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Justification of the design parameters of improved equipment for tomato processing

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Abstract. The implementation of a full-cycle tomato processing operation is a complex technological task that requires precise control of various parameters to ensure the high quality of the final product. The main stages of the process include raw material preparation, mechanical crushing of tomatoes, separation of juice from pulp and skin, as well as additional treatment to enhance the organoleptic and nutritional properties of the juice. The objective of this study was to investigate the relationship between processing performance and the optimal parameters of improved tomato processing equipment, specifically: the clearance between beaters and sieve, the rotational speed of the perforated drum, and the feed rate of the crushed mass. The article presented an improved structural solution for tomato processing equipment, characterised by the integration of crushing and pulping operations, which reduces both the metal intensity of the design and the energy consumption of the process. The study involved determining the percentage content of components in the crushed tomato mass by weighing each fraction. Based on the collected data, an a priori ranking of influencing factors was performed using expert evaluation. The most significant factors affecting the technological process were identified. Through mathematical modelling and experimental studies, the optimal operating modes of the equipment were established to achieve maximum juice yield with minimal energy consumption. Special attention was given to the consideration of design and operational parameters such as angular drum speed, productivity, and equipment power. The analysis of constructive and technological factors influencing the process showed that the optimal configuration includes a beater-sieve clearance of 2 mm, a pulp feed rate of up to 80%, and a drum rotational speed of up to 25 m/s, which ensures a pulping efficiency of approximately 90%. The obtained results can be used for upgrading existing tomato processing lines and developing new production facilities in accordance with current market demands

Keywords: tomato crusher; raw material pulping; pulp; agro-industrial sector; mechanical processing

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INTRODUCTION

To develop and improve tomato processing equipment, several key factors need to be considered: the type of product to be processed, technological requirements, productivity and economic aspects. Tomato sorting and washing lines must ensure that tomatoes are thoroughly cleaned and sorted by quality and size. Capacity depends on the needs of the enterprise and can vary from several hundred kilograms to several tonnes of tomatoes per hour. The technological processes of processing companies require high accuracy of technological operations, but the design of food production lines faces the problem of excessive energy and metal consumption and the need to adapt equipment to the mechanical and technological properties of a particular product. A classic variant of the tomato processing scheme is to perform the crushing and mashing stages separately. Insufficient attention is paid to the study of the design and technological parameters of tomato processing equipment that affect the productivity of the production line. Therefore, determining the optimal parameters of the equipment for wiping tomato pulp is a key issue in the implementation of the technological process of tomato juice production. Improvement of tomato processing equipment should be aimed at increasing efficiency, quality of the final product and reducing operating costs.

According to K. Mukhopadhyay *et al.* (2021), it is important to consider materials, performance, automation, and environmental aspects when designing, which will allow creating equipment that meets the modern requirements of the food industry and meets the needs of both small and large businesses. To justify the design parameters of advanced tomato processing equipment, several key aspects should be taken into account: production requirements, raw material properties, technological processes, and final product quality requirements. In the study by V. Shebanin *et al.* (2019) noted that production requirements are determined by the required volume of tomato processing per unit of time. It depends on the scale of production and the planned volume of output. Tomatoes contain a large amount of water, which must be taken into account when choosing methods of processing them. The design parameters of cutting and chopping machines should ensure product homogeneity and minimal loss of raw materials.

The analysis of tomato processing machines focuses on machines for wiping and crushing raw materials. These include: crushers with toothed rollers, disc grinders equipped with a centrifuge for grinding and further separation, and wiping machines for separating juice from pulp. In the work of Z. Kaliniewicz *et al.* (2021) noted that the size of the crushed particles and the ratio of the average size before and after deformation is key to the process. However, despite the variety of crusher designs, it should be noted that the main design requirement is the easy replacement of working bodies and parts. Researchers B. Kotov *et al.* (2019) noted that the crushed product requires pieces of the same size in each fraction. When designing a structure, it is also important to take into account the lowest permissible metal consumption of the structure and the presence of elements that prevent clogging of the working bodies, which can lead to an accident. Shredding machines can be divided into impact, crushing, splitting, and abrasion based on the nature of the applied force. In the context of practical use of machines, it is advisable to combine different types of deformation. The choice of deformation type directly depends on the type and characteristics of the material to be processed (DSTU 8439:2015, 2015; DSTU 7160:2020, 2020).

Z. Despotovic *et al.* (2019) argued that determining the amount of work to break the mutual adhesion of particles is one of the key aspects in the theory of grinding. G. Kaletnik *et al.* (2020) noted that volumetric deformation and heat generation are the main components of the deformation work of grinding machines. Researchers E. Eslami *et al.* (2025) studied the effect of tomato packaging on different types of processed tomato products in terms of the requirements for sustainable production of different categories of processed tomatoes. C. Sena *et al.* (2025) presented algorithms for efficient sowing of tomatoes for industrial processing in arid regions. E. Eslami *et al.* (2024) identified resource conservation strategies in tomato processing that led to significant savings in water (23.4%), electricity (14.7%) and methane (28.7%) and, as a result, to 16 and 19% reduction in global warming potential in peeled tomato and tomato puree production lines, respectively.

Research in the field of tomato processing has presented such key aspects of the issue as the study of the mechanical and technological properties of raw materials, production requirements for tomato processing, and general requirements for the technological process. However, the analysis of scientific sources did not reveal numerous studies on the improvement of tomato processing equipment, so the justification of the design parameters of improved tomato processing equipment is an important subject of research. The aim of the study was to substantiate the methodology for determining the angular velocity, determining the productivity and determining the power consumption of the proposed design solution for tomato processing, to determine the optimal parameters, and to study their impact on the technological process performance.

MATERIALS AND METHODS

Studies involving experimental work with plants, including the collection of plant material, were carried out in accordance with the established norms and requirements of the institutional, national or international level. The authors followed the standards of the Convention on Biological Diversity (1992). The mass obtained after grinding, consisting of juice, pulp and crushed peel, was of the greatest interest for the study. Therefore, in the course of laboratory research, two types of objects were investigated: the mass after the grinding device and the tomato fruit. The study was conducted at a temperature of 20-22 °C and relative humidity of 60-70%. For weighing the samples, we used laboratory scales with an accuracy of 0.01 g Ohaus Pioneer PX 3202 (Minebea Intec, Germany), measuring cylinders SBP-1, a set of sieves LS-20 with holes of different diameters. The methodology is based on well-known recommendations (Bortz & Schuster, 2010), as well as the specific conditions of experiments with the development and manufacture (Bezusov & Totsenko, 2017). The average value of the set of obtained values X_a was determined by the formula for the statistical mean:

$$X_a = \sum_{k=1}^{N} X_{av \cdot k} \cdot P_k, \tag{1}$$

where P_k is relative frequency or weight of the k-th group/variant in the total amount of data; $X_{av \cdot k}$ – is the average value for the k-th group.

The formula for the mean square of the deviation S was used to estimate the divergence of the values of the random variable X around the average value X_a:

$$S = \sum_{k=1}^{N} (X_{av \cdot k} - X_a)^2 \cdot P_k. \tag{2}$$

The standard deviation σ demonstrates a comparison of the spread of values near the centre of the distribution and a random variable:

$$\sigma = \sqrt{S}, \tag{3}$$

where S is the variance.

The coefficient of variation was also found v:

$$v = \left(\frac{\sigma}{X_{av}}\right) \cdot 100\%. \tag{4}$$

The error rate (error) of the experiment p, should not exceed 4.0%:

$$p = \pm \frac{\sigma}{X_a \cdot \sqrt{n}} \cdot 100\%, \tag{5}$$

where n is the number of experiments.

Determination of the percentage of components of the crushed mass of fruit C_{ps} was carried out by weighing each fraction according to the formula:

$$C_{ps} = \left(\frac{m_i}{\sum_{Ci=1}^{n} m_i}\right) \cdot 100\%, \tag{6}$$

where $Ci\, m_i$ is percentage of both the mass and the i-th fraction.

The relationship for determining the ratio between the components is as follows:

$$C_{ps} = \left(\frac{m_j}{\sum_{Cj=1}^{n} m_i}\right) \cdot 100\%, \tag{7}$$

where $Cj\, m_j$ is respectively, the percentage ratio of both the mass and the i-th component.

Determine the dynamic and kinematic parameters, it is necessary to investigate the dependence of fetal deformation on the applied static and dynamic load. For this purpose, the least squares method was used, followed by an adequacy test using Fisher's criterion. The determination of the functional dependence $y = f(x)$ of the trait under study was carried out at j fixed argument values, with $j \geqslant 4$. The repetition of the experiment at each point of the fixed argument value was $n = 5$. Also, to check the uniformity of the results obtained, the average value of the function at each point was calculated, i.e:

$$Y_j = \frac{1}{n} \cdot \sum_{s=1}^{n} Y_{ij}, \tag{8}$$

where Y_{ij} is the average value of the function at the j-th point.

It was also assumed that the obtained dependence could be described by a 1st degree function:

$$Y = ax + b, \tag{9}$$

where x is influence factor; a is an indicator that indicates the change in Y when X changes; b is a free term or the ordinate of the origin.

After that, the adequacy was checked by Fisher's criterion F_k. If the condition $F_{table} \geq F_k$ is met, with a given number of degrees of freedom, the hypothesis is confirmed. To characterise the general population by discrete variational features, sample statistical observation is used. The extreme values are denoted as X_{min} and X_{max}. The total number of samples n for each of the attributes was taken to be at least 50. At the same time:

$$n = \sum_{i=1}^{n} l(i), \tag{10}$$

where l is a number of elements in the i-subgroup.

The statistical series of the feature X was divided into a number of classes N_k. $N_k = 10$ with $n \geqslant 50$. The class step t is determined from the expression:

$$t = \frac{X_{max} - X_{min}}{N_k}, \quad (11)$$

where X_{max}, X_{min} – maximum and minimum sample values.

The bounds for any k-th class were defined as: lower bound:

$$X_{k-1} = X_{min}, \quad (12)$$

upper bound:

$$X_k = X_{k-1} + t. \quad (13)$$

Relative frequency of observations for any k-th class:

$$P_k = \frac{n_k}{n}, \quad (14)$$

where n_k is the number of variants falling into the k-th class; n is the total number of observations. Check formula for verifying the calculations performed:

$$\sum_{k=1}^{N} P_k = 1. \quad (15)$$

Arithmetic mean value of the trait by classes:

$$N_{k.cp} = \frac{(X_{k-1} + X_k)}{2}. \quad (16)$$

The adequacy of the description of the dependence is accepted with a significance level of 0.95, which is recommended for research in agriculture. If $F_k > F_{table}$ the hypothesis about the linear nature of the dependence under study was rejected and the description of the dependence by the expression:

$$Y = a \cdot X^2 + b \cdot X + C; \; Y = a \cdot X^3 + b \cdot X^2 + c \cdot X + d. \quad (17)$$

With repeated checking of the adequacy. The percentage of each component of the crushed mass was determined by the formula:

$$C_{pj} = \left(\frac{m_{pj}}{m}\right) \cdot 100\%; \; C_{ps} = \left(\frac{m_{ps}}{m}\right) \cdot 100\%;$$

$$C_p = 100\% - (C_{pj} + C_{ps}), \quad (18)$$

where C_{pj}, C_{ps}, C_p is the percentage of pure juice, peel with seeds and pulp in the crushed mass; m_{pj}, m_{ps} is the mass of pure juice, peel with seeds in the crushed mass; m is the total mass of crushed tomatoes.

The percentage of peel with seeds in each group was determined by the following relationship:

$$C_1 = \left(\frac{m_1}{m_k}\right) \cdot 100\%; \quad (19)$$

$$C_5 = \left(\frac{m_5}{m_k}\right) \cdot 100\%; \quad (20)$$

$$C_7 = \left(\frac{m_7}{m_k}\right) \cdot 100\%, \quad (21)$$

where m_1, m_5, m_7 – is the weight of the peel with seeds of each size group contained in the pulp; m_k is the total weight of the crushed peel with seeds.

The principle of operation of the advanced tomato processing equipment is that by placing wiping beats in the inner perforated drum, the tomato pulp is separated, and its final wiping and separation into fractions is carried out in the gap between the inner and additional perforated drum (Fig. 1). The fraction of peel and pulp that has not been crushed is discharged by screw turns.

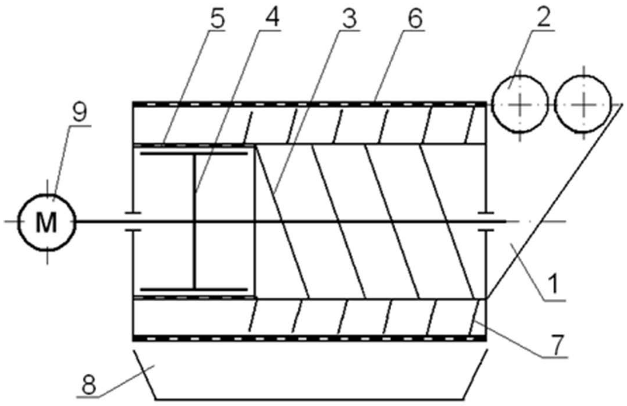

Figure 1. *Diagram of the laboratory installation of the improved design solution*

Note: *1 – intake neck; 2 – rollers; 3 – coils for moving raw materials; 4 – wiping beats; 5 – internal perforated drum; 6 – additional perforated drum; 7 – auger; 8 – juice collection tray; 9 – drive*

Source: *developed by the authors*

As criteria for optimising the technological process of tomato processing, the juice yield Q (%) spent on the technological process was chosen. The factors influencing the course of the technological process included the rotor rotation speed V (m/min); the gap of the scourge-sieve l (mm) and the level of supply of the crushed mass for wiping M (%). The study of the design (gap between the scourge and sieve) and technological (rotation speed of the perforated drum, level of inflow of the crushed mass) factors of the improved tomato processing equipment was carried out. In order to avoid overloading the equipment for wiping tomatoes and to avoid clogging of the sieve, an acceptable level of inflow of the crushed mass for wiping was selected.

RESULTS AND DISCUSSION

Taking into account the analysis of design solutions for tomato processing machines, the improved design meets the following parameters: increased juice yield, increased productivity, preservation of the physical and chemical properties of the crushed material, reduced energy consumption and increased productivity, increased reliability by preventing screw clogging. The assembly drawing of the improved design is shown in Figure 2.

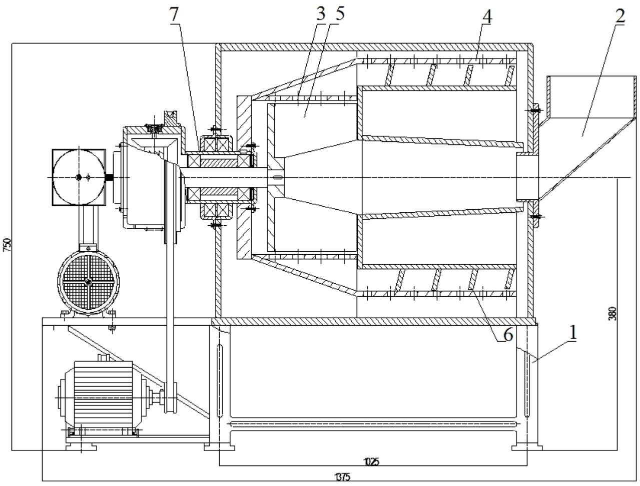

Figure 2. *Improved design solution*

Note: *1 – frame; 2 – receiving chamber; 3 – perforated drum; 4 – outer drum; 5 – grinding device; 6 – auger; 7 – shaft*

Source: *developed by the author on the basis of Patent No. 154661 (2023)*

The proposed design solution allows to significantly reduce the stages of the technological process of tomato processing by combining the processes of grinding and rubbing (Fig. 3). To determine the design parameters of the proposed solution, we determined the angular velocity of movement of raw materials, determined the productivity and power.

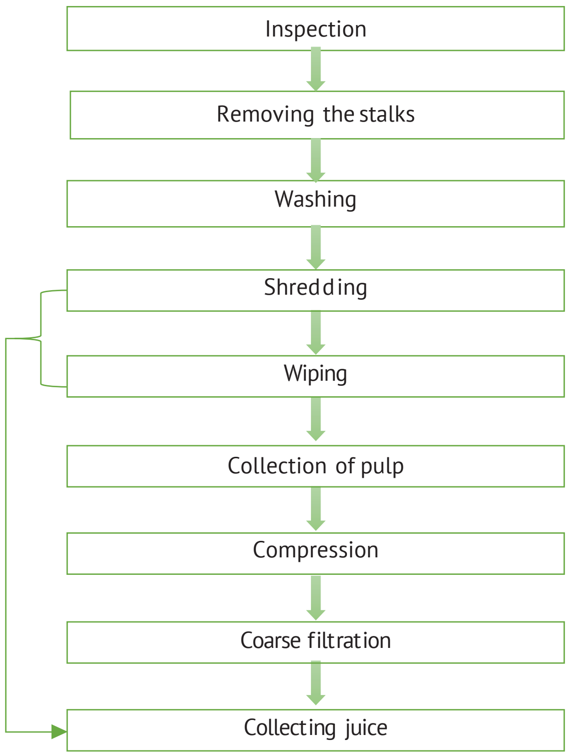

Figure 3. *Stages of the technological process of tomato processing with the participation of an improved design solution*

Source: *developed on the basis of Patent No. 58968 (2011)*

Determining angular velocity

The essence of the process of separating juice from pulp using advanced tomato processing equipment is the passage of the crushed mass along a rotating inner surface. This surface can be either an angled cylinder or a conical surface with a horizontal axis. Separation processes on these two surfaces do not differ from each other, since the angle of inclination of a conical surface in practice does not exceed 5-6°. Thus, the theoretical basis for separating material from a cylindrical, inclined surface is fully applicable to a conical surface. When a conical surface is used, a correction factor is introduced to account for the reduction in area compared to an inclined cylinder. In the case of a machine with a horizontal cylindrical drum, if the cylindrical rotor is stationary, the material is retained on its inner surface no higher than point *A* (Fig. 4a), for which the angle *AOD* with the vertical is equal (Lerner & Trigg, 1991):

$$\alpha = \varphi, \tag{22}$$

where φ is friction angle of the crushed mass.

