PETKUS Technologie GmbH (Germany), Zanin F.lli s.r.l. (Spain), Westrup (Denmark), Akyurek (Turkey). However, even the proposed integrated approach, including the use of universal cleaning machines, does not allow systematising and developing the technological basis for the processes of cleaning and separating seeds of a number of oilseed varieties, such as flax, mustard, rapeseed, ginger, sage, amaranth, etc. [3]. One of the options for solving this problem is to improve existing technical means for separation by creating mechatronic systems for automated control of their design and operating parameters.

Therefore, *the purpose of the study* is to analyse seed separators for small-seeded crops and to develop an appropriate mechatronic system for their control, the use of which would allow performing the technological process of separation with lower specific operating costs and higher productivity.

THEORETICAL FOUNDATIONS OF THE SORTING PROCESS

Seed sorting is an important step in the overall seed processing. In the seed mixture collected from the fields, there are such impurities as stems, leaves, mineral impurities, etc. In addition, the seed material contains: low-quality seeds of other crops, broken and damaged seeds of the main crop, weed seeds [4-6]. The quality of seed material increases due to its processing by removing impurities and excess moisture. Separation machines are based on physical differences in characteristics that may exist between seeds of cultivated plants and other undesirable particles. Seed sorting can be considered as a subtask of separation and improving the quality of seed material.

The result of separation depends on various individual physical properties of seeds [7]. Examples of such physical characteristics are: size, length, weight, shape, colour, etc. [8]. Conducting an overview of the physical characteristics of various types of seeds is important for the further customisation of modern seed cleaning machines [9; 10] and for the development of new types of machines [11; 12]. Several such reviews were published [13-15], the generalisation of which allowed forming a modern technological line of processes for separating seed material of small-seeded crops according to their physical and mechanical characteristics (Fig. 1). New methods for determining these characteristics continue to be developed [16].

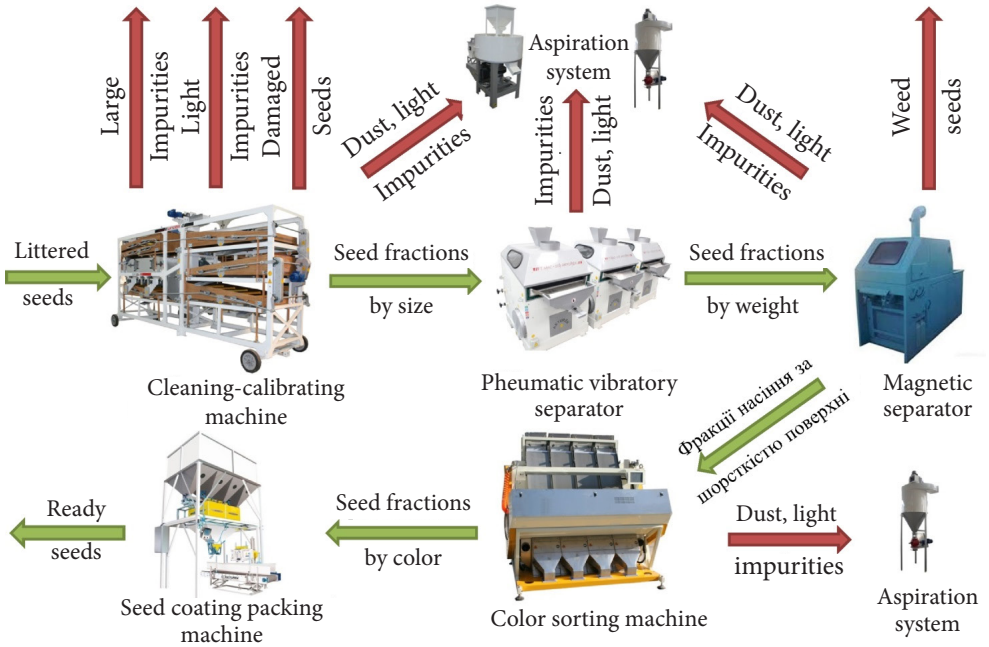

Figure 1. *Modern technological line of oilseed separation*

Source: *[3]*

All methods of seed material separation can be divided according to the corresponding physical and mechanical properties of seeds [17-19]: according to aerodynamic properties (in pneumatic columns and other air channels); according to dimensional characteristics (width and thickness – on sieves with round and rectangular holes, length – on indented separators); according to density or bulk volume (on pneumatic tables, pneumatic vibratory separators) [20-22]; according to surface properties and shape (on slides, friction separators); according to elasticity (on reflective sorting tables); according to electrophysical properties (in dielectric separators, separators in the corona discharge field); by colour (colour sorting machines) [23-25].

There are some preliminary studies in the field of mechanical seed separation and optimisation. For example, [26] investigated the improvement of the winnower and rice cleaning machine to reduce the amount of impurities and the loss of viable seeds. A prototype winnower and regression models were developed, through which the researchers drew conclusions about the choice of basic parameters such as air velocity, humidity, and feed rate. Other researchers [27] developed a mathematical model of cleaning efficiency in a stationary thresher. The model applies the principles of dimensional analysis as a theoretical basis. Dimensional analysis was also used in [28] for mathematical modelling of the cleaning process on flat sieves.

In [29], a hybrid intelligent approach was used to control pneumatic separators to obtain the most optimal result, including the use of an artificial neural network and genetic algorithms. A pneumatic separator was developed [30] and analysed using crushed mixtures of three lupine varieties. The researchers identified correlations between the parameters of the separation process and its efficiency. Automated modelling and control of post-harvest aspects have also been studied for seed drying and sorting systems [31]. Recently, there has been interest in the use of artificial intelligence methods to control such processes.

A cylinder with cells is used to sort or improve the quality of seeds using length as the main distinguishing feature. The cellular cylinder divides the seed mass into 2 fractions: "long" seeds and "short" seeds. There are also other seed sorting machines. The next machine used after the cylindrical separator is the gravity separator. This device separates seeds based on their weight. It is necessary that the seeds are relatively uniform in physical characteristics or length – any that a cylinder with cells can capture. The researchers [32] modelled the granular flow on the gravity separator table. Particle motion was modelled as a stochastic process [33]. In further analysis, the researchers [32] used digital imaging technologies and computer scanning (or image analysis) techniques as a mechanism for the empirical sampling of some of the corresponding initial cellular cylinder variables.

Work in related fields such as artificial intelligence and object recognition has been carried out for at least 60 years, starting with the invention of the first digital computers. Since then, these areas have developed and a large number of studies are being conducted in these areas. Over time, they gave rise to the field of computer scanning – an area of research aimed at developing methods for extracting visual information encoded by pixels of a digital image. The goal is to obtain digital or symbolic information necessary for decision-making [34; 35]. Both the main and applied discipline of computer science, this branch relies heavily on methods of geometry, statistics, physics, learning theory, etc., to obtain visual information from data stored in pixels [36; 37].

Automation and optimisation of seed validation and classification using computer scanning/image analysis remain important, especially for non-invasive seed germination testing [38]. Recently, the line of equipment for seed sorting has been supplemented with the use of a simple form of image analysis – colour division. Such a machine classifies certain types of seeds based on their colour using various sensors. Seed sorting machines are used at the end of the machining process [39; 40].

Classifying non-moving seeds is usually seen as a simple object recognition task. Researchers [41] addressed the problem of seed crops classification, focusing on various characteristics and categorisers. The artificial neural network (ANN) was one of the categorisers used. Discriminant analysis and k-nearest neighbour (k-NN) were used in the control (controlled) classification. A fairly popular and generally successful approach with controlled ANN was used to assess wheat quality [42]. Studies [43] have taken a very careful approach to the assessment of the quality and classification of barley seeds. The method used estimates of placement, orientation, direction, and surface structure of individual barley grains.

The studies mentioned so far are united by the fact that they do not deal with the actual physical separation of seeds. Instead, the studies were focused on the task of analysing images to classify seeds that were statically placed in front of the camera. The main focus was on developing new sorting machines – usually based on colour separation as a reference. An automatic seed sorting system based on machine scanning for automated classification of red and white wheat seeds was developed in [44]. The system was capable of processing 15 seeds per second with a classification coefficient of more than 92%. A similar system was developed [45] for testing wheat and other grain crops. The system was capable of processing 30 seeds per second with an accuracy of 95 to 99%. The experiment was conducted using red and white wheat grains.

The study [46] developed another low-cost image-based sorting device capable of processing 75 seeds per second. Minor colour deviations and small defects in the seed surface were the main criteria for classification.