Then the friction coefficient can be expressed as:

$$f = tan\varphi. \tag{23}$$

This is based on the equilibrium condition of a body of mass G on an inclined plane with an angle of inclination α (Fig. 4b):

$$G \cdot \sin\alpha - F = 0, \tag{24}$$

where the friction force:

$$F = f \cdot G \cdot \cos\alpha, \tag{25}$$

when the drum is rotating at a circular speed:

$$V = \frac{2 \cdot \pi \cdot R \cdot n}{60} = \frac{\pi \cdot R \cdot n}{30}, \tag{26}$$

where n – is the number of its revolutions per minute.

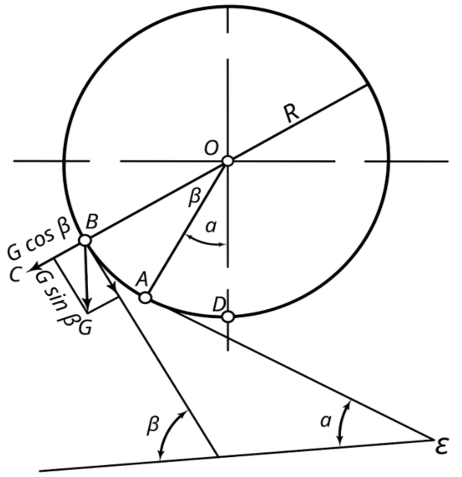

Figure 4a. *Condition of equilibrium and movement of raw materials before determining angular velocity*
Source: *compiled by the author on the basis of A. Maas (2017)*

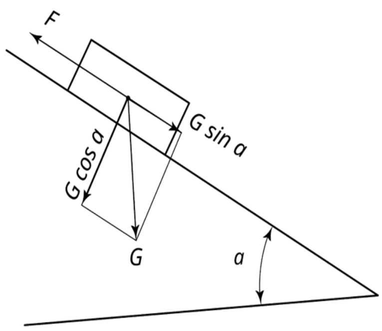

Figure 4b. *Equilibrium condition for raw materials on an inclined plane*
Source: *compiled by the author on the basis of A. Maas (2017)*

A centrifugal force of inertia occurs:

$$C = m \cdot j = \frac{G}{g} \cdot \frac{v^2}{R}, \tag{27}$$

pressing the material of mass G against the inner surface of the rotor and causing an additional friction force equal to:

$$f \cdot c = f \frac{G}{g} \cdot \frac{v^2}{R}. \tag{28}$$

Therefore, when a cylindrical drum rotates, the material can rise above point A, for example to point B, for which the angle of rise $BOD = \beta > \alpha$. The lifting angle increases as the angular speed of rotation n increases. You need to derive the relationship between the angle of elevation β and the angular velocity of rotation of the cylinder n. The equilibrium of the material at the desired point B is possible only if the following conditions are met:

$$G \cdot \sin\beta - f(c + \cos\beta) = 0, \tag{29}$$

or:

$$\sin\beta = f\left(\frac{v^2}{g \cdot R} + \cos\beta\right), \tag{30}$$

therefore:

$$\frac{\sin(\beta - \varphi)}{\cos\varphi} = \frac{\sin\varphi \cdot v^2}{g \cdot R \cdot \cos\varphi}, \tag{31}$$

and finally:

$$\sin(\beta - \varphi) = \frac{\sin\varphi \cdot v^2}{g \cdot R}. \tag{32}$$

The angle $AOB = \alpha - \varphi$ at any circumferential velocity v can be determined when the material friction angle φ and the drum radius R are known. The lifting angle β increases with the increase in the circumferential speed v. The higher the material rises above point A, the greater the angle $\beta - \alpha$, the faster the material will move down, the less efficient the wiping of the raw material will be, which is generally possible only up to the relative material speed mm/min, which is determined by the formula:

$$v = 73.5\sqrt{d}, \tag{33}$$

where d is diameter of holes; sieves, mm.

At a sufficiently high-speed v, the centrifugal force C keeps the material pressed against the inner surface of the cylinder at all times; in this case, in the absence of relative movement of the material along the sieve, any possibility of grinding and passage of raw materials can be excluded. Optimal operating conditions of a rotary shredder can be achieved at a rotational speed sufficient to lift the material to some point B, which is higher than point A, so the angle of lift should be slightly greater than the angle $\alpha - \varphi$. Based on the data from the practice of using rotary shredders, the lifting angle β is equal to:

$$\beta = \alpha + (5° - 10°) = \varphi + (5° - 10°), \tag{34}$$

therefore:

$$\beta - \varphi = 5° - 10°. \tag{35}$$

Solving the equation with respect to v, the expression is transformed as follows:

$$v = \sqrt{\frac{g \cdot R \cdot \sin(\beta - \varphi)}{\sin\varphi}}, \tag{36}$$

then the number of rotation n:

$$n = \frac{30 \cdot v}{n \cdot R} = \frac{30}{n \cdot R}\sqrt{\frac{q \cdot R \cdot sin(\beta - \varphi)}{sin\,\varphi}} = 30\sqrt{\frac{sin(\beta - \varphi)}{R \cdot sin\,\varphi}}, \tag{37}$$

where R measured in meters, and the acceleration of gravity $q = 9.81$ measured in m/min^2.

Since the material has to start moving not only on the shredder's screen surface, the upper pieces of material can slide on the layers of material below, the angle of friction of material on material at rest can be assumed to be on average: $\varphi = 35°$, this gives for the lifting angle $\beta = 40° - 45°$.

Now it is obtained under $\beta - \varphi = 5°$.

$$n = 30\sqrt{\frac{\sin(\beta-\varphi)}{R\cdot\sin\varphi}} = 30\sqrt{\frac{\sin 45°}{R\cdot\sin 35°}} \cong \frac{12}{\sqrt{R}}, \quad (38)$$

where R measured in meter.

The angular velocity of the rotary shredder ranges from:

$$n = \frac{8}{\sqrt{R}} \div \frac{14}{\sqrt{R}}. \quad (39)$$

The angular velocity of a rotary shredder is inversely proportional to the square root of its diameter, which is fully confirmed by the practice of their operation. In general, the linear (circumferential) speed v of a rotary shredder is in the range of:

$$v = 0.6 - 1.25\left(\frac{m}{min}\right). \quad (40)$$

At the lower limit of the circumferential velocity, the material layer on the sieve increases and the efficiency of the grinding passage deteriorates; at speeds above the upper limit, the drum sieve openings stick under the centrifugal force and the passage also deteriorates.

Defining productivity

The shape of the individual pieces of material, the value of the friction coefficient and the rotational speed have a direct impact on the angle of rise. That is, the material can either actually rise with the points on the inner surface of the rotor and then slide rapidly down the line of greatest slope. The projection of the average material velocity onto the slow, continuous sliding of the material downwards and out of the plane of rotation itself must be equal to the circumferential velocity v of the rotor and correspond to the continuity and uniformity of the process. In the case where the movement of the material up and down occurs with pauses, as evidenced by how much material rises up in a unit of time, the same amount must fall down in the same time, since the material cannot leave the constant zone at a constant rotational speed. This pattern of material movement is only valid for machines with conical or cylindrical perforated surfaces that have a low angular speed. Consequently, the material moves internally in a regular helical line with a lifting angle $W = 2\alpha$.

Thus, the relative trajectory of the material on the cylindrical surface of the rotor deployed in the plane will be depicted as a straight-line *AF* (Fig. 5), going at an angle, and to the deployed circle by the formula:

$$AB = 2k\cdot\pi\cdot R, \quad (41)$$

where k is the number of revolutions that a rotor with a diameter of $2R$ must make so that a particle of material, moving along the line AF, passes the entire length L; M is the direction of material supply.

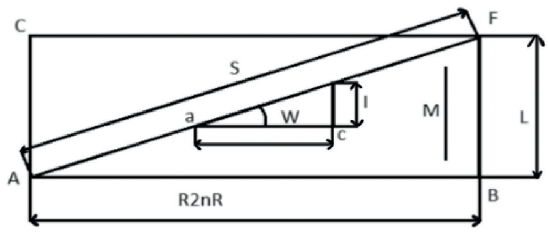

Figure 5. *Relative trajectory of material movement on a surface deployed in a plane*
Source: *developed by the authors on the basis of A. Maas (2017)*

Based on the above, it can be noted that the material moves along the helical spiral, represented in the unfolded form by the line AF, with such an average speed that its projection onto the plane of rotation is equal to the v-circular speed of the latter. It follows that the length of the path V metres per second along the circumference of the rotor corresponds to the path L along the rotor axis, equal to:

$$L = v\cdot \mathrm{tg}\omega = v\cdot \mathrm{tg}2\alpha, \quad (42)$$

but since this path is travelled by the material in one second, as is the path v, L and is the average feed rate along the axis:

$$v_0 = L = v\cdot \mathrm{tg}2\alpha, \quad (43)$$

hence the feed rate is equal:

$$v_0 = v\cdot \mathrm{tg}2\alpha = \mathrm{tg}2\alpha = 0.105R\cdot n\cdot \mathrm{tg}2\alpha. \quad (44)$$

The feed rate is therefore directly proportional to the rotor diameter, its angular velocity and the tangent of the double angle of inclination; this shows that the feed rate increases very rapidly with increasing rotor angle. The feed rate at a steady state is completely independent of its length. The performance is expressed by the formula:

$$Q = \psi\cdot y\cdot v0\cdot F, \quad (45)$$

where ψ is the loosening coefficient of the moving material; y is the specific gravity, kg/m^3; v_0 is the average feed speed, m/s; F is the cross-sectional area of the moving material layer, m^2.

The productivity is equal to:

$$\mathrm{Q}i = \mathrm{Q}\frac{60\cdot 60}{1{,}000} = 3.6\cdot\psi\cdot y\cdot v0\cdot F\,(\mathrm{m/h}). \quad (46)$$

It is necessary to express the cross-sectional area *F* of the moving layer of material depending on the rotor radius *R* and the layer thickness *h*:

$$\frac{d}{2}\sqrt{R^2-(R-h)^2}=\sqrt{2R}\cdot h-h^2. \quad (47)$$

Since the height of the material layer must be negligible for successful juice separation, its value h^2 can be neglected in practice compared to the value $2R \cdot h$. Then, for the chordal value $AB=d$:

$$d=2\sqrt{R}\cdot h=2.83\sqrt{2R}\cdot h. \quad (48)$$

Taking the formula for the area of a small segment F as the area of a parabolic segment, the expression is:

$$F=\frac{2}{3}d\cdot h=\frac{2}{3}h\cdot 2.83\sqrt{2R}\cdot h\cong 1.9\sqrt{R\cdot h^3}. \quad (49)$$

Now the performance can be expressed as follows:

$$Q_t=3.6\psi\cdot y\cdot 0.105R\cdot n\cdot\tan 2\alpha\cdot 1.9\sqrt{R\cdot h^3}, \quad (50)$$

or after simplification:

$$Q_t=0.72\psi\cdot y\cdot n\cdot\tan 2\alpha\sqrt{R^3\cdot h^3}. \quad (51)$$

If we assume that the coefficient of loosening of a material moving in a quiet thin layer is equal to:

$$\psi\cong 0.8, \quad (51)$$

then the sedimentary expression for performance:

$$Q_t=0.6\cdot y\cdot n\cdot\tan 2\alpha\sqrt{R^3\cdot h^3}, \quad (52)$$

where linear dimensions R and h are measured in meters.

The productivity is directly proportional to the rotational speed, the tangent of the double angle of inclination, the drum radius and the material layer thickness – both of which are in the power of 3/2, so it increases dynamically with increasing angle of inclination, drum radius and material layer thickness; changes in the rotor speed have a smaller effect on the machine's productivity. The thickness of the material layer h to some extent depends on the rotor radius R. The larger R, the smaller h for the same amount of material entering the rotor at the same time. Typically, the thickness of the material layer is in the range of $1.5\div 5$ cm. That is, h cannot be less than the transverse pieces entering the separation. The length of the path S of the material passing through the sieve, represented by the line AF, is equal to:

$$S=\frac{L}{\sin W}=\frac{L}{\sin 2\alpha}. \quad (53)$$

The value of S characterises the degree of separation perfection: the higher the S, the more efficient the separation. Therefore, it is better at small angles α; however, at small angles of inclination α, the performance drops rapidly. If α is changed from 2° to 14°, the path length will be determined by

$$S=\frac{L}{\sin 4°}-\frac{L}{\sin 28°}=14.3L-2.13L. \quad (54)$$

Therefore, it is necessary to determine how many revolutions the rotor must make so that the material has time to pass the entire length of its L:

$$L=k\cdot 2\pi\cdot R\cdot\tan W, \quad (55)$$

from where the desired number of rotor turnovers is determined as:

$$k=\frac{L}{2\pi\cdot R\cdot\tan 2\alpha}, \quad (56)$$

so, the longer the rotor, the more is k.

Determining power consumption

According to practical observations, the most appropriate design is the one with a central drive shaft, as opposed to the option with support rollers. This is due to the fact that the total length does not exceed 3,500 mm. The design with a central drive shaft is much less bulky and more compact than the one with support rollers (Lee *et al.*, 2010).

In this case, the following static moments around the shaft are applied during operation:

1) Torque from the friction of the shaft trunnions in the bearings:

$$M_1=f_1\cdot r(G+G_0), \quad (57)$$

where f_1 is a rolling friction coefficient, f=0.03; r is shaft journal radius, *m*.

2) Friction torque of the crushed mass on the inner surface of the rotor sieve:

$$M_2=f_2\cdot G_0\cdot R, \quad (58)$$

where f_2 is mass a friction coefficient on the perforated surface, naturally f_2 = 0.15-0.25; G_0 is a weight of the material in the rotor, kg; R is rotor radius, m. When calculating a conical machine, the largest cone radius is used.

3) The moment from lifting the material to a certain height *H*, determined by the angle of lifting β = 45° φ is 35°, (Fig. 6). The height of the material is determined by the segment *bb'*, where *b* is the centre of gravity of the material layer *ABC* in the lowest position. The distance *x* of the centre of gravity *b* in segments *ABC* from the centre of the circle *O* is determined by the formula

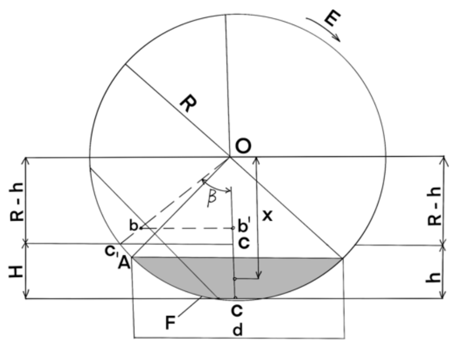

Figure 6. *Location of the material on the inner sieving surface*
Source: *compiled by the authors on the basis of L.N. Hand & J.D. Finch (2008)*

$$x = \frac{d^3}{12F}. \qquad (59)$$

For the chord *b*, we have: $d = 2.83\sqrt{R \cdot h}$, and for the square *F* segment: $F = 1.9\sqrt{R \cdot h^3}$. Hence, it is used for small *h*:

$$x = \frac{d^3}{12F} = \frac{(2.83\sqrt{R \cdot h})^3}{12 \cdot 19\sqrt{R \cdot h^3}}. \qquad (60)$$

Therefore, instead of the exact value of *bb*, the following interval is taken as the magnitude of the rise *cc* = *H* (Fig. 6).

$$R - H = R \cdot \cos 45°, \qquad (61)$$

hence:

$$\mathrm{H} \cong 0.3\mathrm{R}. \qquad (62)$$

Thus, the material in the rotor with mass G_0 rises to a height *H* during the time the rotor rotates by an angle $\beta = 45°$, i.e. 1/8 of a complete revolution. If we denote the time of one complete revolution of the rotor by *T* (in seconds), then at n revolutions per minute, it is obvious:

$$T = \frac{60}{n}, \qquad (63)$$

then the rotor turnover time per angle , the material is lifted to a height of *H*, is equal to:

$$t = \frac{45°}{360} T = \frac{1}{8} T = \frac{1}{8}\frac{60}{n} = \frac{7.5}{n}, \qquad (64)$$

hence the power consumed to lift the material to a height *H* is equal to:

$$W = \frac{G_0 \cdot H}{T} = \frac{0.3R \cdot n \cdot G_0}{7.5} = \frac{R \cdot n \cdot G_0}{25} \left(\frac{kgm}{m}\right). \qquad (65)$$

Power consumption for lifting the material is equal to:

$$N_3 = \frac{W}{102} = \frac{R \cdot n \cdot G_0}{102 \cdot 25} = \frac{R \cdot n \cdot G_0}{2.550} (kWh). \qquad (66)$$

As for the power consumption in the first two stages, it can be determined, knowing the static moments, by the formula:

$$M = 716.2 \frac{N}{n}, \qquad (67)$$

whence:

$$N = \frac{M \cdot n}{716.2} = \frac{f \cdot r(G + G_0) \cdot n}{716.2}. \qquad (68)$$

Then the expression takes the form:

$$N_1 = \frac{M_1 \cdot n}{716.2} = \frac{f \cdot r(G + G_0) \cdot n}{716.2}, \qquad (69)$$

where *r* is radius of the shaft journal, *m*.

$$N_2 = \frac{M_2 \cdot n}{716.2} = \frac{R \cdot n \cdot G_0 \cdot f}{716.2} (kWh). \qquad (70)$$

Thus, the total static moment is equal:

$$M = M_1 + M_2 + M_3 = 2f \cdot G_0 \cdot R + f_1 \cdot r(G + G_0). \qquad (71)$$

The friction coefficient of the crushed mass on the wet sieve should be assumed to be *f* = 0.25, and the rolling friction coefficient of the rotor shaft bearing supports (*f* = 0.03). The ratio of the rotor radius *R* to the shaft radius varies within the limits:

$$\frac{R}{r} = 12 - 17. \qquad (72)$$

This ratio decreases as the rotor diameter decreases. Assume an average of *R/r* = 15 and, increasing the total torque by 10% due to the centrifugal force of the material, the expression will be:

$$M = 1.1[2 \cdot 0.25G_0 \cdot 15r + 0.03r(G + G_0)] = \frac{r(G + 25lG_0)}{30}, \qquad (73)$$

and for greater clarity and practicality, the expression will look like:

$$R = 15r,$$

then the total static moment:

$$M = \frac{R(G + 251G_0)}{450}. \qquad (74)$$

The power required for the drive will be:

$$N = \frac{M \cdot n}{716.2 \cdot 1.36} = \frac{R \cdot n(G + 251G_0)}{716.2 \cdot 1.36 \cdot 450} = \frac{R \cdot n(G + 251G_0)}{44 \cdot 10^4}. \qquad (75)$$

Determination of optimal design and technological factors of advanced tomato processing equipment
Rotary juicer machines are manufactured with a diameter of 700 to 1,300 mm, with a length of up to 4,000 mm. As a rule, the central shaft is tubular, 75 mm in diameter, with additional stiffeners. Only stamped sieves made of

galvanised steel sheet with a thickness of 1 mm are used. When installing stamped sieves, the most serious attention must be paid to the correct location of the punch holes on the drum surface. The rough side of the sheet (from the side of the stamp exit) should be a non-working surface. The working side is smooth. The correct installation of the sieves ensures that the material slides easily on the inner working surface – 0.540 and 0.438, and on the steel surface – 0.532, 0.428 and 0.495. The laboratory setup had the following main parameters: the length of the wiping drum was 650 mm, 4 wiping beats and the diameter of the drum holes was 5 mm (Dotsenko, 2019).

During the selection of the optimal technological parameters of the tomato processing equipment, the drum rotation speed varied from 5 to 30 m/s. When analysing the results of the laboratory study, it can be concluded that the maximum juice passage through the holes of the grinding drum occurs at a rotor speed of 20 m/min. This is due to the fact that at the lower value of the rotor rotation speed, the value of centrifugal force is insufficient, and, consequently, the juice yield does not meet the technological requirements, and in the case of the maximum value of the drum rotation speed, the drum holes stick and the juice yield decreases. The level of supply of shredded mass to the wiping, which varied from 65 to 85%. The research determined that in order to achieve a juice yield of 90-95%, the level of supply to the grinding mass should be in the range of 75-80%. Also, during the research, the gap between the scourge and the sieve was adjusted within the range of 1 to 3 mm. When the gap was set at 3 mm, the juice yield was minimal, while when the gap was set at 1 mm, the peel and seeds were damaged, which partially fell into the juice fraction instead of the waste fraction. Therefore, the optimal gap for the scourge sieve was 2 mm. Analysing the data in Table 1, it can be concluded that the optimal design and technological parameters of tomato processing equipment are a drum rotation speed of 25 m/min, a level of supply of crushed mass for wiping up to 80% and a sieve gap of 2 mm. These parameters will help to avoid overloading the equipment, clogging the sieves and maximise the juice yield at 90-95%.

Table 1. *Study of design and technological factors of improved equipment for tomato processing*

Q, %	*V*, m/min	*M* , %	*l* (mm)
75	5	65	3
80	10	75	3
85	15	75	3
90	20	75	2
95	25	80	2
100	30	85	1

Note*: Q – juice output, V – drum rotation speed, M – level of chopped mass entering the wiping, l – gap of the scourge-sieve*
Source: *developed by the authors*

While theoretical models can provide a general understanding of the process, experimental studies are needed to fine-tune equipment and parameters. These studies will help to determine the optimal conditions for different tomato varieties and types of equipment, as well as identify possible problems and solutions. The technological process of tomato processing includes preparatory stages: inspection, sorting, washing and stem removal, and the actual processing stages: chopping, wiping, juicing and filtration. Tomatoes have high demands on the market as they are used for everyday food needs and the colour of a tomato determines its level of maturity. Using computer analysis, it is possible to sort tomatoes by colour. For the study by S. Widiyanto *et al.* (2021), a computer was trained using Faster R-CNN models to recognise the maturity of tomatoes, as Faster R-CNN supports image classification and object detection. Technologies based on automated machine learning are becoming increasingly important in agriculture and the food industry. J.R. Pangilinan *et al.* (2022) evaluated the performance of neural network algorithms in terms of the accuracy of tomato ripeness determination. C.N. Vanitha *et al.* (2023) noted that the ripeness of tomatoes is one of the main conditions for high-quality processing, so automated colour identification facilitates the processes of sorting and preparing for processing tomatoes in the context of agricultural production. Using the proposed design solution, the tomato processing equipment is integrated into modern processing lines of processing enterprises, which include not only equipment for mechanical processing of raw materials, but also electronic machines for sorting.

O. Vitriak *et al.* (2025) noted that the processing of tomato products and the introduction of canned food production technologies based on the use of fruit and vegetable raw materials in small farms contribute to the development of processing enterprises and strengthening of the Ukrainian canned fruit and vegetable market. The researcher M.A. Cherier (2020) assessed the efficiency of the operation of equipment for processing tomato raw materials and concluded that it is necessary to develop technologies and improve the equipment of processing enterprises based on the assessment and selection of the best enterprises for the supply of raw materials. The developed methodology is used to rank alternatives in order to select the best tomato farms. The use of the constructive solution proposed by the authors will provide both additional processing of tomato raw materials in private farms growing tomatoes and for improving the production lines of canneries. J.T. Teleken *et al*. (2022) noted that theoretical research on the processes of processing enterprises is an important condition for the design and modernisation of equipment. H. Ghaffari *et al*. (2024) investigated the degree of crushing of tomato fruits after single and multiple dynamic loads and their ability to withstand successive impacts, which play a crucial role in the processing process, which is an important aspect in the development of food processing equipment. This correlates with the authors' study that when designing tomato processing equipment, it is important to take into account the conditions of balance and movement of raw materials, the relative trajectory of the material on the surface that is deployed in a plane and the location of the material on the internal screening surface.

S. Haniva & S.F.A. Iskandarini (2023) outlined alternative strategies for increasing the income of tomato farmers, namely optimising existing potential by increasing equipment productivity and reducing production costs. D. Mengistu & T. Sharew (2024) analysed the level of product losses that occur during harvesting, packaging, transport, storage, and processing. The reasons for these losses include outdated processing equipment and lack of technological advances in production processes. Solving these problems is important for increasing the efficiency and sustainability of tomato production and minimising production losses. The use of the proposed constructive solution contributes to solving these problems, namely, it will reduce energy consumption for the production of tomato products by combining the technological processes of crushing and rubbing and increase the productivity of tomato processing lines. Despite the potential, the tomato processing industry faces challenges such as inadequate processing capacity. M. Kaundal *et al*. (2024) noted that the demand for tomato processing products has been growing in recent years, with an increasing range of products being offered. The introduction of advanced processing methods can reduce losses and increase product value. M. Dalvi-Isfahan & M. Mahmoodi-Eshkaftaki (2024) emphasised the need to optimise tomato processing methods, thereby improving the quality of canned tomato products and saving resources for canneries. A team of authors (Kedir *et al.*, 2025) carried out a comparative study of the physicochemical properties of the product obtained using different types of tomato crushers. The study correlates with the authors' point of view that the choice of the optimal design solution for processing tomato raw materials contributes to increasing the productivity of equipment and the overall efficiency of processing enterprises.

S.G. Ye & A.K.H. Lingani (2022) outline the practical aspects of the use and maintenance of technological equipment at a tomato puree processing enterprise. The authors outline the technical and operational characteristics of the equipment of a tomato processing plant, the processed products and the design and kinematic parameters of the equipment, as well as the methods of care or maintenance of the equipment before and after use. The authors noted that the process of crushing and mashing tomatoes to produce juice is a complex and multi-stage technological process that requires careful analysis and optimisation of various parameters. At the grinding stage, it is necessary to take into account the size of the particles obtained as a result of grinding, the uniformity of grinding and minimisation of juice losses. The main parameters for mashing tomatoes after crushing to separate the juice from the skin, seeds and other particles include the size of the mesh, the mashing speed and the pressure applied to the tomato mass. Optimising these parameters maximises juice yield and quality while minimising solids content. The authors confirm the thesis stated in the paper that the main technological parameters affecting the process of crushing and mashing tomatoes are: the speed of rotation of the chopper blades: high speed produces smaller particles, but can lead to overheating and oxidation of the juice; the size of the sieve opening: smaller openings provide cleaner juice, but can reduce productivity and straining pressure: high pressure can increase juice yield, but requires more powerful equipment. Therefore, the use of the proposed design solution and compliance with the design and technological parameters outlined in this paper will allow obtaining optimal process parameters, reducing energy consumption and increasing productivity.

CONCLUSION

Tomato processing is a complex and multi-stage process that requires careful optimisation at each stage. Based on the analysis of the known designs of tomato processing lines, the article selects the complete equipment for the technological line for tomato processing, which is proposed for implementation in production conditions. The stages of the technological process of tomato processing with the participation of an improved design solution are considered. A constructive solution for tomato processing equipment that combines two technological operations – grinding and rubbing – is presented, as well as a laboratory setup. The design of the equipment for processing tomato raw materials was based on the study of the conditions of equilibrium and movement of raw materials, the relative trajectory of the material on the surface deployed in a plane and the location of the material on the internal sieving surface. The design parameters of the improved equipment for tomato processing, namely, performance indicators, power, and determination of the angular speed of rotation of the drum, were calculated. The technical characteristics of the proposed design solution are presented.

A study of the process of pulp grinding and wiping has been carried out, which shows that the gap between the beaters and the sieve of the wiping drum should be 2 mm, the drum rotation speed should be 25 m/s, the level of supply of crushed mass for wiping should be up to 80%, which ensures pulp wiping at the level of 90%. The selection of optimal design and technological parameters of tomato processing equipment will increase the overall productivity and have a positive impact on the technological process. The use of the proposed constructive solution of equipment for wiping tomatoes is promising in the conditions of farms of various forms of ownership and canning shops. Prospects for further research are the calculation of the energy intensity of the process and ways to optimise it to reduce costs and increase efficiency. Further research and innovation in this area can significantly improve product quality, reduce costs, and increase production sustainability.

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Обґрунтування конструктивних параметрів вдосконаленого обладнання для переробки томатів

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Анотація. Здійснення повного циклу переробки томатів це складне технологічне завдання, що вимагає ретельного контролю різноманітних параметрів для забезпечення високої якості кінцевого продукту. Основними стадіями процесу є підготовка сировини, механічне подрібнення томатів, відділення соку від м'якоті і шкірки, а також додаткова обробка для поліпшення органолептичних і поживних показників соку. Робота ставила на меті дослідження залежності продуктивності від оптимальних параметрів вдосконаленого обладнання для переробки томатів, а саме: зазор бич-решето, швидкість обертання перфорованого барабану та рівень надходження подрібненої маси. В статті представлене вдосконалене конструктивне рішення обладнання для переробки томатів, особливістю якого є поєднання технологічних операцій подрібнення і протирання, за рахунок чого знижується металоємність конструкції та енергоємність процесу. В дослідженні здійснювалося визначення процентного вмісту компонентів подрібненої маси плодів шляхом важення кожної фракції. На основі отриманих даних проведене апріорне ранжування чинників, яке виконується методом експертної оцінки. Визначені чинники, які найбільше впливають на технологічний процес. За допомогою методу математичного моделювання та експериментальних досліджень визначено оптимальні режими роботи обладнання, що забезпечують максимальний вихід томатного соку при мінімальних енергетичних витратах. Основна увага приділялась врахуванню конструктивних і експлуатаційних параметрів, таких як визначення кутової швидкості обертання барабана, продуктивності та потужності обладнання. На основі аналізу конструктивних та технологічних чинників, які впливають на технологічний процес визначено, що зазор бич-решето повинен бути 2 мм, рівень надходження на протирання подрібненої маси до 80 %, швидкість обертання барабану до 25 м/с, що забезпечить протирання пульпи на рівні 90 %. Отримані результати можна використати для модернізації існуючих ліній переробки томатів і створення нових виробничих потужностей з урахуванням сучасних вимог ринку

Ключові слова: подрібнювач томатів; протирання сировини; пульпа; агропромисловість; механічна обробка

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Experimental research on rice seeds based on high-voltage electric field treatment

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Abstract. Mechanical forces can induce internal microcracks and latent damage, significantly compromising grain quality during rice seeds harvest, and conventional mechanical sorting fail to detect such defects. As a dielectric material, seeds exhibit polarisation under non-uniform electric fields, and closely correlated to their dielectric properties. The purpose of this study was to investigate the effects of high-voltage electric field treatment on the germination potential and seedling growth of rice seeds, and to clarify the underlying dielectric mechanisms. A simplified seed model and equivalent circuit were developed. By analysing the dielectric polarisation process and calculating the field strength inside and outside the seeds, the macroscopic electromagnetic motion laws of the dielectric in seeds were determined. Orthogonal experiments on electric field seed treatment were conducted. Range analysis identified the primary and secondary factors affecting germination potential and average seed height, while variance analysis determined the optimal treatment combination and tested the model's significance. Results indicated that the complex impedance of the seed equivalent circuit depends on the circular frequency (ω) of the applied electric field, the film capacitance (C) and film resistance (R) of the seed. The relative dielectric constant ε and the macroscopic polarisation rate χ are equivalent in describing the dielectric constant of seeds. The external electric field has a more significant effect on seeds with higher vitality. The optimal parameters for higher germination potential and average seed height are an alternating current electric field with an intensity of 520 kV·m-1 for 150 seconds under experiments. Stronger field strength and longer treatment time result in higher average seed height, benefiting long-term seed vitality. This is because a lower dielectric constant in seeds is advantageous. Therefore, seeds treated by high-voltage electric fields can significantly enhance seed vitality and increase yield, promoting the development of efficient, precise, non-destructive, and automated selection and grading technologies

Keywords: electrostimulation; vigour enhancement; germination potential; average plant height; dielectric constant; orthogonal optimisation

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INTRODUCTION

Seed vigour is a key indicator of seed quality. High-vigour seeds demonstrate greater resilience against adverse environmental conditions, enabling uniform emergence of early, healthy seedlings with optimal stand establishment. This not only reduces sowing and cultivation costs but also establishes a solid foundation for high crop productivity. Therefore, enhancing seed vigour is critical for improving both yield and seed quality.

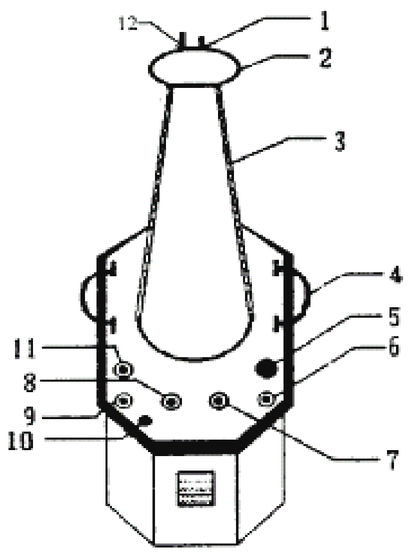
Prior to sowing, viable crop seeds are typically in a dormant state. Artificial electric field treatment of these dormant seeds can significantly improve various vigour-related indicators. Studies conducted across the globe have demonstrated that electric field treatment effectively enhances germination capacity, breaks seed dormancy, and repairs damaged tissues, while also promoting root development and improving resistance to drought, disease, and lodging. M. Chenah *et al.* (2024) investigated the effects of ultrasound and pulsed electric field treatments on the germination of two durum wheat varieties. The results showed that ultrasound treatment significantly improved early germination rate and speed, while pulsed electric field primarily enhanced radicle elongation. These findings provide new insights into physical pre-treatment technologies for improving wheat germination efficiency, but the study did not compare the long-term growth effects (e.g., biomass or yield) of the two methods, suggesting a need for further parameter optimisation. Similarly, L.M. Ferroni *et al.* (2023) found that electrostatic fields significantly enhanced seed germination potential, though the effect varied depending on plant species, treatment duration, and germination temperature. This indicates that the applicability of electric field treatments requires optimisation based on specific crops and environmental conditions. While the study offered valuable guidance for practical applications of electric field technology, it did not explore the physiological mechanisms behind species-specific responses, which could be addressed through omics analyses in future research. At a mechanistic level, X. Wu *et al.* (2024) revealed the intrinsic regulatory mechanisms of high-voltage electrostatic fields on cotton seedling growth, confirming their feasibility and effectiveness. By employing multi-omics approaches, the experiments provided molecular-level evidence, strengthening the reliability of electric field applications in agriculture. However, since cotton is an economic crop, further validation is needed to determine whether these conclusions apply to staple crops like rice or wheat.