An interesting innovation in seed sorting was a device patented in [47]. The idea that became the basis of this invention is a pellet sorting machine, which is based on the performance characteristics of an indented cylinder separator.

The presented analysis indicates the need to improve indented separators based on automated control of its parameters using photo or video recording of the seed separation process with subsequent processing.

SEPARATION OF SEEDS ON INDENTED SEPARATORS

The length of the seed is used as an excellent physical characteristic in the cellular cylinder. As a rule, the seed material sent to the machine is divided into 2 groups: long seeds and short seeds. Cellular cylindrical machines are known as an indented separators. They sort seeds by length.

Figure 2 is a graphical representation of the perfect separation process in a cellular cylinder along the length. At the top is a graph of two normal distributions with different mean and standard deviations. These are examples of possible distribution of seeds by length in the input mixture. A circle in the centre represents a cellular cylinder. The cleaning process depends on several parameters: seed mix, machine settings, and interference that can and cannot be measured (controlled and uncontrolled). The input mixture is two-component – long (1) and short (2) seeds. The last 2 graphs show two separate divisions of long and short seeds into separate components. The scenario shown in Figure 2 is very simplified and can be considered unrealistic. The separation of input material by length in most cases cannot be statistically modelled as an ideal two-component mixture of long and short seeds. A more realistic way to statistically model the separation of the source material by length is to use the separation of a mixture of normal random variables with the corresponding mixture density.

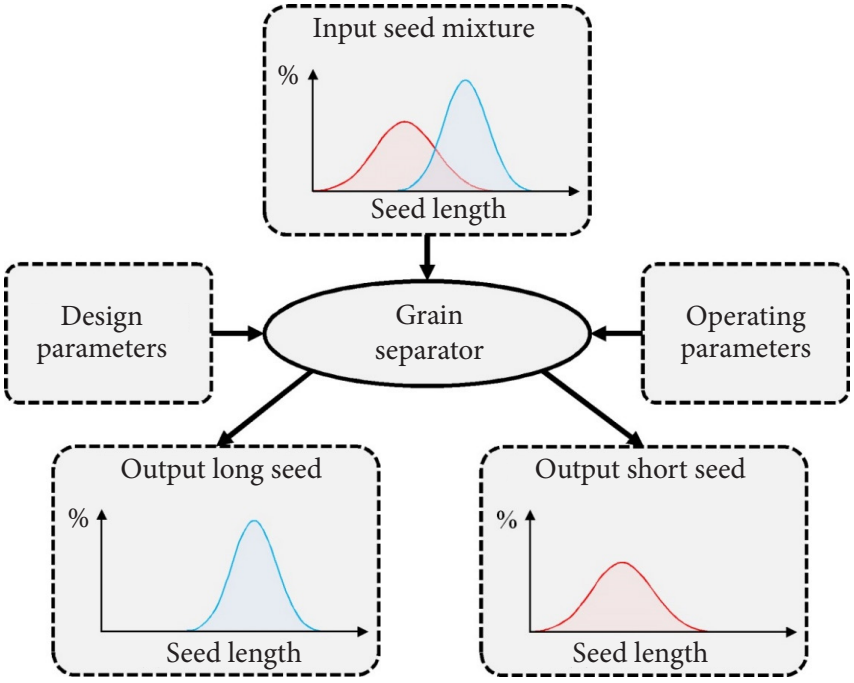

***Figure 2**. Conceptual model of the operation of indented grain separator*
***Source**: compiled by the authors based on [18]*

The working body of a cylindrical cellular separator is an inclined steel cylinder with cells of a certain shape and size. These cells are tightly located on the inner surface of the cylinder. Such a cylinder is usually made of a steel sheet that has indentations on the surface.

The cylinders have recesses with identical geometric dimensions or close to those shown in Figure 3. An overview of the principle of operation of an indented cylinder separator is shown in Figure 4. While the cylinder rotates at a constant speed, the seed enters the cylinder continuously from the raised end (for example, using a vibrating feeder). The seed falls to the bottom of the cylinder, where a layer of seeds is subsequently formed. The input material consists of seeds and other large components that do not fit in cells. In this case, they are affected by friction with the surface of the cylinder between the cells. Alternatively, they can fit, but due to their longer length, the centre of gravity will not be in the cells. These two scenarios usually result in a low level of rest during rotation. Other seeds and other small fractions (dust, broken seeds) are quite small and do not fit in cells (where they will remain dormant for some time before falling out of the cells). This is especially relevant for seeds with a length equal to or less than the depth of the cell. The centre of gravity of such seeds is usually located inside the cells, which means that the seed is securely fixed in the cell during rotation.

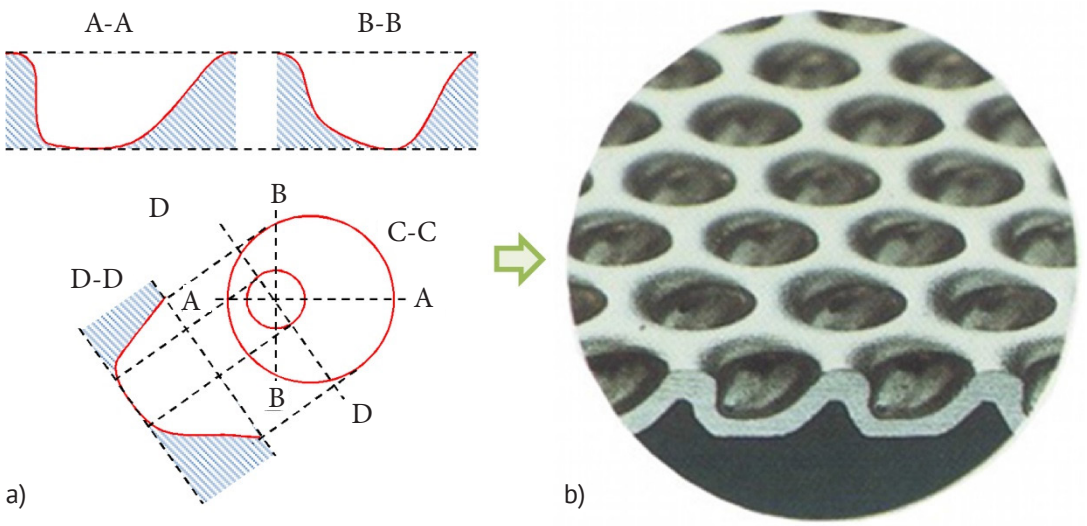

Figure 3. *Geometry and photos of stamped drop-shaped cells on the inner surface of the cylinder: a – geometry of stamped drop-shaped cells on the inner surface of the cylinder; b – photo of drop-shaped cells*

Source: *[48]*

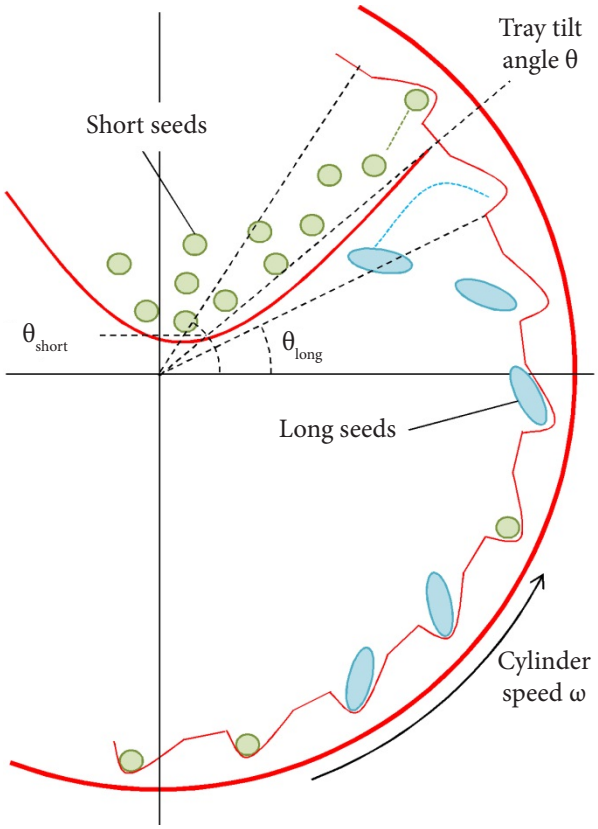

Figure 4. *Cylinder with cells, front view (the superimposed graph shows the angles of long and short seeds at which seeds fall out of the cylinder cells along a parabolic trajectory)*

Source: *[48]*

The next two fractions of material are formed during continuous rotation of the cylinder. "Unreclaimed" fraction – a fraction of a material with low support at rest in a cell during rotation. Seeds in this fraction are transferred in the direction of rotation of the cylinder and fall out of the cell at a certain angle. This part of the source data is called the unselected fraction. "Raised" fraction – a fraction of a material with high support at rest during rotation. During rotation, the seeds are in the cells up to a certain departure angle, after reaching which the seeds fall out of the cells. This fraction is called raised. Usually, due to the difference in support at rest Θ_{long} less than Θ_{short}. Hence the name "raised" and "not raised". This expected physical phenomenon is referred to as the "lifting phenomenon".