L. Lin *et al.* (2025) investigated the impact of different discharge powers in low-temperature plasma (LTP) treatment on soybean seed vigour, concluding that moderate LTP exposure enhances seed vigour and seedling growth, while excessive treatment exerts inhibitory effects. This conclusion establishes critical parameter thresholds for the safe application of LTP technology. However, the physiological basis of the inhibitory effect (e.g., oxidative damage) remains unclear, warranting further investigation through reactive oxygen species (ROS) assays. Further studies support these findings: C.Q. Wu *et al.* (2022) observed that high-voltage electrostatic field pre-treatment significantly increased average seedling height and yield in coarse cereals, demonstrating its potential to enhance crop productivity. However, the study lacked detailed analysis of yield components (e.g., tiller number, grains per spike) and did not assess the sensitivity of different growth stages to electric fields, highlighting the need for long-term field trials. R. Górski *et al.* (2019) reported that varying electric field intensities and repeated radiation treatments differentially affected germination rate and sprout length in onion seeds, with optimal voltage and exposure duration maximising germination and sprout growth. The study underscores the importance of precise parameter control but did not examine the impact of electric fields on secondary metabolites (e.g., antioxidants), which may limit its applicability in functional agriculture. Similarly, M.K. Abhary & A. Akhkha (2023) demonstrated that appropriate electric field strength and treatment duration promoted root and shoot growth in tomato 'Yellow Rose' seeds, along with increased α-amylase activity, suggesting enhanced energy metabolism. These results directly link electric field effects to physiological and biochemical indicators, but the study did not evaluate subsequent fruit quality changes, which could be explored in future harvest-stage assessments.

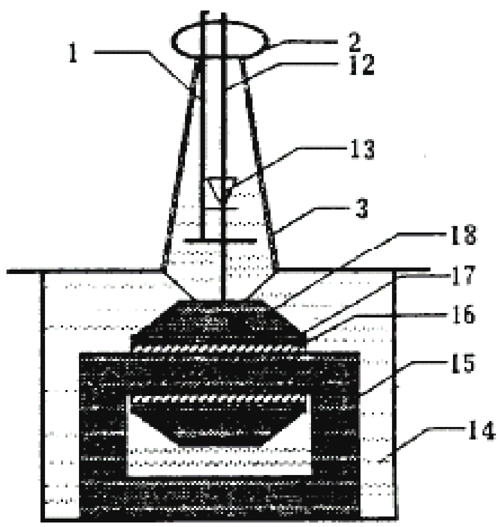
In summary, high-voltage electric field treatment can effectively stimulate the synthesis of physiological and biochemical substances required for seed germination, offering a novel approach to optimising germination conditions. However, most existing studies remain confined to experimental observations, lacking the theoretical analysis necessary to guide electric field intensity design and seed electro-selection. In order to better understand the mechanism of seed electric field treatment and fully utilise the effect of seed polarisation force on seed vigour sorting, the previous experiments on high-voltage electric field treatment of soybean seeds concluded that appropriate electric field intensity and treatment time could significantly improve relevant vigour indicator. The purpose of the study was to elucidate the fundamental dielectric principles and assess the impact of high-voltage electric field therapy on the germination potential and seedling growth of rice seeds.

MATERIALS AND METHODS

Plump and uniformly-sized rice seeds were harvested and divided into 16 groups, with 50 seeds per group. Each group underwent treatment followed by germination and growth tests, with two replicates performed for each group. Dark-condition germination and growth experiments were conducted using a thermostatic incubator with towel coverage method. The germination assays were carried out under controlled conditions: 28 ± 0.5°C, 75 ± 5% RH. All procedures involving plant materials adhered to the ethical standards outlined in the Convention on Biological Diversity (1992), ensuring sustainable utilisation and conservation of biological resources throughout this study. In the orthogonal experiment of electric field treatment for rice seeds, a YD/JZ-type AC/DC test transformer was employed. The YD/JZ lightweight transformer adopted a single-frame core-type structure, where the primary winding was wound around the iron core and the high-voltage winding was placed externally. This coaxial arrangement reduced leakage flux, thereby enhancing the coupling between windings. The transformer core was designed with a relatively low magnetic flux density to prevent excessive excitation currents that could generate significant harmonics. The external and internal structural diagrams are shown in Figure 1, respectively.



a) exterior structure



b) interior structure

Figure 1. *Structure of experiment transformer*

Note: *1 – Shorting rod D; 2 – Equalising ball; 3 – High-voltage bushing; 4 – Handle; 5 – Oil valve; 6, 7 – Primary voltage input a, x; 8, 9 – Measuring terminals E, F; 10 – Transformer grounding terminal; 11 – High-voltage tail X; 12 – High-voltage output A; 13 – High-voltage silicon stack; 14 – Transformer oil; 15 – Core; 16 – Primary low-voltage winding; 17 – Measuring winding; 18 – Secondary high-voltage winding*

Source: *compiled by the authors*

The principle of the high-voltage electric field treatment device is shown in Figure 2. It consists of two metal plates as the electrodes, and two glass plates as the insulating plates. The distance between the two metal plates – 20 mm, which can generate a relatively large electric field strength. In a uniform electric field, when the voltage is continuously applied, the insulation characteristics of the air are rather complex.

Under DC and power frequency conditions, the breakdown voltage can be calculated using the following empirical formula:

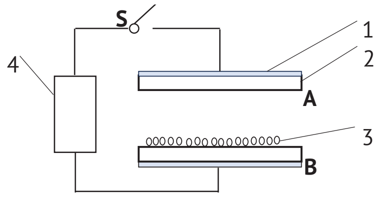


Figure 2. *High-voltage electric field processing device*

Note: *1 – insulating board; 2 – plates; 3 – seeds; 4 – high-voltage power supply; A – upper electrode plate; B – Lower electrode plate; S – switch*

Source: *compiled by the authors*

$$U_b = 24.22\delta d + 6.08\sqrt{\delta d}, \qquad (1)$$

where U_b – gap breakdown voltage (peak value); δd – clearance distance, mm; δ – relative density of air.

The experiments were conducted in May 2024. Using the uniformly and plump 'Shennong 262' rice seeds harvested in 2023 provided by the Rice Farming Laboratory of Shenyang Agricultural University, the seeds were divided int o 16 groups, with 50 seeds in each group. After treatment, the seeds were subjected to germination and growth tests, with each group undergoing 2 repetitions. The light-shielding germination and growth tests were carried out using the method of covering with an incubator and a towel. Inside, equation for calculating seed germination potential (*G*) was:

$$G = \frac{G_1}{N} \times 100\%, \qquad (2)$$

where G_1 – number of all normally germinated seeds in the initial stage of the germination test (the number of seeds germinated within 3 days); *N* – number of seeds for the experiment.

The high-voltage electric field treatment experiment on rice seeds examined three factors at two levels each: field type *S* (*A*), intensity *E* (*B*), and duration *t* (*C*) (Table 1). Response variables were germination potential (*G*) and 5-week seedling height (*H*).

Table 1. *Factors and levels*

Levels	Factors		
	A Electric field forms *S*	*B* Electric field intensity E/kV·m^{-1}	*C* Processing time t/s
1	DC field	360	90
2	AC field	520	150

Note: *S(A) – field type; E/ kV·m-1(B) – intensity; t/s(C) – duration*
Source: *compiled by the authors*

The experiment was conducted using an $L_8(2^7)$ orthogonal array, the optimal solution was derived using an interactive intuitive analysis method that evaluates factor prioritisation and interaction effects to determine the best parameter combination. ANOVA was performed on the orthogonal experiment results to provide recommendations for optimising experimental conditions. Data normality (Shapiro-Wilk, $p > 0.05$) and homogeneity (Levine's, $p > 0.1$) were confirmed before ANOVA. By comparing *F*-ratio and $F\alpha$, the significance level was determined. Specifically, when *F*-ratio was less than $F_{0.25}$, it was considered insignificant; the larger the *F*-ratio, the higher the significance level. To investigate the changes in electric field intensity caused by the introduction of seeds in an electric field and the electric field intensity within the seeds, the electric image method was employed for the research.

Seeds vary greatly in external form and structure. However, from the perspective of plant morphology, the internal structure of the vast majority of seeds has commonalities. Each seed was composed of three main parts: the seed coat, the embryo, and the endosperm. Given the structural and compositional characteristics of seeds, a single seed can be analysed layer by layer. Each layer was separated by a biological membrane with selective permeability, and the chemical composition and water content of the contents in each layer are also significantly different, resulting in different dielectric constants and densities. Although it can be assumed that the dielectric within each layer was isotropic, it was still very difficult to investigate its various properties in an electric field. Therefore, it was necessary to further simplify the seed to obtain a simple dielectric model. For a vigorous seed, the biological membrane capacitance can not only store electrical energy but also dissipate it. Each layer of the membrane was simplified into a parallel connection of a resistor and a capacitor, as shown in Figure 3.

a) Seed stratification and simulation circuit   b) Seed simplifies the circuit

Figure 3. *The equivalent circuit of the seed*
Note: *R – equivalent resistance; C – equivalent capacitance*
Source: *compiled by the authors*

The electric field acting on the biological membrane was equivalent to acting on the equivalent *RC* circuit. Due to the non-uniformity of biological tissues, the current flow in the intracellular and extracellular fluids was different, thereby changing the charge distribution on the membrane. Assuming that the potential within each layer was uniform, the simplified equivalent circuit can be obtained as shown in Figure 3(b). Among them:

$$R = R_1 + R_2 + R_3\ C = \frac{C_1 C_2 C_3}{C_1 C_2 + C_3 C_1 + C_3 C_2}, \quad (3)$$

where, R – equivalent resistance; C – equivalent capacitance.

According to the principles of electricity the equivalent complex impedance Z of the seed simulation circuit can be expressed as (Zhang & Wang, 2021):

$$Z_1 = \frac{R}{1+\omega^2 C^2 R^2}, \quad (4)$$

where Z_1 – real part of Z represents the part that stores electrical energy; ω – represents the circular frequency of the applied electric field. When $\omega = 0$, that is, when a direct current electric field is applied, the equivalent impedance is $R = R_1 + R_2 + R_3$.

$$Z_2 = -\frac{\omega C R^2}{1+\omega C^2 R^2}, \quad (5)$$

where Z_2 – imaginary part of Z represents the portion that dissipates electrical energy.

$$Z = Z_1 + jZ_2, \quad (6)$$

where $j = \sqrt{(-1)}$ – imaginary unit.

It can be seen from equation (1) that the complex impedance of the seed equivalent circuit depends on the circular frequency (ω) of the applied electric field, the film capacitance (C) and film resistance (R) of the seed, and is independent of the applied voltage or the current passing through. According to Maxwell's equations, the electromagnetic motion law of the dielectric in the seed can be known:

$$\nabla \cdot D = \rho, \nabla \cdot B = 0, \quad (7)$$

where ∇ – LaPlace operator; D – electric displacement vector; ρ – free charge density; B – magnetic induction intensity.

$$\nabla \times E = -\frac{\partial B}{\partial t}, \nabla \times H = j + \frac{\partial D}{\partial t}, \quad (8)$$

where E – electric field intensity; t – time; H – magnetic field intensity; J – conduction current density vector; ∂ – partial derivative, i.e., the rate of change.

Since the electric displacement is caused by the electric field. Therefore:

$$D = \varepsilon_0 \varepsilon E, \quad (9)$$

where ε_0 – dielectric constant of vacuum; ε – relative dielectric constant.

$$B = \mu_0 \mu H, \quad (10)$$

where μ_0 – vacuum permeability; μ – relative permeability.

In the seed dielectric, the free charges are merely responsible for the conduction function. The truly active component is the bound charges. Then the electrical conductivity (σ) of the seed can be expressed as:

$$\sigma = \frac{j}{E}. \quad (11)$$

According to the definition of electric displacement (equation 9), it can be known that the relationship between electric displacement and electric polarisation intensity is:

$$D = \varepsilon_0 E + P. \quad (12)$$

When the applied electric field is zero, the polarisation electric field intensity $P = 0$. In the above formula, P can also be regarded as an additional effect caused by the electric field intensity E, and it satisfies:

$$P = \chi \varepsilon_0 E, \quad (13)$$

where χ – polarisation rate of seeds, is a scalar constant.

It can be known from equations (9), (12) and (13):

$$\varepsilon = 1 + \chi. \quad (14)$$

From the above equation, it can be seen that: in a physical sense alone, describing the dielectric constant of seeds with relative dielectric constant and macroscopic polarisability is equivalent, and the difference between the two is only 1. Assuming that the seed is a dielectric sphere with a radius of a and a dielectric constant of ε_r, and placing it in a uniform electric field with an intensity of E_0. The electric field is formed by two parts of charges, one being the known uniform electric field E_0 with a potential of Φ_0, and the other part is the electric field E' formed by the polarised charges σ' on the surface of the seed with a potential of Φ', and at infinity is zero. Using the partition solution method, the indicators within the seed are represented by subscript 1, and the indicators outside the seed are represented by subscript 2:

$$\left\{ \begin{array}{c} \Phi_1 = \Phi_0 + \Phi_1' \\ \Phi_2 = \Phi_0 + \Phi_2' \\ \Phi_2{}' = \sum_{n=1}^{\infty} \frac{B_n}{r^{n+1}} P_n(\mu) \end{array} \right\}, \quad (15)$$

where r – radial distance of the seeds in polar coordinates.

Since the polarised charges are only on the surface of the seed, the polarised charges inside the seed are, therefore:

$$\nabla^2 \Phi_1' = 0; \nabla^2 \Phi_2' = 0. \quad (16)$$

The interface equation:

$$\left\{\Phi_1|_{r=a} = \Phi_2|_{r=a},\ \ \varepsilon_r \frac{\partial \Phi_1}{\partial r}\bigg|_{r=a} = \frac{\partial \Phi_2}{\partial r}\bigg|_{r=a}\right\}. \tag{17}$$

Introduced boundary conditions: when $r = 0$, Φ_1' is finite; When $r = \infty$; Φ_2' $\rightarrow 0$. By solving it, which can be obtained:

$$\begin{Bmatrix} \Phi_1 = C - \frac{3E_0}{\varepsilon_r + 2} r\cos\theta\ ,\ \ E_1 = -\frac{\partial \Phi_1}{\partial z}k = \frac{3E_0}{\varepsilon_r + 2} \\ \Phi_2 = C + E_0 a^3 \frac{\varepsilon_r - 1}{\varepsilon_r + 2}\frac{\cos\theta}{r^2} - E_0 r\cos\theta \end{Bmatrix}, \tag{18}$$

where θ – polar angle of the seeds in polar coordinates; k – unit vector in the z-axis direction; a –geometric dimensions of the seeds.

RESULTS AND DISCUSSION

The smaller the relative permittivity (ε_r) of the seed, the greater the electric field intensity (E_1) inside the seed. Notably, it is precisely the internal electric field that affects the seed characteristics. Experimental results have demonstrated that high-vigour seeds exhibit lower relative permittivity compared to low-vigour seeds. Consequently, under the same applied electric field, high-vigour seeds experience greater field effects than their low-vigour counterparts. The growth experiment is shown in Figure 4, which recorded the germination of the seeds.

The average seedling height in 8 groups classification measurement is presented in Figure 5.

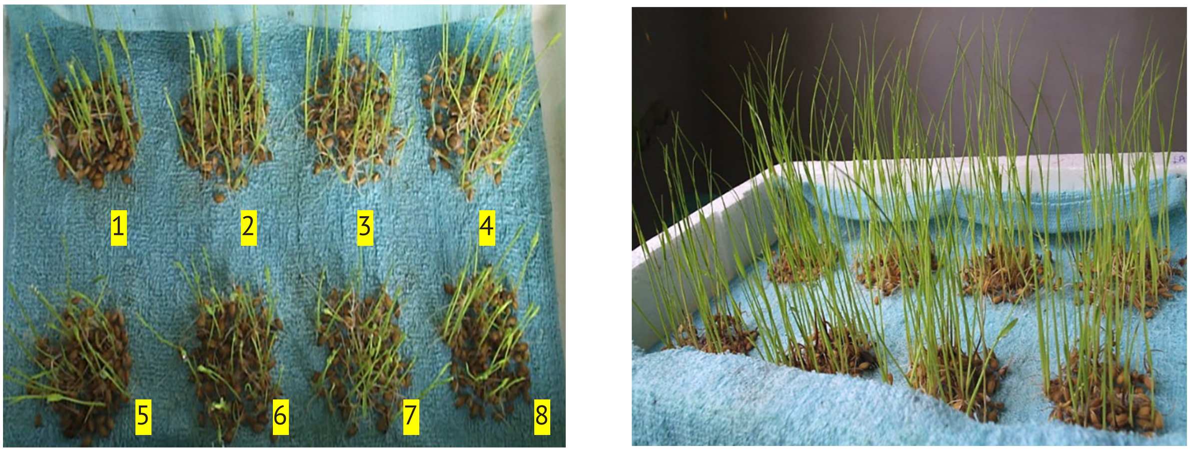


Figure 4. *Growth experiment of paddy rice*

Source: *compiled by the authors*

Figure 5. *Seedling height of paddy rice*

Source: *compiled by the authors*

The orthogonal experimental design and range analysis of results as presented in Table 2, among the three investigated factors, analysis of the germination potential indicator revealed the following order of influence: treatment duration $C >$ interaction between electric field intensity and treatment time $B \times C$ (i.e., treatment dose) $>$ interaction between electric field type and treatment time $A \times C >$ electric field intensity $B >$ electric field type A.

Table 2. Orthogonal experimental design and range analysis of results

Test number	Factors							Test indexes	
	A (1)	*B* (2)	*A* × *B* (3)	*C* (4)	*A* × *C* (5)	*B* × *C* (6)	Empty (7)	Germination potential *G*/%	Average plant height *H*/mm
1	1(DC)	1(360)	1	1(90)	1	1	1	38.0	52.4
2	1(DC)	1(360)	1	2(150)	2	2	2	44.5	63.8
3	1(DC)	2(520)	2	1(90)	1	2	2	43.5	59.7
4	1(DC)	2(520)	2	2(150)	2	1	1	45.0	70.6
5	2(AC)	1(360)	2	1(90)	2	1	2	31.5	50.9
6	2(AC)	1(360)	2	2(150)	1	2	1	48.0	68.3
7	2(AC)	2(520)	1	1(90)	2	2	1	39.5	66.5
8	2(AC)	2(520)	1	2(150)	1	1	2	44.0	71.7
KG1	171.0	162.0	166.0	152.5	173.5	158.5	170.5		
KH1	246.5	235.4	254.4	229.5	252.1	245.6	257.8		
KG2	163.0	172.0	168.0	181.5	160.5	175.5	163.5		
KH2	257.4	268.5	249.5	274.4	251.8	258.3	246.1		
kG1	42.8	40.5	41.5	38.1	43.4	39.6	42.6		
kH1	61.6	58.9	63.6	57.4	63.0	61.4	64.5		
kG2	40.8	43.0	42.0	45.4	40.1	43.9	40.9		
kH2	64.4	67.1	62.4	68.6	63.0	64.6	61.5		
RG	2.0	2.5	0.5	7.3	3.3	4.3	1.8		
RH	2.7	8.3	1.2	11.2	0.1	3.2	2.9		
	Germination potential							Average plant height	
Primary – secondary order	*C B* × *C A* × *C B A*							*C B B* × *C*	
Optimal level combination	$A_2 B_1 C_2$							$A_2 B_2 C_2$	
Optimal Level Combination (with Comprehensive Balancing)				$A_2 B_2 C_2$					

Source: *compiled by the authors*

The range value of the *A* × *B* interaction term was smaller than that of the error column, indicating it was not statistically significant. Considering both interaction effects and non-significant terms, the optimal factor levels were determined as: *A* at level 2, *B* at level 2, and *C* at level 1. The best treatment combination was $A_2 B_1 C_2$. For the evaluation metric of average seedling height, the order of factor influence was: treatment duration *C* > electric field intensity *B* > interaction between electric field intensity and treatment time *B* × *C* (i.e., treatment dose). The interaction terms *A* × *B* (electric field type × intensity) and *A* × *C* (electric field type × duration), along with the main effect of electric field type *A*, all showed range values smaller than the error column, indicating they were statistically non-significant. Considering both interaction effects and non-significant terms, the optimal factor levels were determined as: *A* at level 2 (electric field type *A* being non-significant, the level selection is arbitrary), *B* at level 2, *C* at level 2, and the best treatment combination was $A_2 B_2 C_2$.

During the seed germination stage, a higher germination potential (*G*) determines better seedling establishment rate and uniformity. However, from the perspective of long-term growth potential, greater seedling height (*H*) indicates stronger seedling vigour and stress resistance, which is more beneficial for subsequent growth. Therefore, by integrating both evaluation metrics, the optimal treatment combination under experimental conditions was determined to be $A_2 B_2 C_2$. The experimental results further revealed that: Germination potential (*G*) exhibited a dose-dependent relationship with treatment dose: moderate doses enhanced germination performance, excessive doses potentially inhibited seed germination. Growth metrics (e.g., seedling height) showed a significant positive correlation with treatment dose: higher doses consistently improved long-term growth vigour. ANOVA was performed on the orthogonal experiment results to provide recommendations for optimising experimental conditions. The analytical results are presented in Table 3.

Table 3. *Variance analysis for germinability*

SV	SS	df	MS	F-ratio	
C	105.125	1	105.125	31.736	0.05
B×*C*	36.125	1	36.125	10.906	0.1
A×*C*	21.125	1	21.125	6.377	0.25
B	12.5	1	12.5	3.774	0.25
A	8	1	8	2.415	-
Error	6.63	2	3.315		
Total	189.505	7	$F_{0.25}$ (1.2) = 2.57. $F_{0.1}$ (1,2) = 8.53 $F_{0.05}$ (1.2) = 18.5. $F_{0.025}$ (1,2) = 38.51		

Source: *compiled by the authors*

Table 3 demonstrates that for the germination potential indicator: Treatment duration (*C*) emerged as the most significant factor (= 0.05); the interaction between electric field intensity and treatment time (*B* × *C*) showed secondary significance (= 0.1); both the *A* × *C* interaction and electric field intensity (*B*) itself exhibited marginal effects (α = 0.25), Electric field type proved statistically non-significant, indicating no substantive difference between AC and DC fields in affecting germination potential. Statistical analysis of average plant height (Table 4) revealed the following significance hierarchy: treatment duration (Factor *C*) demonstrated the strongest effect (α = 0.01); electric field intensity (Factor *B*) showed significant but weaker influence (α = 0.025); the *B* × *C* interaction (electric field intensity × treatment duration) exhibited marginal significance (α = 0.25).

Table 4. *Variance analysis for average seedling height*

SV	SS	df	MS	F-ratio	
C	252.001	1	252.001	28.822	0.01
B	136.951	1	136.951	15.663	0.025
B×*C*	20.161	1	20.161	2.306	0.25
Error	34.97	4	8.7425		
Total	444.083	7	$F_{0.25}$(1.4) = 1.81. $F_{0.1}$(1.4) = 4.54 $F_{0.05}$(1.4) =7.71. $F_{0.025}$(1.4) = 12.22 $F_{0.01}$ (1.4) = 21.20		

Source: *compiled by the authors*

Notably, seeds exhibiting higher initial viability show greater responsiveness to these electrical treatment parameters, revealing a clear positive correlation between treatment intensity and biological effects. The electric field that affects the seeds should precisely be the electric field inside the seeds. According to equation (13), it can be concluded that the electric field inside the seeds is positively correlated with the magnitude of the applied field strength and negatively correlated with the dielectric constant of the seeds. Research findings indicate that seeds with high dielectric constants are usually associated with higher electrical conductivity, suggesting that the cell membrane is damaged and the cell's vitality is low. Just as P.Y. Chen *et al*. (2022) research indicated, seeds with high dielectric constants are usually associated with higher electrical conductivity, suggesting that the cell membrane is damaged and the cell's vitality is low. Therefore, the greater the applied field strength, the smaller the dielectric constant of the seeds and the higher the seed viability.

The study systematically investigated the effects of high-voltage electric field (HVEF) treatment on rice seed germination and seedling growth through orthogonal experimental design and equivalent circuit modelling. Comprehensive approach demonstrated that both electric field intensity (Factor *B*) and treatment duration (Factor *C*) significantly influence seed viability, with optimal combinations enhancing germination potential (*G*) by up to 48% and average seedling height (*H*) by 71.7 mm. These findings not only align with but substantially extend current knowledge in bioelectrical agriculture, offering novel insights into the dielectric mechanisms governing seed-electro field interactions. The dielectric modelling (equation 4-9) revealed a fundamental inverse correlation between seed vigour and relative permittivity (ε_r), providing a quantitative explanation for the enhanced field responses observed in high-viability seeds. This finding strongly supports the paper by G.A. Evrendilek *et al*. (2021), who documented 20-30% reductions in ε_r for primed maize seeds subjected to 300-500 V/cm AC fields. However, in this study, it advances this understanding by incorporating RC circuit analysis (Fig. 3), which precisely quantifies energy dissipation dynamics – a significant refinement over the empirical approaches of Z. Song *et al*. (2021), who linked *Arabidopsis* germination enhancement to membrane depolarisation without characterising impedance properties.

The dose-dependent response observed in the orthogonal experiments (Table 2) mirrors results reported by M. Chenah *et al*. (2024), where moderate HVEF exposure (400 V/cm, 60 s) maximised wheat germination rates, while excessive treatment durations (>120 s) induced oxidative stress. Notably, ANOVA results (Tables 3-4) identified treatment duration (Factor *C*) as the dominant influence ($\alpha = 0.01$), contrasting with the conclusions of Z. Mamlić *et al*. (2021), who prioritised electric field intensity in plasma-treated soybeans. This discrepancy likely arises from species-specific dielectric properties, highlighting the critical need for crop-specific optimisation of electrostimulation protocols. The results challenge the findings of N. Osokina *et al*. (2024), who reported DC field superiority in enhancing spelt seed germination. Instead, it observed no statistically significant difference between AC and DC fields (Factor $\underline{A}$, $p > 0.25$), a conclusion that aligns with the mechanistic explanations proposed by X. Wu *et al*. (2024) in their study of cotton seedling growth regulation. The interaction analysis ($B \times C$) further suggests that pulse frequency – a parameter not controlled in current study – may outweigh waveform differences in determining treatment outcomes, as hinted at in the work of T.C. Polachini *et al*. (2023) on wheat grain treatment. The sustained improvements in seedling height under HVEF treatment (Fig. 5) corroborate the findings of C.G. Liu (2022), where 5 kV/m pre-sowing treatment increased tomato biomass by 40%. However, while their study focused on ROS signalling pathways, this paper dielectric model emphasises intracellular field amplification (equation 18) as a primary mechanism. These perspectives are not mutually exclusive, as evidenced by J. Ceng & J. Wang (2021) who documented concurrent membrane potential shifts and antioxidant system activation in HVEF-treated barley seedlings.

The majority of existing studies (Sun *et al*., 2024a) rely on relatively simple germination indices. By combining orthogonal experimental design with dual evaluation metrics (germination potential and seedling height), this study provides a more comprehensive assessment of treatment effects. Furthermore, the RC circuit model (Fig. 3) directly addresses the methodological gap in analysing seed-electro field interactions, building upon the fundamental theories presented by Z.L. Wang & J.J. Shao (2023) in their study on Maxwell's equations. While this paper provides significant insights, certain limitations should be acknowledged. The omission of biochemical assays (e.g., antioxidant activity measurements) restricts direct comparison with papers such as Y. Song *et al*. (2024), who correlated HVEF effects with superoxide dismutase enzyme upregulation. Additionally, the resolution of $L_8(2^7)$ orthogonal array may obscure higher-order interactions – a limitation successfully addressed by Y.Y. Li (2024) through response surface methodology. This study establishes HVEF treatment as a powerful seed-priming technology, with dielectric properties serving as reliable predictors of seed viability. The identified optimal treatment combination ($A_2 B_2 C_2$: AC field, 520 $kV \cdot m^{-1}$ for 150 s) effectively balances immediate germination enhancement with long-term growth promotion, offering practical protocols for rice cultivation. Frequency-dependent effects and field uniformity optimisation were identified as key factors for translating laboratory findings to agricultural practice, consistent with the systems approach described by S. Sun *et al*. (2024b) in the study on seedling sowing methods. The experimental results of study demonstrated that both electric field intensity and treatment duration significantly influence rice seed viability, affecting short-term germination potential and long-term seedling development. Under controlled conditions, increasing either the electric field strength or exposure time leads to proportional improvements in average seedling height, indicating enhanced long-term viability.

CONCLUSIONS

An equivalent circuit representation of the seed system was established through simplified seed modelling. This approach enabled theoretical derivation of the dielectric polarisation process occurring within the seed structure. Furthermore, employing the electrical imaging method permitted detailed investigation of both internal and external electric field intensity distributions surrounding the seed under applied electrical conditions. The results show that, in the physical sense, the relative dielectric constant ε and the macroscopic polarisability χ differ by only 1, and the dielectric constant used to describe the seeds is equivalent. According to the derivation of E_1, it can be known that the smaller the relative dielectric constant of the seed, the greater the electric field intensity E_1 within the seed. However, the electric field that affects the seed should precisely be the electric field within the seed. Moreover, seeds with high viability have a smaller relative dielectric constant, while seeds with low viability have a larger relative dielectric constant. Therefore, the same external electric field has a greater impact on seeds with high vitality than on seeds with low vitality.

Orthogonal experiments of high-voltage electric field treatment on rice seeds were conducted using three factors and two levels. The effects of different electric field forms, electric field intensities and treatment times on the two indicators of germination potential and average seedling height were investigated respectively, and the primary and secondary order of each factor and the optimal combination were clarified. The results showed that under the experimental conditions, the optimal parameter combination adopted to obtain a higher germination potential and average seedling height is an alternating electric field treatment with an electric field intensity of 520 $kV \cdot m^{-1}$ for 150 seconds. The factors that have the greatest impact on seed germination and seed growth are the treatment time and the treatment field strength, while the effects of alternating current electric field and direct current electric field on the results are not significant. The appropriate treatment dose promotes the germination potential, while an excessive treatment dose may inhibit the germination of seeds. As for the growth indicators, the larger the treatment dose, the better the growth situation in the later stage, showing a significant positive correlation. Under the experimental conditions, the stronger the field strength and the longer the treatment time, the higher the average seedling height of the seeds, which is more beneficial to the long-term viability of the seeds, manifested as a smaller dielectric constant of the seeds. Future investigations should incorporate these advanced statistical approaches while expanding the range of physiological and biochemical measurements.

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CONFLICT OF INTEREST

None.

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Експериментальні дослідження насіння рису на основі обробки високовольтним електричним полем

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Анотація. Механічні сили можуть викликати внутрішні мікротріщини та приховані пошкодження, що значно погіршує якість зерна під час збору насіння рису, а традиційне механічне сортування не дозволяє виявити такі дефекти. Як діелектричний матеріал, насіння виявляє поляризацію в нерівномірних електричних полях, що тісно пов'язано з його діелектричними властивостями. Метою цього дослідження було вивчення впливу обробки високовольтним електричним полем на потенціал проростання та ріст сходів насіння рису, а також з'ясування основних діелектричних механізмів. Було розроблено спрощену модель насіння та еквівалентну схему. Шляхом аналізу процесу діелектричної поляризації та розрахунку напруженості поля всередині та зовні насіння було визначено макроскопічні закони електромагнітного руху діелектрика в насінні. Було проведено ортогональні експерименти з обробкою насіння електричним полем. Аналіз діапазону дозволив визначити первинні та вторинні фактори, що впливають на потенціал проростання та середню висоту насіння, а аналіз дисперсії визначив оптимальну комбінацію обробки та перевірив значущість моделі. Результати показали, що комплексний імпеданс еквівалентного контуру насіння залежить від кругової частоти (ω) прикладеного електричного поля, ємності плівки (C) та опору плівки (R) насіння. Відносна діелектрична проникність ε та макроскопічна швидкість поляризації χ є еквівалентними в описі діелектричної проникності насіння. Зовнішнє електричне поле має більш значний вплив на насіння з вищою життєздатністю. Оптимальними параметрами для підвищення потенціалу проростання та середньої висоти насіння є електричне поле змінного струму з інтенсивністю 520 кВ · м$^{-1}$ протягом 150 секунд в умовах експерименту. Більш сильна напруженість поля та довший час обробки призводять до підвищення середньої висоти насіння, що сприяє довготривалій життєздатності насіння. Це пояснюється тим, що нижча діелектрична проникність насіння є вигідною. Отже, насіння, оброблене високовольтними електричними полями, може значно підвищити життєздатність насіння та збільшити врожайність, сприяючи розвитку ефективних, точних, неруйнівних та автоматизованих технологій селекції та сортування

Ключові слова: електростимуляція; підвищення життєздатності; потенціал проростання; середня висота рослини; діелектрична проникність; ортогональна оптимізація

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Integration of modern land reclamation equipment into the system of precision agriculture using MZURI technology in the south of Ukraine

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Abstract. The purpose of this study was to investigate the possibilities of increasing the efficiency of agricultural production in southern Ukraine by using modern land reclamation equipment in combination with precision farming technology to improve soil water regime and the sustainability of agroecosystems. The study employed an experimental approach with variations in tillage and irrigation, determination of physical and water properties of the soil, root system development and plant condition, yield, resource costs, and economic indicators for a comprehensive assessment of the effectiveness of agricultural technologies. The study found that strip tillage, a field-based precision tillage system with row planting, combined with Netafim Uniram drip irrigation provided the greatest soil moisture at 0-20 cm and 20-40 cm (28 m^3/ha and 24 m^3/ha, respectively), reduced soil density to 1.26 g/cm^3 and increased capillary water capacity to 27 m^3/ha. The depth of the root system reached 110 cm, while the normalised difference vegetation index was 0.82. Yields reached 10.8 t/ha, water use efficiency (WUE) was 3.09 kg/m^3, net profit was 21,000 UAH/ha, and profitability was 62%. The variant using the Bauer Rainstar E precision field system with row spacing and precision sprinkling showed a yield of 10.5 t/ha, slightly below the maximum result, but greater than the control. The field system of precision cultivation with row planting without land reclamation yielded 9.5 t/ha, while convention0al irrigation (control) showed the lowest results – 8.9 t/ha. The data revealed that the integration of strip-till with modern irrigation systems increases the productivity and economic efficiency of maize

Keywords: dry conditions; irrigation; yield; water saving; energy consumption

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INTRODUCTION

The southern regions of Ukraine are characterised by challenging climatic conditions, including low natural moisture levels, hot temperatures, and frequent droughts, which negatively affect the productivity of agricultural land. Due to the growing shortage of water resources, soil water management requires increased attention. Precision farming technologies, which include minimal tillage, localised fertilisation, and automated management of agricultural processes, are becoming key to ensuring stable yields and preserving soil fertility. One of the most promising innovations is the MZURI technology (a precision tillage system with row planting), which combines energy and water saving with increased agronomic efficiency. Combined with modern land reclamation measures, this technology opens new opportunities for adapting agricultural production to the arid conditions in southern Ukraine.