The cellular cylinder is also equipped with a

collection hopper mounted on the axial support of the cylinder. This prefab hopper is adjustable and has a horizontal working angle. Particles of the "raised" fraction from the inner surface of the cylinder fall out and enter the collection hopper, provided that its working angle has been correctly adjusted for this purpose. These trapped particles, classified as "short" seeds, are transferred and removed from the total mass. Particles of the "unoccupied" fraction do not enter the collection hopper. These particles, classified as "long" seeds, fall to the bottom of the cylinder and exit the inclined cylinder through the lower end.

An important point is the difference between partitioning and sorting processes. Separation process – separation by length performed by rotating a cell cylinder. The sorting process is the result of the collection hopper capturing the raised fraction and passing the unoccupied fraction. The inner surface of the cell cylinder is an important part of the machine, and this part is responsible for the actual separation of the "raised" and "not raised" fractions. Thus, the separation efficiency does not depend on the existing collection hopper, which acts as a form of adjustable memory of the inner surface of the cylinder. The ability to sort, on the other hand, depends on the collection hopper, because without it, the efficiency of separation quickly "disappears".

To make a conclusion about the correct separation of "long" and "short" seeds, it is necessary to know the actual data of the source material. In other words, the equipment operator needs to know what the sorting result should be. For example, if the source material consisted of a mixture of whole and broken barley grains, the operator expects the broken grain in the short fraction, and the whole grain in the long fraction. Determining the formal performance indicators of a cylindrical cellular separator is not trivial. The optimal sorting result can be one that has a minimum "overlap" of the seed distribution between the two initial subgroups in the source material. This can be considered as a form of "optimality criterion" for a cell cylinder. "Overlap" can be defined as the number of short seeds that fall into the long ones, plus the number of long seeds that fall into the short ones.

INDUSTRIAL SEED CLEANING EQUIPMENT

The cell cylinder is available in two different scales: (1) industrial scale and (2) laboratory scale. Among industrial cylinder separators, the most famous are the BTS, BTHM brands and modern separators of the Westrup A/S, TR series (Fig. 5, 6).

Figure 5. *Industrial cellular cylinder separator (Westrup A/S, TR series) with or without doors*
Source: *[48]*

Figure 6. *Laboratory cellular cylinder separator (Westrup La-T model)*

Source: *[48]*

The disadvantages of cylindrical separators are low efficiency because they require special settings for the optimal mode of its operation for cleaning seeds of various crops, the frequency of vibrations of the separator chute, and when the frequency of oscillation of the chute decreases, its transport capacity decreases or is completely suspended. Therefore, such a separator cannot be used for cleaning complex seed mixtures, which must be separated using small revolutions of the cylinder. Another disadvantage is the short service life of the drive and support rollers assembled in the form of packages of flat rubberised disks. As a result of the wear of the contact surfaces of the rollers, the smoothness of the separators is disrupted, which causes vibration and reduces the separation efficiency. Another significant disadvantage of indented cylinder separators is the high power and, as a result, high energy consumption.

To eliminate the shortcomings of indented cylinder separators, researchers from different countries conducted a large number of studies. In [49], relatively simple models of seed movement in a cell cylinder are presented. In these models, the seed is modelled as a dimensionless body. In addition, the simulation is performed only in two dimensions – provided that the movement of the seed is limited by a plane perpendicular to the axis of rotation of the cylinder. Two main options are usually used: diagrams of the forces acting on the seed between the cells and inside the cell. The active element of the cells is simplified to a small area of a more inclined surface. The event when the seed leaves the surface or cell is expressed by trivial equivalents of forces, including frictional forces and normal pressure forces (depending on the speed of rotation of the cylinder W and the acceleration of gravity g).

In [49] a more complex model is also presented for long and short seeds inside the cell. This model takes into account the fulcrum points in the cell, which would be different for each seed type. These models give definitions for Θ_{long} and Θ_{short}. Moreover, given that they depend on specific biological parameters (seed length, coefficient of friction, humidity, etc.), it is likely that the ranges θ_{long} and θ_{short} intersect, which makes it difficult to completely separate. Observation, identification of the system, and modelling of existing seed sorting devices, such as the cellular cylinder separator, using state-of-the-art technologies such as computer scanning and other computer technologies, received some attention in later years, although to a limited extent.

The basics of modern literature on the analysis of indented cylinder separators are presented in the following papers: in [50], the author contributed to an early and important analysis of perhaps the most complex and least understood parameter of a cylinder cell – the analysis of cylindrical cells (described as cells in the work). H. Fouad provided recommendations on the most optimal ranges of cell shape parameters.

In [51], the researcher continued to improve the cellular cylinder separator. A new cellular device (on a laboratory scale) equipped with perforated metal with round cells has been developed. The new model was equipped with a self-cleaning device in the form of a brush that rotated together with the cylinder and removed seeds that remained in the cells. The conclusions mention that the separation was mainly affected by the speed of rotation of the cylinder W, the tilt of the cylinder, and the working angle of the collection hopper.

In [52], the researchers made some interesting and early attempts to achieve a reproducible set of rules ("decision support system") for length separation using a cylindrical cellular separator (scalable in the laboratory). Three different rotation speeds W, three different working diameters of cells d (here called "pockets" instead of "cells"), and three different working angles of the collection hopper A (Alpha) were used. As a result, 27 experiments were conducted. Stevens' early computer analysis system was used to measure the length of pre-peeled wheat. The authors concluded that all three parameters had a significant effect on seed length separation in the raised fraction ("short" seed) and did not significantly affect seed length separation in the unoccupied ("long" seed) fraction.

In [53], a cellular cylinder separator (scaled in the laboratory) was used to find optimal working conditions for removing broken rice. 41 different rice grades, three different indentation diameters r, and three different settings for the working angle of the collection hopper A (Alpha) were used (the rotation speed W did not change). The study was summarised by providing recommendations on the working cell diameter for different rice varieties. An overview of important mechanical laws regulating the movement of long and short seeds in a cylinder with cells is presented in [54].

The study [55] is extremely relevant and contains several important conclusions. A high-speed camera was installed in front of a laboratory-scaled cylinder with cells. The use of variables from the cells themselves is applied to construct a physical model used to simulate the angle of incidence and parabolic trajectories of short seeds (impurities). A good correlation between the model and reality is shown, and this is despite simplifying assumptions in the mathematical model, such as using point masses and neglecting any seed resistance forces.

Since researchers delved upon universal cleaning machines, and the studies in the field of cleaning various varieties of seeds of small-seeded crops were not conducted, the urgent task remains to improve existing technical means for separation by creating mechatronic systems for automated control of their design and regime parameters.

To solve this problem, a design and technological scheme of the mechatronic system of an indented separator is proposed (Fig. 7), which consists of a frame (1) in which supporting rollers (2) are installed. A drum with

cells (3) is installed in the middle of the frame on rollers. On the frame (1) on the rear part, a gear motor (4) is installed, the shaft of which touches the drum with cells (3) through the drive roller (5). In the middle of the drum with cells (3), a tray (6) is installed, which is fixed to the frame (1) at a horizontal angle with the ability to rotate around its axis. The rear part of the tray (6) is attached to the shaft of the stepper motor (7), which is rigidly mounted on the frame (1). On the frame (1) on the rear part there is a hopper dispenser (8), which dispenses the seed mixture using a flap with a stepper motor (9). On the frame (1) on the front part, a larger seed intake (10) is installed under the drum with cells (3), and a smaller seed intake (11) is installed under the tray (6). A camera (12) is installed on the front of the tray (6), the lens of which is directed to the middle of the drum with cells (3). The control unit (13) is attached to the frame (1). A gear motor (4), a stepper motor (7), a damper stepper motor (9) and a camera (12) are connected to the control unit (13) by means of electrical wires (14).