The problem of effective water management in the arid regions of southern Ukraine continues to be urgent due to the lack of natural moisture and soil degradation. B. Hailu & H. Mehari (2021) investigated the impact of fertigation on plant development in arid conditions. The researchers found that the use of this technology not only increases yields, but also optimises fertiliser use, reducing fertiliser losses. The researchers emphasised that fertigation creates a more even supply of nutrients to plants, which is crucial in conditions of limited soil moisture. Y. Sha *et al*. (2024) addressed the use of deep rippers to accumulate moisture in the root system. The study showed that this technology promotes deeper root penetration and improves water supply for crops in arid regions. Additionally, loosening reduces soil compaction, which increases the efficiency of irrigation use and contributes to more stable plant growth. Y. Lu *et al*. (2022) highlighted the role of the global positioning system (GPS) in precise fertilisation and irrigation control. Accurate positioning enables an even distribution of resources, which increases the efficiency of their use and reduces costs. The study also showed that the integration of GPS technology with modern irrigation systems reduces the environmental impact on the agricultural system.

J. Huang *et al*. (2021) noted that the combination of reclamation measures with strip-till reduces soil erosion. This helps to maintain fertility and a stable water balance, which is critical in arid regions. The researchers also emphasised that this combination of technologies improves the physical properties of the soil, which positively influences the development of the root system of crops. V. Havrysh *et al*. (2021) explored the possibility of using a hybrid power source with a variable frequency drive to automatically move irrigation equipment. The researchers showed that such a system increases energy efficiency and ensures stable operation of the equipment under variable power supply conditions. Additionally, automated movement contributes to more precise irrigation and more uniform water supply to plants, which increases the efficiency of agricultural production. I. Biluk *et al*. (2020) addressed the use of adaptive control in complete electric drives to ensure stable operation of industrial systems. The study found that this approach can improve the accuracy and reliability of drives under variable loads and operating conditions. This is crucial for automated irrigation and soil cultivation systems, where the stability of the equipment directly affects the uniformity of water and nutrient supply. J. Cuaran & J. Leon (2021) demonstrated the benefits of remote monitoring using drones. Due to the prompt detection of plant stress conditions, agrotechnical measures can be adjusted accordingly, which increases crop productivity. This study confirmed the effectiveness of integrating remote monitoring technologies into precision farming systems to increase yields and resource efficiency.

S. Getahun *et al*. (2024) emphasised the need to adapt technologies to local soil and climatic conditions. Adapting to concrete conditions can stabilise yields and increase the efficiency of precision agriculture. The researchers noted that consideration of the local soil and climate characteristics is a key factor in optimising irrigation and fertilisation. X. Fu & H. Niu (2023) pointed out that reducing energy costs with the introduction of modern reclamation systems increases the economic efficiency of production. Lower energy costs can increase profitability and ensure stable productivity of agricultural systems. The cited study emphasised that optimising energy consumption is a vital aspect of sustainable farming, especially in regions with limited access to resources. S. Alharbi *et al*. (2024) investigated an integrated approach to soil water management. Better control of the water balance ensures stable productivity of agricultural systems and improves water supply to plants in arid regions. This confirms that the integration of modern irrigation technologies and precise water management directly affects resource efficiency and crop yields. The findings of these studies confirmed the positive impact of an integrated approach on moisture conservation, yield increase, and energy efficiency of agricultural production in drought conditions. At the same time, there are gaps in the study of the adaptation of these technologies to the specific soil and climatic conditions of the southern region of Ukraine, as well as in the development of integrated methods for monitoring and managing reclamation systems in real agroecosystems. This requires further research to optimise the implementation and increase the sustainability of agricultural production in an arid climate.

The purpose of this study was to assess the effectiveness of the introduction of land reclamation equipment into the precision farming system using the MZURI technology to increase the productivity and stability of agrocenoses in the region. The objectives of the study were to investigate the influence of tillage technologies on the physical and chemical properties of the soil; to assess the effect of these technologies on the development of the root system and vegetative performance of plants; and to conduct economic and resource analysis by determining the consumption of water, fertilisers, and fuel and calculating key economic indicators such as net profit and profitability ratio.

MATERIALS AND METHODS

The study was conducted from April to August 2024 at the farm "Dzhondir-B", located in Bolhrad district of Odesa region, which is part of the Southern Steppe of Ukraine. This farm was chosen due to its location in the Southern Steppe zone with typical soil and climatic conditions for the region, which ensured the representativeness of the results. A 12-hectare plot was allocated for the study, which was divided into four replications of 3 ha each, enabling the assessment of the impact of different tillage and irrigation technologies on the productivity of mid-season maize (*Zea mays* L.), a hybrid selected for its adaptability to the Southern Steppe and stable yields in the study area. The soils of the site were represented by southern medium loamy chernozem with a humus content of 2.8%, and the weather conditions of the season were characterised by an average annual rainfall of about 320 mm and an average temperature of the growing season of +22.4°C with possible rain-free periods of up to 50 days (Hydrometeorological centre…, n.d.).

The study followed international and national ethical standards for conducting experiments with plants and soils, in particular, the principles of Convention on Biological Diversity (1992). All agrotechnical tests were conducted without compromising the biological integrity of plants and soil ecosystems. The principles of rational use of natural resources and sustainable soil management were applied, which was emphasised in studies on bioeconomics and soil protection in Ukraine (Petrukha *et al*., 2024; Tretiak *et al*., 2024). Additionally, methodological approaches to minimising the negative impact on soil properties during experiments, recommended in the context of military and environmental risks, were considered (Andrews *et al*. 2004). Adherence to these ethical standards ensured the reliability, safety, and representativeness of the findings. The tillage and irrigation technologies included four variants that helped to compare conventional and conservation approaches in terms of their impact on soil properties, plant development, and yields. The first option involved conventional irrigation by sprinkling with continuous tillage at 12-14 cm, which served as a control option for comparison with other technologies. The second variant implemented strip tillage without land reclamation with simultaneous sowing using a MZURI Pro-Til 3T seeder (UK), which helped to assess the effectiveness of the resource-saving approach. The third variant combined strip-till with Netafim Uniram™ drip irrigation (Israel) with built-in compensating emitters for precise water dosing, and the fourth variant involved strip-till combined with a Bauer Rainstar E sprinkler (Austria) to evaluate modern mechanised technologies.

Soil moisture at depths of 0-20 cm and 20-40 cm was determined using Soilmoisture Equipment Corp. tensiometers (USA) installed at the points of each experiment to obtain data on the soil water regime during the growing season. Soil density was measured by the cylinder method using an Eijkelkamp drill (Netherlands), which helped to assess the impact of different tillage technologies on soil structure. Capillary moisture capacity was determined in the laboratory using soil samples from the relevant layers. The depth of the root system was recorded with a RootMeter profilometer (Germany) during critical phases of plant growth. The dynamics of the normalised difference vegetation index (NDVI) was recorded by a DJI Phantom 4 Multispectral drone (China) to assess the condition of plants and photosynthesis intensity. The yield was determined by weighing on a CAS CI-2001A scale (South Korea) after harvesting. Water and fertiliser consumption was monitored by Maddalena Woltman meters (Italy), water loss through evaporation was determined by ETgage® Model A sensors (USA), and fuel consumption was recorded by Flowmate fuel meters (Japan), which helped to comprehensively assess the effect of the applied technologies on water regime, soil physical properties, plant development, and economic efficiency.

Water use efficiency (*WUE*) was calculated as the ratio of yield to total water consumption for transpiration and evapotranspiration (1):

$$WUE = \frac{Y}{ET}, \tag{1}$$

where *Y* is the yield (kg/ha); *ET* is the total water consumption for transpiration and evaporation (m^3/ha).

To assess the economic efficiency, net profit was calculated as the difference between the value of gross output and total costs (2):

$$NP = G - C. \quad (2)$$

Profitability was calculated using the following formula (3):

$$CR = \frac{NP}{C} \times 100\%, \quad (3)$$

where *NP* is the net profit; *G* is the gross production value; *C* is the total costs (UAH/ha).

Statistical processing of the data was performed using one-factor analysis of variance (ANOVA) to compare the average yield, *WUE*, *NP*, and *CR* between the variants. In case of violation of the assumptions of normal distribution or homogeneity of variances, the non-parametric Kruskal-Wallis test was used. The analysis was conducted in the *R* software environment (version 4.3.0), with data reliability checks for omissions and abnormal values. The level of statistical significance was set at $p < 0.05$.

RESULTS

Analysing the efficiency of modern agricultural technologies requires a comprehensive approach, as the effectiveness of maize cultivation is determined not by one single parameter, but by the interaction of several interrelated factors. First and foremost, the physical properties of the soil – its moisture content, density, and capillary water capacity – play a significant role, as they shape the water-air regime and create the basis for the development of the root system. The depth of root penetration directly depends on these characteristics: looser and more moist soil provides plants with access to moisture and nutrients at different levels of the profile. As a result, vegetative development changes, which is reflected in the NDVI index, an integral indicator of photosynthetic activity and leaf condition. NDVI correlates with yield, which is the final criterion for the effectiveness of agrotechnical solutions. Therewith, the resource component should also be considered, which determines the economic feasibility of implementing a particular technology. It includes water and fertiliser consumption, the level of their losses, and fuel consumption, which together form the cost of production and affect the profitability of the farm. Thus, to objectively assess the effectiveness of agricultural technologies, it is necessary to simultaneously consider soil, biological, and economic indicators, identify correlations between them and determine which technologies provide the optimum balance between yield, resource efficiency, and sustainability.

Conventional irrigation in the control variant provided relatively low moisture content – 22 m^3/ha in the top layer and 18 m^3/ha in the deep layer. This result is conditioned by the intense disturbance of the soil structure during continuous cultivation: the surface layer dries faster, and water is absorbed unevenly, which reduces the ability of the soil to retain moisture in critical horizons for the root system. In the MZURI variant without reclamation, where belt cultivation with simultaneous sowing was used, an increase in moisture content of up to 25 m^3/ha in the top layer and 20 m^3/ha in the deeper layer was observed. This is because belt cultivation disturbs the soil only in the rows, leaving the row spacing relatively stable and less compacted. This partial disturbance of the structure reduces evaporation and improves the capillary supply of water to the roots. The greatest moisture values were recorded when MZURI was applied in combination with Netafim Uniram™ drip irrigation – 28 m^3/ha in the top layer and 24 m^3/ha in the deep layer. Drip irrigation provides a point supply of water without unnecessary losses due to evaporation and penetration into unnecessary horizons, which allows plants to use the available moisture more efficiently. Furthermore, uniform moistening of the root-bearing horizons promotes better root development and stabilises the soil microstructure. The Bauer Rainstar E precision sprinkler variant provided an analogous moisture level of 27 m^3/ha, demonstrating that the combination of belt cultivation with localised water application also contributes to moisture conservation, although some water may be lost to evaporation if irrigation is less precise.

The control variant with conventional irrigation and continuous cultivation had a density of 1.32 g/cm^3. This high value indicates a more compacted soil structure, which is a consequence of the intense mechanical impact of cultivation. Compaction restricts porosity, reduces aeration, and inhibits the movement of water into deeper horizons, which negatively affects root development and water use efficiency. In the MZURI variant without reclamation, the density decreased to 1.28 g/cm^3, reflecting improved structural stability of the soil. This is caused by the use of strip tillage, which disturbs only a part of the soil profile and leaves the row spacing relatively undisturbed. Lower compaction promotes better aeration, facilitates capillary water movement, and provides favourable conditions for the growth of the maize root system. Even lower density values were observed in the variants with MZURI combined with Netafim Uniram™ drip irrigation and Bauer Rainstar E precision sprinkling – 1.26 g/cm^3 and 1.25 g/cm^3, respectively. This significant reduction in density reflects the increased porosity and aeration of the soil, which provides optimum conditions for water penetration, nutrient transport, and the development of a branched root system. The combination of belt cultivation with precision water supply or deep loosening allows maximising the physical properties of the soil, combining minimal mechanical disturbance with efficient water supply.

In the control variant with conventional irrigation, the capillary water capacity was 21 m^3/ha. This limited water retention is explained by soil compaction and intense mechanical impact during continuous tillage. The disturbed structure reduces porosity and inhibits the uniform infiltration of water into deeper horizons, which makes it difficult for plants to access moisture during dry periods. The use of MZURI without reclamation increased the capillary water capacity to 24 m^3/ha, which demonstrates an improvement in soil structure and its ability to store moisture. Belt tillage disturbs only a part of the soil profile, leaving the row spacing relatively undisturbed, which reduces compaction, increases porosity, and facilitates more efficient water movement to plant roots. Even greater values were obtained in the variants with a combination of MZURI and modern irrigation systems: Netafim Uniram™ drip irrigation provided 27 m^3/ha, while Bauer Rainstar E precision sprinkling – 26 m^3/ha. This demonstrates the effective preservation of water in the soil due to the point supply of moisture and the optimisation of soil physical properties. Drip irrigation minimises water loss due to evaporation, evenly moistens the root horizons, and creates favourable conditions for the development of a powerful root system. Summarising the results of the preliminary analysis, the study assessed changes in the moisture content of the top and deep soil layers, its density, and capillary moisture capacity, which helped to comprehensively compare the effectiveness of different tillage and irrigation technologies in providing plants with moisture and creating favourable conditions for the development of the root system (Table 1).

Table 1. *Key physical properties of the soil under different tillage and irrigation options*

Technology variant	Moisture content, m^3/ha (top layer/depth)	Density, g/cm^3	Capillary moisture capacity, m^3/ha
Control (conventional sprinkling)	22/18	1.32	21
MZURI without land reclamation	25/20	1.28	24
MZURI + Netafim Uniram™ drip irrigation	28/24	1.26	27
MZURI + precision sprinkling Bauer Rainstar E	26/22	1.25	26

Source: *compiled by the authors of this study*

The analysis of the data obtained showed a close relationship between the three indicators – with a decrease in soil density, there is a simultaneous increase in moisture in the upper and deep layers and an increase in capillary moisture capacity. In the control variant with a density of 1.32 g/cm^3, the lowest values of moisture content (22/18 m^3/ha) and water capacity (21 m^3/ha) were recorded, indicating limited infiltration and water retention. The transition to MZURI without reclamation reduced the density to 1.28 g/cm^3, which gave an increase in moisture content (25/20 m^3/ha) and capillary water capacity (24 m^3/ha). The best result was obtained in the MZURI variant with drip irrigation – the minimum density of 1.26 g/cm^3 was accompanied by the greatest values of moisture (28/24 m^3/ha) and moisture capacity (27 m^3/ha). A comparable trend, albeit slightly lower, was shown by the variant with precision sprinkling (26/22 m^3/ha at a density of 1.25 g/cm^3). Thus, all three indicators demonstrated a consistent trend: a decrease in soil density creates conditions for the accumulation and better retention of moisture, which ensures uniform water supply to the root system and increases irrigation efficiency. To determine the conditions for the development of the maize root system, the relationship between soil density and root penetration depth under different tillage and irrigation technologies was investigated (Fig. 1).