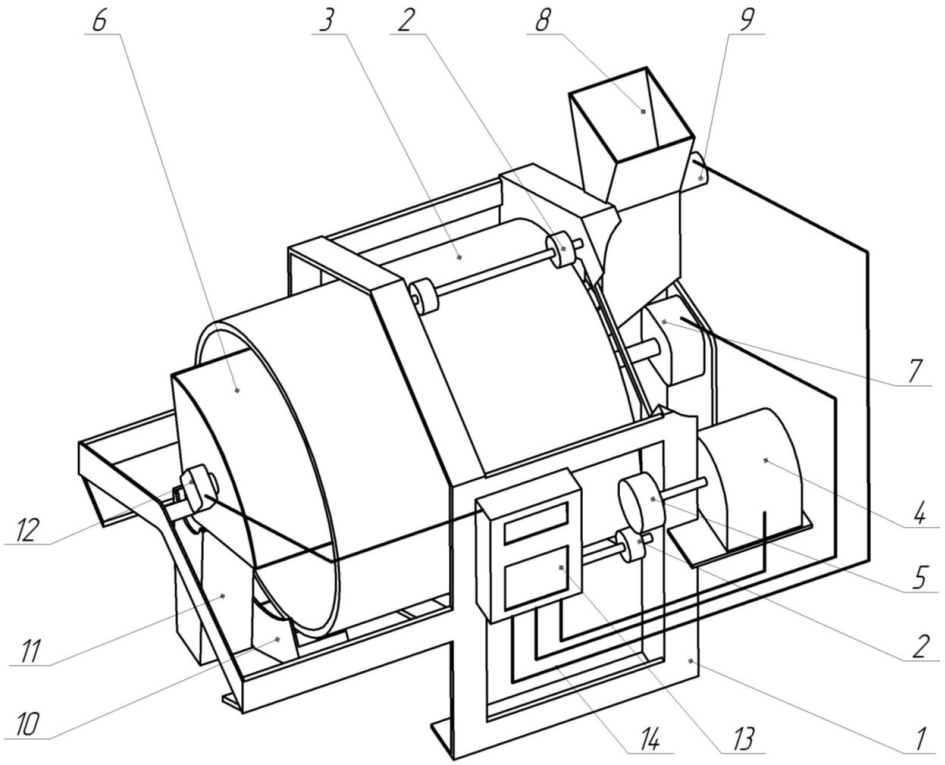

Figure 7. *Design and technological scheme of the mechatronic system of an indented cylinder separator: 1 – frame; 2 – supporting rollers; 3 – drum with cells; 4 – gear motor; 5 – drive roller; 6 – tray; 7 – stepper motor; 8 – hopper dispenser; 9 – flap with stepper motor; 10 – larger seed intake; 11 – smaller seed intake; 12 – camera; 13 – control unit; 14 – electrical wires*

Source: *[2]*

The difference between the proposed mechatronic indented separator system and the conventional one is that the camera (12) captures the trajectory of seeds (Fig. 8). This information is processed in the control unit, which in turn changes the speed of rotation of the gear motor (4) and, as a result, the drum with cells (3), the angle of inclination of the tray (6), the angle of rotation of the flap with the stepper motor (9) of the hopper dispenser (8). These manipulations with the operating parameters of an indented separator allow adjusting it to changes in the composition of the seed mixture, thereby improving the quality of separation. In addition, due to the automatic adjustment of the operating parameters of the indented separator, the participation of the operator in the separation process is practically not required, which reduces labour costs.

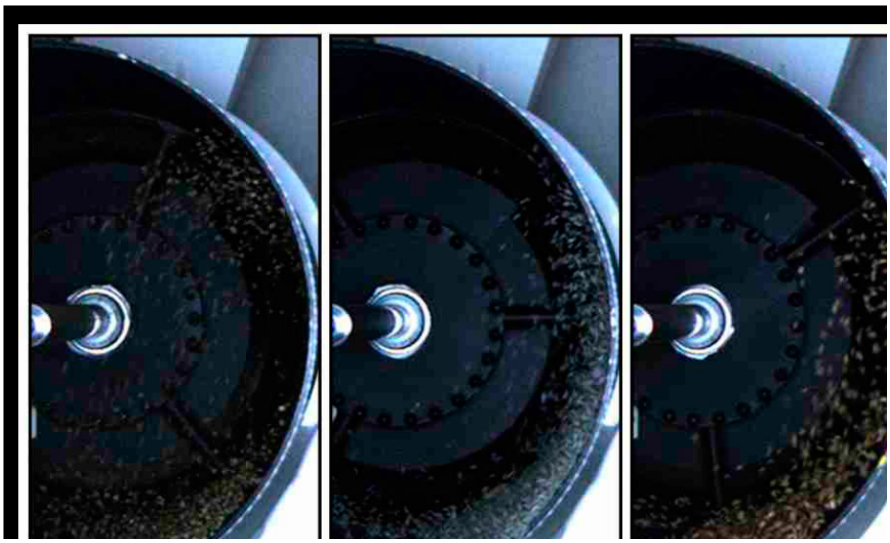

Figure 8. *Photo recording of the seed trajectory of mechatronic indented separator system*
Source: *[48]*

CONCLUSIONS

The presented analysis of the technical support of the process of separation of seed material of small-seeded crops indicates the need to improve indented separators based on automated control of its parameters using photo or video recording of the separation of seed material with subsequent processing. It has been established that the determination of formal performance indicators of an indented separator cylinder is not trivial. The optimal sorting result can be one that has a minimum "overlap" of the seed distribution between the two initial subgroups in the source material. This can be considered as a form of "optimality criterion" for a cell cylinder. "Overlap" can be defined as the number of short seeds that fall into the long cells, plus the number of long seeds that fall into the short cells.

Based on the results of the analysis, a design and technological scheme of the mechatronic system of an indented separator has been developed. The difference between the proposed system and the conventional one is that the camera captures the trajectory of seeds. This information is processed in the control unit, which in turn changes the speed of rotation of the gear motor and, as a result, the drum with cells, the angle of inclination of the tray, the angle of rotation of the flap with the stepper motor of the hopper dispenser. These manipulations with the operating parameters of an indented separator allow adjusting it to changes in the composition of the seed mixture, thereby improving the quality of separation. In addition, due to the automatic adjustment of the operating parameters of the indented separator, the participation of the operator in the separation process is practically not required, which reduces labour costs.

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Передумови створення мехатронної системи трієрних сепараторів насіннєвого матеріалу дрібнонасіннєвих культур

Ельчин Бахтияр огли Алієв[1], Кристина Олегівна Лупко[2]

[1]Інститут олійних культур Національної академії агарних наук України
69093, вул. Інститутська, 1, с. Сонячне, Запорізький р-н, Запорізька обл., Україна

[2]Дніпровський державний аграрно-економічний університет
49600, вул. Сергія Єфремова, 25, м. Дніпро, Україна

Анотація. В умовах сьогодення важливим аспектом для досягнення високого рівня виробництва насіння залишається розширення асортименту якісного насіннєвого матеріалу, завдяки чому порушується технологічний процес сепарації, зростають витрати. Метою досліджень є аналіз насіннєочисних трієрних сепараторів для очищення дрібнонасіннєвих культур і розробка відповідної мехатронної системи їх керування, завдяки застосуванню якої технологічний процес сепарації буде характеризуватися зниженими питомими експлуатаційними витратами і більш високою продуктивністю. Представлений аналіз технічного забезпечення процесу сепарації насіннєвого матеріалу дрібнонасіннєвих культур дає змогу стверджувати про необхідність удосконалення трієрних сепараторів базуючись на автоматизованому керуванні їх параметрами з використанням фото- або відеофіксації процесу сепарації насіннєвого матеріалу із подальшою обробкою. Встановлено, що визначення формальних показників продуктивності циліндричного чарункового трієра не є тривіальним. За результатами аналізу розроблено конструктивно-технологічну схему мехатронної системи трієрного сепаратора. Відмінність запропонованої системи від традиційної полягає в тому, що фотокамера фіксує траєкторію польоту насінин. Ця інформація обробляється в блоці керування, який у свою чергу змінює частоту обертання мотор-редуктора і як наслідок барабана із чарунками, кут нахилу лотка, кут повороту заслінки із кроковим двигуном бункера-дозатора. Дані маніпуляції із режимними параметрами трієрного сепаратора дозволяють підлаштовувати його до зміни складу насіннєвої суміші, тим самим підвищуючи якість і продуктивність сепарації. Окрім цього, через автоматичне підлаштування режимних параметрів трієрного сепаратора, участь оператора установки в процесі сепарації практично нівелюється, що зменшує трудові витрати

Ключові слова: насіння, трієр, керування, автоматизація, параметри, режими

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Obtaining and Use of Compost from the Organic Component of Household Waste

Zosya Masliukova[1*], Hennadiy Chetveryk[1], Anthony Neokleous[2], Finn Otto[3]

[1]Institute of Renewable Energy of the National Academy of Science of Ukraine
02094, 20a Hnat Khotkevych Str., Kyiv, Ukraine

[2]Vrije Universiteit Amsterdam
1081 HV, 1105 De Boelelaan, Amsterdam, Noord-Holland, Netherlands

[3]Case Western Reserve University
OH 44106, 10900 Euclid Ave., Cleveland, United States

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Abstract. The relevance of the study is conditioned by the need to develop and implement technological solutions for processing food and garden waste into compost. The purpose of this study is to investigate the methods of obtaining compost from the organic component of household waste and analyse composts for compliance with the requirements for their use as fertilisers. Theoretical research on the issues of the application of an organic component of a firm household waste as a raw material for compost production is carried out. According to statistical information on the accumulation of household waste in Ukraine, the amount of food and garden waste in the regions of Ukraine has been calculated. Modern methods of industrial processing of food and garden waste into compost are analysed, and the most effective technology from the standpoint of ecology and energy saving is determined. Data on the influence of composted digestate on crop yields are given. Composts were analysed for compliance with the requirements for their use as fertilisers The data show that the difference between the content of heavy metals in the composted digestate and compost from food waste is not significant and both composts meet the German quality requirements of compost. Data on the influence of composted digestate from food waste on the growth of winter grain yields are given. It has been found that the use of composts can supplement conventional mineral fertilisers in crop cultivation. The practical significance of the study is to determine the prospects of obtaining fertiliser from the organic component of solid waste and to determine its effectiveness when applied to the soil

Keywords: mineral fertilisers, composting, digestate, food and garden waste

*Corresponding author

INTRODUCTION

In Ukraine, the problem of environmental pollution by household and industrial waste has become acute. In this regard, the Cabinet of Ministers in 2017 approved the National Waste Management Strategy until 2030. The strategy is aimed at solving problems in the field of waste management [1].

Biodegradable waste is not allowed to be disposed of in landfills in accordance with the EU Waste Management directive [2] and Directive 1999/31/EC on waste disposal [3]. It can be recycled using controlled biotechnological processes that partially or completely transform substances. One way to recycle biodegradable waste is to compost it. This strategy suggests processing the organic component of household waste by composting. This applies to waste from private households. This method requires a significant size of the land plot and it is a long, time-consuming process. The strategy provides for an increase in the volume of waste sent for recycling by up to 50% and the development of an action plan to reduce the volume of disposal of biodegradable household waste. The study suggests that measures aimed at reducing the volume of disposal of biodegradable household waste and increasing the volume of waste sent for processing should include: separate collection of solid household waste (SHW); commissioning of waste sorting lines; introduction of projects for biological processing of mixed household waste.

The organic component of solid household waste is a high-energy raw material for the production of biogas. For example, the theoretical yield of biogas from a tonne of kitchen waste is 180-200 m^3. For comparison, the theoretical yield of biogas from a tonne of solid household waste is 100 m^3, from a tonne of cattle manure – from 50 to 70 m^3, from a tonne of a mixture of manure and plant biomass – up to 150 m^3 [4]. One of the methods of energy utilisation of the organic part of solid waste is the technology of solid-phase methane fermentation (SMF). SMF is the process of recycling organic waste, the humidity of which does not exceed 80% and allows obtaining biogas, liquid fertilisers, and compost.

The Department of Renewable Organic Energy Carriers of IRE NASU deals with issues related to the production of biogas from various organic substrates, including the organic component of household waste. When obtaining biogas from household waste, after press separation of the fermented mass, digestate is formed, the solid fraction of which can be composted and used as fertilisers. Admittedly, compost from the organic component of household waste can be obtained by other methods. Therefore, the task is to analyse various methods of processing the organic component of household waste into compost.

Organic fertilisers consist of components of animal and plant origin, during the decomposition of which minerals are formed. Organic fertilisers contain plant nutrition elements in the form of organic compounds. Organic fertilisers include peat, manure, bird droppings, straw, and various types of compost. One of the sources of raw materials for the production of such fertilisers can be individual organic components extracted from solid household waste (SHW) and processed into compost. These organic components include food and garden waste (leaves of trees and shrubs, mown grass). Therefore, the task is to analyse compost for compliance with the requirements for their use as fertilisers.

In recent years, many research papers have been published that reflect the issues of obtaining compost from the organic component of household waste. Successful attempts to present the problems and possibilities of this direction are presented in [5-7]. O. Sagdeeva investigated composting of a mixture of food, agricultural and garden waste in an aerobic reactor depending on microbiological additives to accelerate this process [8]. M. Tereshchuk determined the energy parameters of the bio-raw material conversion process in a drum-type reactor [9]. Y. Xu reported on the need for pretreatment of household waste before its conversion to compost [10].

The principles of operation of well-known technologies of solid-phase methane fermentation of household waste are covered in [11]. Anaerobic technology of fermentation of several types of organic waste is considered in [12]. C. Yirong investigated the effect of ammonium on the fermentation of food waste [13]. L. Wilson investigated the process of fermentation of waste, for which the dry matter in the substrate starts from 40%. The author proposed using a hydrolysis reactor and recirculation of the liquid fraction of the fermented mass to accelerate the fermentation process [14]. A. Shewani was engaged in optimising the fermentation of solid waste by recycling percolate [15]. D. Pezzolla investigated the effect of Percolate recycling frequency on biogas yield [16]. The paper [17] presents Chinese technologies for waste fermentation.

KYIV Logan provides methods for processing digestate after anaerobic digestion of household waste [18]. KYIV Reilly highlights the suitability of digestate after fermentation of food waste for application to agricultural land as an organic fertiliser [19]. In France, there is a standard for the quality of organic additives NFU 44051, which in particular regulates the indicators of compost obtained from the organic component of solid waste [20]. Study on the processing of the organic component of solid household waste into compost helps to better understand the possibilities and future prospects for obtaining and using organic fertilisers from this raw material.

The purpose of the study is to investigate methods for obtaining compost from the organic component of household waste and to analyse compost for compliance with the requirements for their use as fertilisers. For the furtherance of this goal, the following *tasks* were set: to estimate the amount of food and garden waste by regions of Ukraine; to investigate various methods of

processing the organic components of household waste into compost; to analyse composts for compliance with the requirements for their use as fertilisers.

MATERIALS AND METHODS

The research materials for this paper are fundamental and applied studies of Ukrainian and foreign authors on the problem of recycling the organic component of solid waste into compost. The solution of the tasks set in the study was carried out using well-known scientific theoretical methods: critical analysis, systematisation and generalisation of results. To search for scientific information, the method of obtaining a finished information product was applied. A detailed review of a number of research papers was carried out, from which the most informative works were selected for further use as research material. The selection criteria were the degree of study and completeness of the presentation of questions about the possibility of using the organic component of solid waste as a raw material for compost production. At the same time, research papers were considered in which:

– information on the component composition of food and garden waste is provided, and factors affecting this composition are revealed;

– studies related to the problem of obtaining organic fertilisers using various technologies for composting food and garden waste are reflected;

– technologies of industrial processing of food and garden waste into compost (composting and anaerobic fermentation in bioreactors), and the main advantages and disadvantages of these technologies are revealed;

– alternative methods of solid waste processing are given, and the basics of anaerobic decomposition of organic matter are described;

– the energy parameters of the bio raw material conversion process in a closed fermentation chamber are investigated;

– the issues of anaerobic digestion of several types of organic waste are considered and the need for pretreatment of raw materials before their conversion into compost is considered;

– study of industrial technologies of solid-phase methane generation from solid household waste, which are now the most common in the world, is reflected;

– data on the use of composted digestate from food waste as fertiliser are provided;

– composted digestate obtained from the organic component of household waste is compared with compost obtained by the conventional method from the same waste for the content of heavy metals in them;

– the indicators of composted digestates obtained by anaerobic digestion of the organic fraction of household waste according to the requirements of standards of different countries are considered.