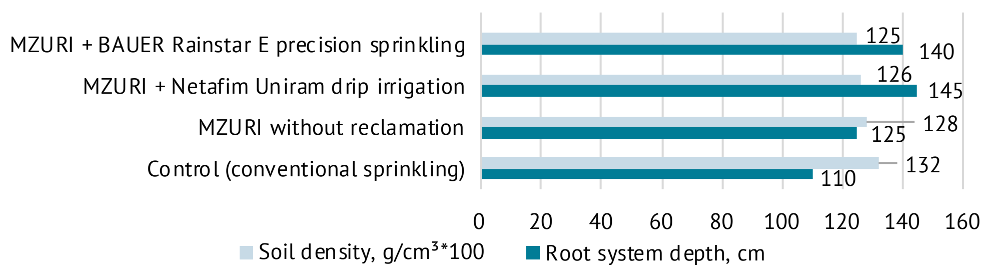

Figure 1. *Effect of soil density on the depth of the maize root system*

Source: *compiled by the authors of this study*

The analysis of the results revealed a clear relationship between soil density and the development of the maize root system. In the control variant with conventional sprinkling, the greatest soil density was recorded (1.32 g/cm^3), which limited root penetration to a depth of 95 cm. This combination of indicators reflects excessive compaction of the soil profile, which reduces porosity, impairs water and air permeability, and leads to limited access of plants to moisture and nutrients in deeper horizons. In the MZURI variant without reclamation, a reduction in density to 1.28 g/cm^3 increased the depth of the root system to 102 cm. This confirms that even a moderate reduction in compaction promotes more active root growth in depth, which improves their ability to use soil moisture. The most pronounced effect was observed when combining MZURI technology with Netafim Uniram™ drip irrigation, where the density decreased to 1.26 g/cm^3 and the root system reached 110 cm. An analogous result was obtained in the Bauer Rainstar E precision sprinkler variant (1.25 g/cm^3; 108 cm). Thus, there is a stable inverse relationship: as soil density decreases, the depth of root penetration increases. This confirms that optimisation of soil physical properties in combination with modern irrigation systems creates conditions for deeper root development, which increases *WUE* and nutrient uptake, ensures drought resistance of maize, and contributes to greater yields. To assess the vegetative state of plants and its impact on productivity, the study analysed the dynamics of the NDVI index in combination with maize yield (Fig. 2).

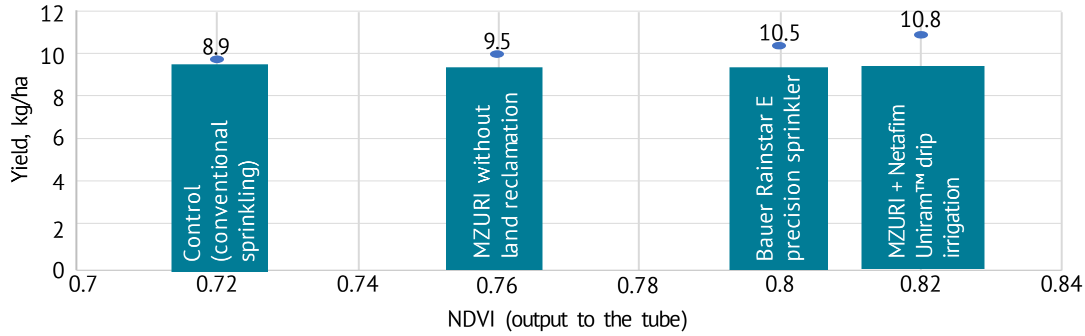

Figure 2. *Relationship between NDVI index and maize yield under different technologies*
Source: *compiled by the authors of this study*

The analysis of the obtained results revealed a close relationship between the dynamics of NDVI and maize yield. In the control variant with conventional sprinkling, the lowest NDVI values were observed at all vegetation stages (0.58-0.72), which was reflected in the minimum yield of 8.9 t/ha. This is explained by soil compaction and uneven distribution of moisture, which limits the development of the root system and reduces *WUE* and nutrients. The use of MZURI without reclamation contributed to an increase in NDVI (up to 0.76 at the tube stage) and a yield increase of up to 9.5 t/ha, which indicates improved water and nutrient supply due to more favourable soil physical properties. The greatest NDVI values (0.82) were recorded in the MZURI variant with drip irrigation, which correlated with the maximum yield of 10.8 t/ha. A comparable result was shown by precision sprinkling with Bauer Rainstar E (NDVI up to 0.8; yield 10.5 t/ha), which confirms the effectiveness of modern localised irrigation technologies. Thus, there is a direct correlation: an increase in NDVI at all stages of the growing season is accompanied by an increase in yield, while optimisation of water supply and improved soil aeration create conditions for more intensive plant growth. This proves that the integration of innovative tillage and irrigation technologies ensures not only a stable increase in NDVI, but also a sustainable increase in maize productivity in the southern steppe. To assess the feasibility of introducing modern tillage and irrigation systems, the study calculated the economic efficiency of agricultural technologies, as well as *WUE*, which reflects the productivity of the moisture used (Table 2).

Table 2. *Water, fertiliser, and fuel consumption for different cultivation and irrigation technologies*

Technology variant	Water, m^3/ha	Water losses, m^3/ha	Fertilisers, kg/ha	Fuel, l/ha
Control (conventional sprinkling)	4,200	480	180	6.5
MZURI without land reclamation	3,800	360	175	5
MZURI + Netafim Uniram™ drip irrigation	3,500	250	170	5.8
MZURI + precision sprinkling Bauer Rainstar E	3,600	270	172	6

Source: *compiled by the authors of this study*

The analysis of the table shows a clear relationship between tillage technologies, irrigation systems, and resource use efficiency. In the control variant with conventional sprinkling, water consumption was 4,200 m^3/ha, water losses were 480 m^3/ha, fertiliser was 180 kg/ha, and fuel was 6.5 L/ha. This suggests a prominent level of resource intensity associated with continuous cultivation and uneven distribution of water, which leads to excessive losses and low efficiency. The use of MZURI technology without reclamation reduced water consumption by up to 3,800 m^3/ha, losses by up to 360 m^3/ha, fertiliser by up to 175 kg/ha, and fuel by up to 5 L/ha, demonstrating savings due to the localisation of strip tillage and simultaneous sowing. The combination of MZURI with Netafim Uniram™ drip irrigation provided the lowest water consumption (3,500 m^3/ha) and minimum water loss (250 m^3/ha), while reducing fertiliser application to 170 kg/ha, although fuel consumption increased slightly to 5.8 L/ha due to irrigation system maintenance. The Bauer Rainstar E precision sprinkler variant showed intermediate results: water consumption of 3,600 m^3/ha, water loss of 270 m^3/ha, fertiliser – 172 kg/ha, and fuel – 6 L/ha.

Overall, there is a direct correlation between the accuracy and localisation of irrigation and resource savings: the more precisely water and fertiliser are applied, the lower the losses and the lower the costs. Additionally, the integration of MZURI reduces fuel costs by reducing the intensity of tillage, and the combination with drip or precision sprinkling ensures a balance between energy consumption and the efficiency of water supply and plant nutrition. Thus, the integrated use of strip tillage and modern irrigation systems increases resource efficiency and contributes to sustainable farming (Shebanin *et al.,* 2025). For a comprehensive assessment of the effectiveness of agrotechnologies, economic indicators such as *NP* and *CR* were analysed in combination with the *WUE* indicator. *WUE* was calculated using the formula (1) as the ratio of maize yield (*Y*, kg/ha) to total water use (*ET*, m^3/ha), including water applied through irrigation and the effective fraction of precipitation actually available to plants. Two key indicators were determined in the experiment: net profit (*NP*, UAH/ha) and profitability (*CR*, %), which were calculated using formulas (2)-(3). This helped to simultaneously assess the financial return and water efficiency of different tillage and irrigation options, which is essential in the arid Southern Steppe (Table 3).

Table 3. *Economic efficiency of agricultural technologies and water efficiency*

Technology variant	*NP*, UAH/ha	*CR*, %	*WUE*, kg/m^3
Control (conventional sprinkling)	15,200	45	2.12
MZURI without land reclamation	17,000	50	2.5
MZURI + Netafim Uniram™ drip irrigation	21,000	62	3.09
MZURI + precision sprinkling Bauer Rainstar E	20,000	58	2.92

Source: *compiled by the authors of this study*

The analysis of the presented data revealed a clear correlation between economic efficiency and water efficiency of the applied technologies. Compared to the control, the use of MZURI without land reclamation increases net profit by 1,800 UAH/ha and profitability by 5%, while increasing *WUE* to 2.5 kg/m^3, which indicates a more rational use of water and resources. The combination of MZURI with drip irrigation delivers the greatest *NP* of 21,000 UAH/ha, *CR* of 62%, and *WUE* of 3.09 kg/m^3, demonstrating that point-of-use water delivery simultaneously increases financial returns and water productivity. The Bauer Rainstar E precision sprinkler variant also significantly outperformed the benchmarks, although slightly behind drip irrigation, with *NP* 20,000 UAH/ha, *CR* 58%, and *WUE* 2.92 kg/m^3. The increase in profitability and profitability correlates with the increase in water efficiency, which confirms the effectiveness of integrating modern tillage technologies and localised or precision irrigation to optimise resources and economic outcomes. MZURI technology in combination with Netafim Uniram™ drip irrigation demonstrates the greatest efficiency among all the tested options, as it provides the best performance by all criteria. It helps to improve the physical and chemical properties of the soil, increases the depth and weight of the root system, supports uniform plant development, which is reflected in high NDVI values, increases yields and reduces water and fertiliser consumption. Additionally, this technology allows achieving better *WUE* and provides a considerable increase in economic return, net profit, and profitability. Taken together, this makes MZURI with Netafim Uniram™ drip irrigation the most optimum solution for resource-saving and cost-effective maize cultivation in the Southern Steppe.

The analysis of all the studied indicators revealed a close relationship between the physical properties of the soil, the development of the root system, vegetation indices, yield, and economic results of production. Reducing soil density in the variants with minimal tillage and reclamation measures is accompanied by an increase in moisture and capillary water capacity, which creates favourable conditions for the development of a deeper root system of maize. This provides better access to water and nutrients, which is confirmed by greater NDVI values and greater yields in drip and precision irrigation. At the same time, resource consumption has a clear link to economic efficiency: reduced consumption of water, fertiliser, and fuel directly translates into lower production costs and increased profitability. Specifically, MZURI's drip irrigation and precision sprinkler technologies combine optimum soil moisture and density with efficient use of resources to achieve the greatest net profit, profitability, and *WUE*. Thus, the results showed a systemic effect: improved soil conditions lead to more active root development, which increases water and nutrient supply, which is reflected in greater NDVI and yields, while economic efficiency increases due to more efficient use of resources. This sequence confirms that land reclamation technologies can simultaneously ensure environmental sustainability and economic benefits for agricultural production.

DISCUSSION

A study of the integration of MZURI technology into a precision farming system in the south of Ukraine found that strip-till improved soil moisture retention. The use of minimal tillage and localised fertilisation helped to reduce evaporation and erosion, which was particularly significant due to the low rainfall and hot temperatures in the region. Preserving the soil structure also positively influenced its aeration and water permeability, which together maintained soil fertility. G. Taye *et al.* (2024) also studied this problem, confirming that the analysis of the impact of technology on moisture conservation and soil structure improvement shows that modern agricultural practices help reduce evaporation and erosion. Improving the soil structure increases its permeability and ability to retain moisture. This creates more favourable conditions for plant growth and increases their resistance to drought. M. Rozewicz *et al.* (2024) also showed that agrophysical changes in the soil when using strip-till technology demonstrate an improvement in the porosity and aeration of the topsoil. This method reduces compaction and promotes the development of the root system, which positively influences crop productivity. The introduction of strip-till increases resource efficiency and yield stability. M. Li *et al.* (2024) confirmed that the integration of strip-till with precise local application of water and fertiliser increases resource efficiency and yield stability in dry conditions. The introduction of these technologies also reduces the risk of soil erosion and degradation in the long term. Additionally, the adaptation of agricultural practices to specific climate and soil conditions ensures an optimum balance between productivity and ecosystem conservation. Notably, the implementation of moisture conservation technologies is not always a one-size-fits-all solution and requires adaptation to concrete climatic conditions and soil types. The effectiveness of such methods depends on the right combination of agricultural practices and regular monitoring of soil conditions. Therefore, an integrated approach to soil management is key to achieving sustainable results in agriculture.

Additionally, the introduction of modern reclamation equipment, including drip irrigation with automatic control, demonstrated the efficient use of water resources. Automation of irrigation using GPS and humidity sensors reduced excessive water consumption and ensured optimum conditions for plant growth. Localised fertilisation through fertigation systems increased the efficiency of plant nutrition, reducing the negative environmental impact. A. Abioye *et al.* (2023) concluded that the evaluation of the efficiency of automated drip irrigation shows a considerable reduction in water consumption due to the precise dosing of moisture according to plant needs. This system avoids waterlogging and reduces losses due to evaporation and runoff. As a result, crop productivity increases and the pressure on water resources decreases. A. Jiménez *et al.* (2022) found that the use of smart irrigation systems using GPS and IoT opens new opportunities for real-time monitoring of field conditions. These technologies allow accurately identifying areas with different water needs and automatically adjusting the irrigation regime. This approach contributes to a noticeable increase in water conservation and agricultural production efficiency. M. Seyar & T. Ahamed (2024) additionally showed that the integration of soil moisture sensors and automatic irrigation control systems provides more uniform moisture and reduces energy consumption for water supply. This enables optimised resource use on a farm-wide basis. Furthermore, the use of intelligent irrigation systems helps reduce the risk of plant stress during dry periods. These results confirm the study presented above, as automated drip irrigation does provide more precise water management. It allows adapting the water supply to the changing needs of plants in different growth phases, which reduces overall water consumption. Thus, the introduction of such systems is a major step towards the sustainable use of water resources in agriculture.

The use of strip-till technology helped to improve moisture storage in deeper soil layers. This was essential for providing plants with water during dry periods, which is typical for the southern regions of Ukraine.

Furthermore, such measures helped to reduce soil compaction and improve soil structure, which positively influenced the development of the root system of crops. M. Pulido-Moncada *et al.* (2021) showed that the destruction of compacted soil layers improves its water permeability. This increases the accumulation of moisture in deeper horizons and reduces its loss through surface runoff. As a result, the availability of water to the root system of plants increases, which positively influences their development and yield. Additionally, the efficiency of soil cultivation largely depends on the technical characteristics and design parameters of machine and tractor units. V. Hruban *et al.* (2025) showed that optimisation of the design parameters of rotary tillage units under variable loads can increase their stability and productivity. It was established that the optimum angle of attack of the working bodies (20-30°C) reduces soil resistance and contributes to an even distribution of loads. Changing the curvature radius of the working elements reduces stress concentration and increases their durability. The use of special alloy steels containing chromium and manganese increases wear resistance, reduces maintenance requirements, and extends the service life of the units. A crucial design solution was the introduction of rubber shock absorbers at the mounting points, which reduced the amplitude of vibrations and increased the stability of the equipment. As a result, the improved machines ensure uniform distribution of the tillage depth, reduce soil compaction, save fuel, and improve crop growth conditions.

Y. Yang *et al.* (2023) concluded that a combination of different tillage methods optimises soil physical properties. This approach contributes to the development of a more stable structure that better retains moisture and prevents erosion. This improves the soil's water-saving properties, which is essential for maintaining productivity even in dry conditions. S. El-Hendawy *et al.* (2022) also noted that the use of strip-till in combination with mulching the soil surface reduces evaporation and promotes more even water penetration. This helps to create optimum conditions for the development of the root system even during long periods of dry weather. Additionally, this integration of agronomic practices increases plant resistance to drought and improves overall yields. These findings are consistent with the theses presented in the previous section, as they confirm the effectiveness of measures aimed at improving water permeability and increasing soil moisture reserves. They demonstrate that removing compacted layers contributes to a more even distribution of water and reduces the risk of water loss. This underlines the significance of such mechanisms for ensuring a stable water balance and increasing yields in the face of climate change.

The use of precision farming systems enabled high-precision monitoring of field conditions using mapping, UAVs, and sensors. This allowed differentially controlling irrigation and fertilisation rates depending on the concrete conditions of each field. As a result, the overall efficiency of resource use increased and losses were reduced, increasing the economic viability of the technology in the region. E. Bwambale *et al.* (2022) also confirmed that the use of precision farming technologies to monitor soil moisture and fertility enables real-time, detailed data on field conditions. This allows promptly responding to changes and optimising agronomic practices, which increases overall production efficiency. The use of such technologies contributes to a more rational use of resources and reduces losses. M. Padhiary *et al.* (2024) also found that the use of GPS navigation and unmanned aerial vehicles provides accurate and adaptive irrigation and fertilisation management. These tools can create maps of fields with different cultivation intensities that factor in the local soil and vegetation characteristics. This helps to increase yields and water conservation, while reducing the negative impact on the environment. H. Shahab *et al.* (2025) showed that the integration of sensor networks and real-time data analysis allows predicting plant water and nutrient needs with high accuracy. This helps to plan agrotechnical measures based on the actual condition of plants and soil, rather than on standard regulatory values. The use of such integrated approaches increases the efficiency of resource conservation and yield stability. Comparing the data obtained during the research, it can be concluded that precision farming technologies markedly increase the efficiency of water and fertiliser use. They allow not only controlling soil conditions but also adapting agrotechnical measures to the concrete conditions of each site. Thus, the introduction of such innovative approaches is a key factor for sustainable agricultural development.

The benefits of integrating MZURI technology with modern land reclamation systems in southern Ukraine resulted in a considerable increase in yields while reducing the cost of fuel and lubricants, water, and fertilisers. Additionally, the integrated approach contributed to the improvement of the ecological state of agricultural landscapes: erosion was reduced, soil fertility was maintained, and the system became more resilient to climate challenges such as droughts. G. Branca *et al.* (2021) concluded that the integration of modern technologies into agricultural production in the southern region brings significant economic benefits by increasing yields and reducing input costs. At the same time, it helps to reduce negative environmental impacts through the rational use of water and preservation of soil fertility. This approach helps ensure the sustainable development of the agricultural sector without depleting natural resources. S. Haque *et al.* (2025) found that climate resilience of agricultural systems increases due to the integrated application of modern land reclamation and precision technologies that enable adaptation to changing weather conditions. They help to improve the water-saving properties of the soil and optimise fertiliser application, which reduces the risks of droughts and floods. As a result, the agricultural sector is becoming more resilient and prepared for the challenges of climate change. A. Djalilov *et al.* (2022) showed that the integration of strip-tills with automated irrigation systems can markedly increase the efficiency of water and fertiliser use. This leads to reduced energy consumption and increases economic profitability of production. Furthermore, the integrated use of such technologies maintains yield stability and contributes to the long-term preservation of soil fertility in arid conditions.