To estimate the amount of food and garden waste in the regions of Ukraine, statistical data were used according to the official website of the State Statistics of Ukraine for various regions of Ukraine. To check the completeness of the selection of sources of scientific information and its ordering, the method of systematisation was used, and for its versatile assessment – the method of critical analysis, which analysed the scientific and practical achievements of specialists in obtaining compost from the household waste and its use to improve soils.

RESULTS AND DISCUSSION

Estimation of the amount of food and garden waste

Food waste includes food products that have completely or partially lost their consumer properties during their production, processing, use, or storage. They are formed in the residential sector and in public institutions. These also include food industry waste. In terms of the volume of food waste accumulation, then its significant share falls on households, retail chains, and the hospitality business.

The study provides brief reference material on the properties of the organic component of solid household waste. Food waste consists of food residues after cooking (the non-edible part of food products) and spoiled products. Figure 1 shows a histogram of the distribution of food waste components (a range of values is taken) [21].

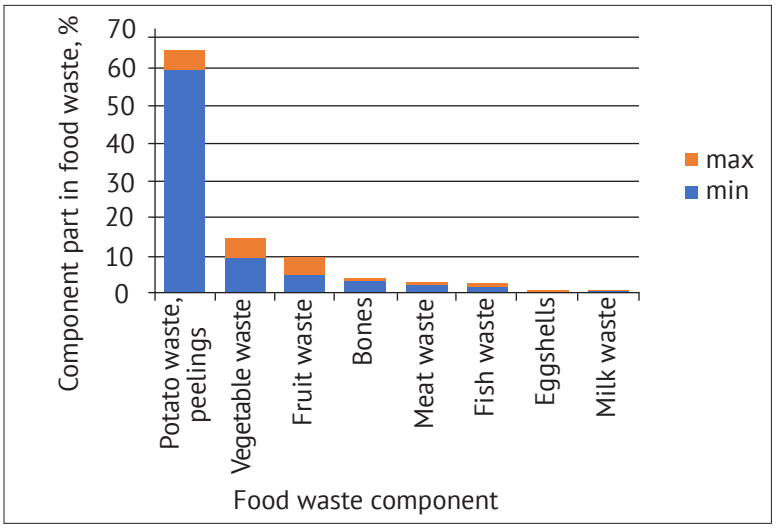

Figure 1. *Distribution of food waste components*

According to the data of [22; 23] and based on statistical information on the accumulation of household waste in Ukraine for 2019 [24], the amount of food and garden waste in the regions of Ukraine is estimated. According to the State Statistics of Ukraine, approximately 11.5-11.9 million tonnes of solid waste are generated in Ukraine annually. The total content of garden and park waste in their composition is approximately 15% [23]. As for food waste, according to the Food and Agriculture Organisation of the United Nations and the All-Ukrainian Environmental League, which conducted a joint assessment of its accumulation, the amount of this waste in Ukraine ranges from 20 to 55% of all SHW [22], or an average of 38%. Based on this, the amount of food and garden waste in the regions of Ukraine was estimated, which is shown in Table 1.

***Table 1**. Amount of food and garden waste by regions of Ukraine, thousand tonnes*

No.	Regions of Ukraine and Kyiv city	Amount of waste, thous. tons		Total, thous. tons
		Food waste	Garden and park waste	
1.	Vinnytska Oblast	99	39	138
2.	Volynska Oblast	66	26	92
3.	Dnipropetrovska Oblast	476	188	664
4.	Donetska Oblast	270	107	377
5.	Zhytomyrska Oblast	88	35	123
6.	Zakarpatska Oblast	122	48	170
7.	Zaporizka Oblast	182	72	254
8.	Ivano-Frankivska Oblast	104	41	145
9.	Kyivska Oblast	469	185	654
10.	Kropyvnytska Oblast	80	32	112
11.	Luhanska Oblast	57	23.	80
12.	Lvivska Oblast	180	71	251
13.	Mykolayivska Oblast	127	50	177
14.	Odeska Oblast	256	101	357
15.	Poltavska Oblast	128	51	179
16.	Rivnenska Oblast	80	32	112
17.	Sumska Oblast	108	43	151
18.	Ternopilska Oblast	55	22	77
19.	Kharkivska Oblast	513	202	715
20.	Khersonska Oblast	25	10	35
21.	Khmelnytska Oblast	87	35	122
22.	Cherkaska Oblast	109	43	152
23.	Chernivetska Oblast	111	44	155
24.	Chernihivska Oblast	145	57	202
25.	Kyiv city	545	215	760
Total		**997**	**394**	**1391**

***Source:** calculated by the authors based on data from the State Statistics of Ukraine on the accumulation of household waste by regions [24], and data on the percentage of food waste (38%) and garden and park waste in their composition (15%) [22; 23]*

As can be seen from the table, the largest amount of food and garden waste was generated in the Kharkivska, Dnipropetrovska, Kyivska oblasts and in Kyiv. The content of food and garden waste in solid waste tends to be unstable and is directly related to the season of the year and the geographical location of the area where this waste accumulates [25].

Based on the above reference material on the properties of the organic component of solid household waste, the amount of food and garden waste was

estimated in the regions of Ukraine, which allows determining the possibility of their use for the production of organic fertiliser and biogas both at the state and regional levels.

Analysis of methods for processing the organic component of household waste into compost

The practice of composting in agriculture goes back a long time. As early as 4,500 years ago, Mesopotamians used compost to improve soil fertility and increase crop yields, which was reflected in their first cuneiform texts. Composting was known to the Mayan civilisation, the ancient Egyptians, Romans, and Greeks. In the middle of the 20th century, mineral fertilisers took the place of compost. However, in private households, waste composting is actively used to this day. Preparations for optimising conditions and speeding up the process in compost pits became marketable. For example, the use of the EM preparation "Baikal" accelerates composting and produces high-quality compost in six weeks [6].

Composting is also widespread in urban households using microorganisms such as bokashi [7]. Not so long ago, a useful invention appeared in stores – a compost container, inside which the necessary temperature regime is maintained. With the help of this invention, residents of villages and summer residents have the opportunity to make their own compost.

Nowadays, research is underway in the field of accelerating the processes of industrial composting of household waste. Thus, in [8], information is provided that the introduction of a bacterial complex accelerates the composting process of the organic household waste by 3.3 times under thermophilic conditions and by 2.1 times under mesophilic conditions of the composting process.

In Ukraine, there are a number of companies that produce compost based on manure, bird droppings, peat, sapropel, etc. Unfortunately, the production of compost on an industrial scale based on the organic component of household waste has not become widespread. At the beginning of 2020, the first city composting station for organic waste was launched in Lviv. This station processes food and garden waste into compost. During 2020, more than 2,500 tonnes of waste were processed [26]. The produced compost can be purchased by residents for the needs of their farms and agricultural enterprises.

The use of the organic solid household waste (SHW) for compost production would help to reduce the volume of landfills, reduce greenhouse gas emissions from them, prevent the formation of smog, and, as a result, preserve public health. Methods of industrial processing of food and garden waste into compost include: composting of digestate obtained by solid-phase methane fermentation of household waste; composting of household waste by conventional methods. Next, the study considers these methods in detail.

1. *Composting of the solid fraction of digestate obtained by solid-phase methane fermentation of household waste*. SMF – the process of recycling organic waste, the humidity of which does not exceed 80% and allows obtaining biogas and digestate. Digestate, which is obtained from droppings, manure, a mixture of droppings, and a mixture of manure with plant biomass, is an organic fertiliser [19]. The solid fraction of digestate may contain heavy metals, depending on the garbage collection and sorting system. At the same time, unsorted household waste contains a sufficient amount of heavy metals [10; 12]. The solid fraction of digestate obtained from food and garden waste can be composted and used as fertilisers [18]. The centralised approach to SMF of food industry waste is currently used only in Europe and California [5], where the disposal of organic waste in landfills is prohibited at the legislative level.

Currently, 26 SMF technologies have been implemented on an industrial scale by commercial companies [27]. The most common and thoroughly studied technologies are those with a single stage of fermentation. These technologies differ in the method of mixing and the mode of fermentation of the substrate. Among the well-known single-stage SMF technologies are the following ones: "Kompogas", "Dranco", "Valorga", "Bekon".

Belgian company OWS it started building biogas plants in 1997. As of the end of 2020, 32 biogas plants were built, which are designed for processing household waste, food waste, industrial organic waste, energy crops, and garden and park waste [28]. The essence of the technology is that household waste is sorted by separating metals, glass, plastic, and the like. The prepared substrate enters a container in which it is mixed with digestate. The mixture is then heated and pumped to the top of the reactor. The mixture moves down the reactor, a vertical structure with a cone-shaped bottom, while self-mixing of waste occurs. Most of the digestate is used for mixing with a fresh portion of waste. The remaining part of the digestate, together with bio-waste, is sent for composting. According to the manufacturer of biogas plants with the "Dranco" reactor, the yield of biogas – 103-147 m^3/t of waste, the dry matter content (DM) – 20-35%, the substrate retention time in the reactor – 15-30 days [28]. The duration of composting digestate with bio-waste is 14 days. Composting of digestate occurs as follows: First, the inert component and the light fraction are separated from the digestate using the "Sordisep" process. The organic component of digestate is composted in structures with automatic control of the composting process, air circulation, oxygen content, and temperature. This method of composting was called tunnel composting. It is designed for aerobic treatment of bio-waste, mixed household waste, kitchen waste, and digestate [28].

French company Valorga International was founded in 1981 to develop solid waste treatment technologies. In the mid-80s, the anaerobic digestion process was introduced on an industrial scale at the French enterprises

La Buisse and Amies for the biological treatment of mechanically treated SHW [29].

The essence of the technology is that waste is automatically sorted, crushed, and the heavy fractions and other pollutants are removed. The sorted waste is fed to the lower part of the reactor, where the inlet is located. From the inlet, the raw material moves around the baffle to the outlet on the opposite side, creating a flow in the reactor. The reactor consists of a vertical steel cylinder with a central baffle. Part of the biogas enters the cogeneration plant, the other part is fed by a compressor to the reactor [29]. According to the manufacturer of biogas plants with the "Valorga" reactor, the yield of biogas – 80-160 m^3/t of waste, the DM content – 25-35%, the substrate retention time in the reactor – 16-35 days [11; 29]. Digestate is dehydrated using a screw press, and the solid fraction is composted. The duration of digestate composting is approximately two weeks.

"Kompogas" technology. The Swiss company Hitachi Zosen Inova started building biogas plants in 1992. By end of 2020, 100 biogas stations were built using SMF "Kompogas" technology, which is designed for processing the organic fraction of urban solid waste, garden and park waste of biological origin (grass, leaves, branches) [30]. The essence of the technology is that the waste enters the shredder, where it is pre-treated to a particle size of less than 10 mm, after which it is mixed in a container with a liquid fraction of the fermented mass and diluted with water to a DM content of 23-28% in the substrate. The prepared mixture is fed to a horizontal reactor with internal slow-rotation rotors. With the help of axial rotors, the substrate is homogenised and moved from the inlet to the outlet. Plug flow reactor with continuous loading of raw materials. Dry heavy components of the substrate are held in a suspended state. The fermented mass is divided into two fractions using a press separator: solid and liquid. Part of the liquid fraction is used for mixing with a new portion of the substrate, the other part is stored in the lagoon and, if necessary, used as liquid fertilisers. The dry part of the fermented mass is composted in a composter [30]. According to the manufacturer of biogas plants with the "Kompogas" reactor, the yield of biogas – 110-130 m^3/t of waste, the DM content – 23-28%, the substrate retention time in the reactor – 15-30 days [30]. The compost yield is 500 kg per tonne of waste [31]. The duration of digestate composting is approximately two weeks. The result is high-quality, nutrient-rich compost.

Notably, recently two stages of fermentation have been used for household waste. For this purpose, studies of the fermentation process are conducted. L. Wilson suggested using a hydrolysis reactor and recirculating filtrate. It was proposed to use filtrate in the hydrolysis reactor to start the fermentation process, the proportion of which is 10% of the initial substrate for dry matter [14]. D. Pezolla showed that the maximum yield of biogas from food waste occurred when percolate was fed four times a day [16]. A. Shevani investigated the optimisation of solid waste fermentation with the addition of straw and cow manure by recycling percolate [15]. It should also be noted that K. Jurong indicated that high concentrations of ammonium lead to inhibition of the fermentation process and instability of the biogas yield. The author established limit concentrations of ammonium, which should not exceed 5 g/dm^3 [13].

In [17], the Chinese technologies "VPD" and "TPAD" are presented, which use two stages of fermentation. They have better indicators of organic matter decomposition compared to single-stage SMF technologies.

2. *Composting in closed reactors*. If land resources are limited, raw materials are composted in closed reactors. Reactors are containers, such as pallets with three walls, or fully enclosed rotating drums. The main condition for composting is mixing and aeration of raw materials [32]. Currently, the most common type of closed reactors are drum-type reactors. Such reactors are capable of processing a large amount of waste in a relatively short period of time (up to 2-3 weeks) [9]. The essence of composting in closed reactors is that raw materials are loaded into the reactor gradually. Inside the reactor, raw materials are mixed and oxygen is constantly supplied. Aeration is carried out by supplying hot air, while controlling the level of humidity and oxygen [9].

3. *Row composting*. The essence of row composting is that compost is formed in long, narrow piles. The equipment for turning and aeration of collars affects the width and height of the composting piles. The size of land plots affects the length of piles. Turning is usually carried out by a bucket loader or tractor. Over time, the piles settle. Row composting can be applied throughout the year. To retain moisture and heat in the piles and to protect them from animals, coverings are used [32]. Field composting requires large areas, and there is a need for environmental protection measures.

4. *Composting in static aerated piles*. The essence of this type of composting is that a perforated pipe is laid in static aerated piles. Aeration of the piles is provided by mechanical fans that supply air through holes in the pipes. The pipe itself is covered with a layer of porous material, on which raw materials are laid, pre-thoroughly mixed. To retain heat and moisture, the pile is usually covered with geotextile material or ready-made compost [32].

Next, the study compares the above methods for obtaining compost from household waste. Consequently, field composting requires large areas, and there is a need for environmental protection measures. Composting in closed reactors is used in conditions of limited land resources. Composting in closed reactors allows controlling and regulating the oxygen content and temperature in the reactors, but at the same time requires large capital and operating costs. Composting of the solid fraction of digestate is usually carried out in automated closed

reactors. This method of composting involves the production of biogas.

Thus, compost from the organic component of household waste can be obtained using such industrial technologies as composting household waste and the solid fraction of digestate obtained by solid-phase methane fermentation of household waste. After analysing the above methods of processing the organic component of solid waste into compost, it can be concluded that taking into account energy saving and environmental protection, compost from the solid fraction of digestate obtained by solid-phase methane fermentation of household waste has significant advantages over the other methods, since, as a result of waste processing, the biogas and compost are obtained, and the emission of greenhouse gases into the atmosphere is zero. The process is carried out in bioreactors that are completely isolated from the environment, and there are no greenhouse gas emissions into the atmosphere. Confirmation of this is found in [33].

Analysis of compost for compliance with the requirements for its use as fertilisers

Compost is a source of organic matter and minerals of natural origin, which are vital for soils. In the process of composting in the organic mass, there is an increase in the content of nutrients available to plants. Thanks to its nutrients, compost increases the level of humus, restores soil fertility, improves the structure and increases the moisture capacity of the soil. Improving the condition of the soil would help to increase the yield of agricultural crops. Such types of organic fertilisers as compost and digestate require testing of their agronomic efficiency and environmental safety in vegetation and field studies. It is necessary to check the environmental safety of organic fertilisers with previously established agronomic efficiency.

A number of EU-27 member states have developed standards and specifications for compost and digestate. In Germany, there is a quality assurance system for digestate, which is controlled by the "Bundesgütegemeinschaft Kompost (BGK)" (Federal Compost Quality Association) and "Güte Gemeinschaft Gärprodukt (GGG)" (Digestate Quality Association). The quality criteria for digestate and instructions for its use in this country are called RAL-GZ 245. Belgium has a voluntary quality assurance system for digestate. In the UK, the quality standards for digestate are called BSI PAS (publicly available certificate of the British Standards Institute 110:2010). The Swedish Quality Guarantee is called SPCR 120. In Switzerland, there are quality guidelines for the solid and liquid fractions of digestate.

In France, compost entering the market must meet the French standard for the quality of organic additives NFU 44051. According to this standard, the indicators of compost with the organic component of solid waste should be within the following limits: dry matter content – more than 30%; organic matter content – 15-25%; phosphorus – not less than 1%; nitrogen – not less than 1%; potassium – at least 1%; C/N ratio – more than 8. The concentration of heavy metals in compost should not exceed the following values, mg/kg DM: zinc – 600; nickel – 60; mercury – 2; lead – 180; copper – 300; chromium – 120; cadmium – 3; arsenic – 18 [20]. Composted digestate obtained at the plant in Burk en Bres meets the French standards NFU 44051 according to the technology of SMF "Dranco", in particular in terms of heavy metals concentration, mg/kg DM: zinc – 402; nickel – 57; mercury – 0.2; lead – 66; copper – 126; chromium – 67; cadmium – 0.8; arsenic – 2.4 [20].

In Ukraine, there is no state standard regulating the quality requirements of composted digestate and the norms for its introduction into agricultural land. This is conditioned by the fact that composted digestate obtained as a result of methane fermentation of food waste is not used in Ukraine, although the practice of producing and using composted digestate based on other types of raw materials is used. Therefore, when determining the suitability of composted digestate as a fertiliser, it is advisable to use standards for fertilisers, for example, the standard of housing and communal services of Ukraine "Household waste. Technology of processing organic matter that is part of the household waste of SOU ZhKH 03.09-014:2010" [34]. The standard sets out the procedure for composting the organic fraction that is part of household waste and its anaerobic processing, and also provides recommendations for the use of compost. According to this standard, the agrochemical and physicochemical parameters of compost with an organic component of solid waste for use as fertiliser in agriculture should be within the following limits: the mass fraction of organic matter should not be less than 40% per dry product; the mass fraction of total nitrogen, phosphorus, and potassium per dry product should be more than 1.8; 2.0, and 0.1%, respectively. The content of fractions with a size higher than 50 mm should not exceed 2%; the wet content should be from 20 to 80%; the pH value should be 6.5-8 [34].

The concentration of heavy metals in compost should not exceed the following values, mg/kg DM: zinc – 2500; nickel – 200; Mercury – 15; lead – 750; copper – 1500; chromium – 750; cadmium – 30 [34]. Thus, regarding the content of heavy metals in compost, the established standards according to the French standard for the quality of organic additives NFU 44051 are more stringent in comparison with the Ukrainian standard of housing and communal services of Ukraine "Household waste. Technology of processing organic matter that is part of household waste SOU ZhKH 03.09-014:2010". In ripe compost, the matter should be homogeneous and loose, the components of raw materials that make up its composition should not differ. Plant seeds should lose their ability to germinate in compost. In accordance with the SOU ZhKH 03.09-014:2010, the presence of pathogenic microflora and viable helminth eggs in compost

is not allowed. It must have no smell, or the smell must have an "earthy" character. Compost should contain humic acids. The colour of the compost should range from dark brown to black.

Composted digestate obtained by anaerobic digestion of the organic fraction of household waste is an important source of humus, rich in nutrients such as nitrogen, phosphorus and potassium, which help to improve the properties of the soil. The introduction of digestate into the soil helps to preserve and improve soil fertility, its structure, the activity of soil microorganisms, retain moisture in the soil, and protect the soil from erosion.

The use of composted digestate from food waste as fertiliser gives an effect even higher than that of more conventional analogues. For example, in England, composted digestate from food waste provided a 10% increase in winter grain yields over an average of 3 years, while compost from green mass – 7%; mixed compost (from green mass and food waste) – by 8%; slurry – by 9%; manure with straw – by 10%. Consequently, the effect of using composted digestate from food waste is not inferior to manure with straw. Therefore, it can be used as a fertiliser to increase soil fertility [35].

G. Riedel compared compost obtained by various methods for the content of heavy metals in them. The author considered composted digestate from food waste and compost from the same food waste. G. Riedel found that the content of heavy metals in composted digestate has the following values, mg/kg DM: zinc – 197; nickel – 11.5; mercury – 0.097; lead – 26.8; copper – 71.5; chromium – 23; cadmium – 0.366. For comparison, the content of heavy metals in compost from food waste has the following values, mg/kg DM: zinc – 191; nickel – 14.4; mercury – 0.126; lead – 37.4; copper – 59.9; chromium – 22.1; cadmium – 0.455. The content of heavy metals in compost from garden and park waste has the following values, mg/kg DM: zinc – 147; nickel – 12; mercury – 0.096; lead – 27; copper – 38.9; chromium – 20; cadmium – 0.383 [36]. Thus, in all indicators, the difference between the content of heavy metals in composted digestate and compost from food waste is insignificant and both composts meet the German quality requirements of compost [36].

Therefore, the study analysed composted digestates for compliance with the requirements for their use as fertilisers. Data suggest that composted digestate obtained at the plant in Burk en Bres meets the French standards NFU 44051 and the Ukrainian standard of housing and communal services of Ukraine "Household waste. Technology of processing organic matter that is part of household waste SOU ZhKH 03.09-014:2010". There are also data showing that the difference between the heavy metal content of composted digestate and food waste compost is insignificant and both composts meet the German compost quality requirements. The use of composted digestate from food waste provided an increase in the yield of winter cereals by 10%. The use of compost allows supplementing conventional mineral fertilisers in the cultivation of agricultural crops.

CONCLUSIONS

Based on the results of the conducted research on the production and use of compost from the organic component of household waste, it was established:

1. The organic component of household waste (food and garden waste) is a promising raw material for compost production. The study estimated the amount of food and garden waste in the regions of Ukraine, which allows determining the possibility of their use for the production of organic fertiliser and biogas both at the state and regional levels.

2. Industrial technologies for obtaining compost from organic household waste are presented and analysed. It is shown that the use of organic household waste for compost production will help reduce the volume of solid waste in landfills, reduce greenhouse gas emissions from them, and prevent the generation of smog. It is revealed that compost from the solid fraction of digestate obtained by solid-phase methane fermentation of household waste has significant advantages over conventional composting, provided that energy-saving and environmental protection are taken into account.

3. Compost can be used as fertiliser in agriculture for landscaping urban and adjacent areas, roads, forest plantations, etc. Composted digestate obtained at the plant in Burk en Bres meets the French standards NFU 44051 and the Ukrainian standard of Housing and communal services of Ukraine "Household waste. Technology of recycled organic matter that is part of household waste SOU ZhKH 03.09-014:2010". A comparative analysis of the content of heavy metals in composted digestate and compost from food waste is carried out. Both of these composts have been shown to meet German quality requirements. The use of compost allows supplementing conventional mineral fertilisers in the cultivation of agricultural crops.

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Отримання і використання компосту із органічної складової побутових відходів

Зося Вікторівна Маслюкова[1], Геннадій Олександрович Четверик[1], Ентоні Неоклеус[2], Фін Отто[3]

[1]Інститут відновлюваної енергетики НАН України
02094, вул. Гната Хоткевича, 20-а, м. Київ, Україна

[2]Вільний Університет Амстердаму
1081 HV, вул. Булелан, 1105, м. Амстердам, Північна Голландія, Нідерланди

[3]Університет Кейс Вестерн Резерв
OH 44106, просп. Евклід, 10900, м. Клівленд, Сполучені Штати Америки

Анотація. Актуальність дослідження обумовлена необхідністю розробки та впровадження технологічних рішень щодо переробки харчових і садово-паркових відходів у компост. Мета даної роботи – аналіз методів отримання компосту з органічної складової побутових відходів і аналіз компостів на відповідність до вимог для їхнього використання як добрив. Проведено теоретичні дослідження питань, пов'язаних із застосуванням органічної складової твердих побутових відходів в якості сировини для отримання компосту. За даними статистичної інформації щодо накопичення побутових відходів в Україні розраховано кількість харчових і садово-паркових відходів. Проаналізовано сучасні методи промислової переробки харчових і садово-паркових відходів у компост. Встановлено, що отримання компостованого дигестату з використанням твердофазної метанової ферментації з урахуванням екології та енергозбереження має суттєві переваги перед іншими методами отримання компосту. Виконано аналіз компостів на відповідність до вимог для їхнього використання в якості добрив. Наведено дані, які показують, що різниця між вмістом важких металів у компостованому дигестаті та компості з харчових відходів незначна і обидва компости відповідають вимогам якості компосту. Наведено дані щодо впливу компостованого дигестату з харчових відходів на зростання врожайності озимих зернових культур. З'ясовано, що використання компостів дає змогу доповнити традиційні мінеральні добрива при вирощуванні сільськогосподарських культур. Практична цінність роботи полягає у визначенні перспективи отримання добрива з органічної складової твердих побутових відходів та у визначенні його ефективності при внесенні в ґрунт

Ключові слова: мінеральні добрива, компостування, дигестат, побутові відходи, харчові та садово-паркові відходи

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Тел. (0412) 22-04-17
E-mail: info@sciencehorizon.com.ua
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