When analysing the results of the conducted study, it is clear that the economic benefits of introducing the latest technologies are directly related to their environmental efficiency. The rational use of resources reduces production costs while reducing the negative impact on the environment. This underlines the significance of a comprehensive approach to agricultural modernisation, especially in the southern region with its specific climate challenges. At the same time, the study found that the application of this technology required extensive initial investment in specialised equipment and training. It also took some time for soils and plants to adapt to the new cultivation conditions, during which a temporary decline in yields was observed. However, considering the long-term benefits, overcoming these barriers seemed to be fully justified and promising for the development of agricultural production in the southern regions of Ukraine.

CONCLUSIONS

The results of the study revealed that the use of strip tillage and various irrigation systems significantly affected the water regime, physical properties of the soil, root system development, productivity, and economic efficiency of maize cultivation. The greatest soil moisture was recorded in the MZURI + drip irrigation (Netafim Uniram™) variant: at a depth of 0-20 cm – 28 m^3/ha, 20-40 cm – 24 m^3/ha, while the control variant had 22 m^3/ha and 18 m^3/ha, respectively. Soil density decreased in all MZURI variants, with the lowest value of 1.25 g/cm^3 observed in the MZURI + Bauer Rainstar E precision sprinkler variant compared to the control at 1.32 g/cm^3. The capillary water capacity increased to 27 m^3/ha under drip irrigation, which was 6 m^3/ha greater than the control. The depth of the root system was maximum in the drip irrigation variant – 110 cm, while in the control it was 95 cm. The NDVI in the dynamics of growth was also greater in the variant of Netafim Uniram™ – 0.82 against 0.72 in the control, reflecting a better vegetative state of the plants. Maize yield was the greatest in drip irrigation – 10,800 kg/ha, which is 1,900 kg/ha more than in the control. Water consumption was optimum for strip-till with drip irrigation at 3,500 m^3/ha versus 4,200 m^3/ha in the control, while water losses were reduced to 250 m^3/ha (control: 480 m^3/ha). Fertiliser consumption was also slightly reduced to 170 kg/ha. Fuel consumption stayed relatively low at 5.8 L/ha in the Netafim Uniram™ variant, while the control used 6.85 L/ha.

WUE was greatest in drip irrigation at 3.09 kg/m^3, which was 0.97 kg/m^3 greater than the control. The economic efficiency was also greater: the net profit in this variant was 21,000 UAH/ha with a profitability of 62%, while the control provided 15,200 UAH/ha and 45%, respectively. The MZURI + precision sprinkling variant also showed a significant improvement over the control, but slightly lower than the drip irrigation, with a yield of 10,500 kg/ha, *WUE* of 2.92 kg/m^3, and a net profit of 20,000 UAH/ha. Thus, the study confirmed that the use of strip tillage in combination with Netafim Uniram™ drip irrigation provides the best indicators of water regime, soil physical properties, root system development, yield, and economic efficiency among all tested variants. The limitation of this study was that its findings were based mainly on short-term experiments, which may not fully reflect the real conditions of long-term application of the technology in diverse soil and climatic zones. For further development of the topic, it is necessary to investigate the long-term impact of integrating MZURI technology with modern land reclamation equipment on soil quality and biodiversity of agroecosystems in the southern regions of Ukraine.

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Інтеграція сучасної меліоративної техніки в систему точного землеробства за технологією MZURI в умовах півдня України

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Анотація. Мета дослідження полягала у вивченні можливостей підвищення ефективності сільськогосподарського виробництва на півдні України шляхом використання сучасної меліоративної техніки у поєднанні з технологією точного землеробства для покращення водного режиму ґрунтів і стійкості агроекосистем. У дослідженні застосовано експериментальний підхід із варіацією обробітку ґрунту та зрошення, визначенням фізико-водних властивостей ґрунту, розвитку кореневої системи й стану рослин, урожайності, ресурсних витрат і економічних показників для комплексної оцінки ефективності агротехнологій. Встановлено, що стрічковий обробіток ґрунту, польова система точного обробітку з рядковим розташуванням рослин, у поєднанні з краплинним зрошенням Netafim Uniram забезпечував найвищу вологість ґрунту на 0-20 та 20-40 см (28 та 24 м^3/га), знижував щільність ґрунту до 1,26 г/см^3 і підвищував капілярну вологоємність до 27 м^3/га. Глибина кореневої системи досягала 110 см, а нормалізований різницевий вегетаційний індекс становив 0,82. Урожайність сягала 10,8 т/га, ефективність використання води (WUE) – 3,09 кг/м^3, чистий прибуток – 21 тис. грн/га, рентабельність – 62 %. Варіант з використанням польової системи точного обробітку з рядковим розташуванням рослин та точного дощування Bauer Rainstar E показав урожайність 10,5 т/га, що дещо нижче максимального результату, проте перевищувало показник контролю. Польова система точного обробітку з рядковим розташуванням рослин без меліорації дала урожайність 9,5 т/га, тоді як традиційне зрошення (контроль) демонструвало найнижчі результати – 8,9 т/га. Дані засвідчили, що інтеграція стрічкового обробітку з сучасними системами зрошення підвищує продуктивність і економічну ефективність кукурудзи

Ключові слова: посушливі умови; зрошення; урожайність; водозбереження; енерговитрати

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The impact of climate change on the forage base in the Republic of Moldova

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Abstract. The study aimed to determine the optimal conditions for using biological products to improve the agroecological efficiency of grain crops, by analysing their impact on plant physiological processes, productivity and soil resources. The study presented the results of the study of the influence of biological products on the yield, product quality, dynamics of plant development phases and soil microflora composition when growing barley of the Helios variety and buckwheat of the Antaria variety in the South of Ukraine. The experiment was conducted using nitrogen-fixing, mycorrhizal and phosphate-mobilising biological products, both individually and in combination, with the establishment of control and experimental plots. The analysis included an assessment of yields, protein content in grain, changes in plant development stages and the activity of soil microorganisms. The results of the study demonstrated that the use of biological products provided a significant increase in yields: barley showed an increase of 20-25%, and buckwheat – by 18-22% compared to the control plots. The protein content of the grain also increased, reaching 12% for barley and 14% for buckwheat. The duration of plant development phases was

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reduced, which contributed to more efficient use of soil resources and optimisation of growth processes. Changes in the composition of soil microflora were particularly noticeable: the number of nitrogen-fixing bacteria increased by 40% and phosphate-mobilising – by 50%, which improved the availability of nutrients for plants. The highest results were achieved when using combinations of biological products that demonstrated a synergistic effect, increasing crop productivity and improving product quality. The results confirmed the effectiveness of biological products in creating sustainable agroecosystems, ensuring environmental safety, reducing the need for chemical fertilisers and increasing the economic profitability of agricultural production. The use of biological products is a promising area for optimising modern agricultural technologies in regions with unfavourable soil and climatic conditions

Keywords: agrotechnology; yield; agroecosystems; environmental sustainability; organic nutrition

INTRODUCTION

In the context of an escalating global climate crisis, the forage base of agriculture is facing increasing challenges, particularly in countries with vulnerable ecological and agricultural systems such as the Republic of Moldova. Climate-related impacts – including loss of livelihoods, food and water insecurity, and adverse effects on human capital – combined with poverty and inequality, pose serious threats to agricultural sustainability. Where climate stressors intersect with other economic and environmental pressures, compound risks emerge, intensifying vulnerability, exacerbate grievances, and deepen existing fragility (IPCC..., 2023). The risk of internal displacement, migration, and rural instability due to environmental degradation has also been increasingly documented (Koubi *et al.*, 2021).

Weather instability, rising average temperatures, more frequent droughts, and irregular precipitation patterns are negatively affecting the cultivation of forage crops by reducing both their yield and nutritional quality. Studies such as that by R. Prăvălie *et al.* (2020) have highlighted that forage production systems in Eastern Europe are particularly sensitive to seasonal droughts, which lower biomass yields and disrupt nutrient cycling. Likewise, research by A. Iglesias & L. Garrote (2019) emphasised that precipitation variability has become the primary driver of forage yield reductions across Southern and Eastern Europe, including Moldova, with extreme weather events now occurring more frequently. This directly impacts the productivity of the livestock sector, as feed is a critical factor in maintaining animal health and performance. S. Ruban *et al.* (2024) have shown that nutrient imbalances in forage under climate-induced stress led to suboptimal animal productivity, especially among ruminants. Additionally, C.M. Godde *et al.* (2021) reported that forage crops exposed to elevated CO_2 and temperature scenarios tend to develop altered fibre composition, reducing digestibility and thus limiting feed efficiency.

The lack of a stable forage base increases dependence on imported feed resources and raises production costs, thereby reducing the economic viability of farms and amplifying food security risks. In support of this, M. MacLeod *et al.* (2023) identified forage instability as a key economic risk factor in livestock supply chains in marginal regions. Under these conditions, it becomes crucial to develop adaptive strategies aimed at preserving and restoring forage productivity, introducing stress-resistant crop varieties, and improving agronomic practices in line with new climatic realities. Studying the impact of climate factors on the forage sector is an essential scientific priority that can support sustainable agricultural development and ensure food security in the region. The objective of the study is to examine how climate variability – particularly changes in temperature and precipitation patterns – affects forage crop cultivation and the resulting implications for livestock production in the Republic of Moldova.

MATERIALS AND METHODS

From 2020 to 2023, a four-year study was conducted in three representative agricultural zones of the Republic of Moldova: Briceni (north), Chișinău (centre), and Cahul (south). These areas were purposefully selected due to their distinct microclimatic and pedological conditions, enabling a comparative analysis of climate impacts on forage production and livestock productivity. The study employed a multidisciplinary methodology that integrated climatological, agronomic, and zootechnical data with literature-based synthesis. Climatic data – including average monthly and annual air temperatures, precipitation levels, and drought occurrence, were obtained from the State Hydrometeorological Service of Moldova (n.d). Data from three meteorological stations corresponding to the selected regions were used to ensure spatial representativeness. The collected data were analysed in relation to the vegetative stages of key forage crops – such as alfalfa, maize for silage, and perennial grasses – with emphasis on deviations from climatic norms and their impact on biomass accumulation.

Agronomic data on forage yield (t/ha) were extracted from field trial reports and official agricultural statistics published by the National Bureau of Statistics of the Republic of Moldova (n.d.) (NBS). Changes in feed quality indicators were used to estimate implications for ruminant nutrition and productivity. Data on livestock production were also sourced from NBS reports and included annual production volumes of milk (litres/cow/year), meat (kg/live weight per animal), and wool (kg/sheep/year). These indicators were analysed in conjunction with forage availability to assess indirect effects of climate anomalies on animal productivity. Where appropriate, analysis was conducted using Microsoft Excel and SPSS (v.26), to quantify the relationships between climate parameters and production outcomes. In addition, Moldovan and international peer-reviewed literature published in the last five years was reviewed to contextualise experimental findings and reinforce methodological validity. The integration of quantitative field data with scientific literature ensured a robust interpretation of climate impacts on the forage-livestock system of Moldova, thereby strengthening the relevance of the proposed adaptation strategies.

RESULTS AND DISCUSSION

The Republic of Moldova is located in the central part of Europe, in the north-eastern Balkans, and covers an area of 33,843.5 km^2. It lies within a moderately continental climatic zone, which is somewhat modified by its proximity to the Black Sea and the influence of warm, humid air masses from the Mediterranean region. According to Law of Republic of Moldova No.438 on "Regional development in the Republic of Moldova" (2006), it was customary to distinguish three main geographical zones – North, Centre, and South (Fig. 1).

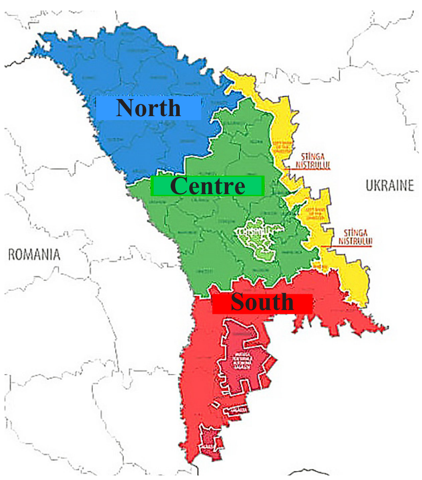

Figure 1. *Geographical areas*
Source: *Law of Republic of Moldova No.438 on "Regional development in the Republic of Moldova" (2006)*

These regions increasingly face unstable meteorological conditions, with drought and rising temperatures becoming the norm in recent decades. Both low and high temperatures negatively impact the plant growth and development, resulting in yields below the actual productive potential of the given crop. The data in Figure 2 show that at temperatures up to +18°C, plants grow very slowly, while temperatures around +22°C enhance plant development. However, the ideal temperatures for most plants range between +22°C and +28°C. Temperatures of +28°C to +30°C reduce reproductive capacity, and at temperatures above +30°C, induced male sterility is observed (Fig. 2).

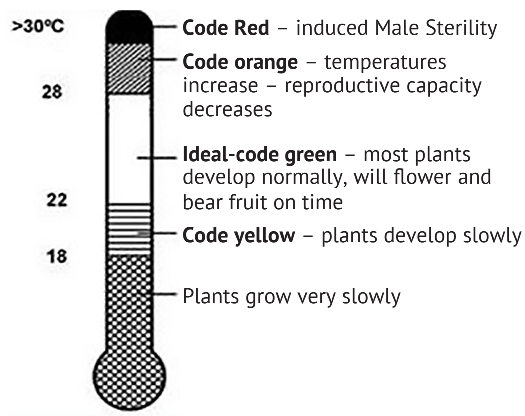

Figure 2. *Influence of temperatures of the Republic of Moldova*
Source: *Climate change knowledge portal (n.d.)*

Agriculture is the sector of the Moldovan economy most susceptible to climate change because of its strong dependence on weather conditions. One of the primary causes of erratic harvests and a natural risk to Moldovan agriculture is climate volatility. Climate conditions have a significant impact on agricultural production. In many parts of Europe, agricultural yields and livestock output are already being impacted by changes in the average temperature and precipitation, as well as weather and climatic extremes. According to research dating back to 1850, the temperature of the Earth and oceans has risen by an average of 0.06°C per decade, with the warming rate tripling since 1982 to approximately 0.20°C per decade (NOA, 2023; Yuan *et al.*, 2024). As L. Kumar *et al.* (2022) reported, climate change is an ongoing process, with spatially varying impacts. Agri-food production could be significantly impacted by projected climate change, either directly through altered temperature and precipitation patterns or indirectly through the effects of invasive plants, pests, and diseases, as well as by coastal flooding, soil salinisation, and invasive plant infestations.

Projections indicate that the agro-ecological zones (AEZs) of the Republic of Moldova will experience a moderate decrease in winter precipitation, ranging from -2.1% in the northern AEZ to -3.8% in the southern AEZ (Fig. 3). In contrast, a slight increase in spring precipitation is expected: from 3.5 to 5.7% in the northern AEZ and from 1.0 to 4.8% in the central AEZ, compared to the reference period of 1995-2014.

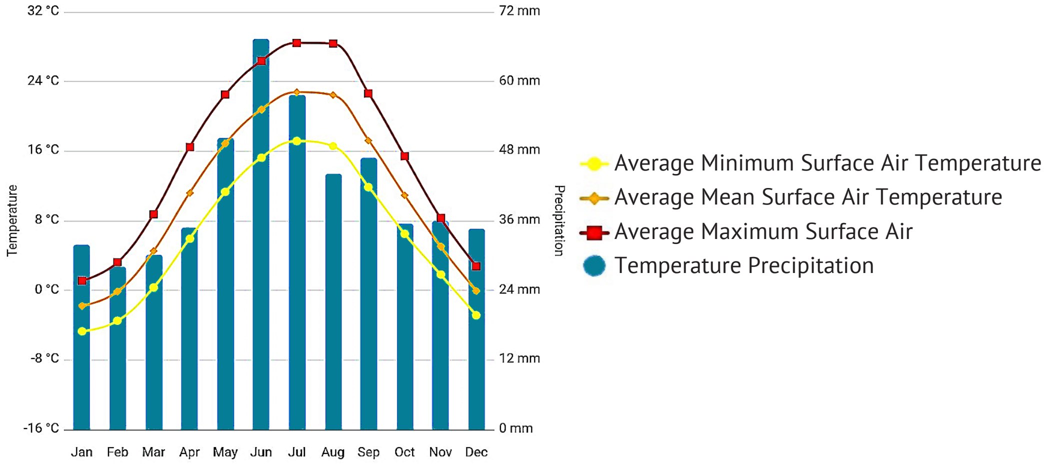

Figure 3. *Climate Projections for Agro-Ecological Zones of the Republic of Moldova*
Source: *Climate change knowledge portal (n.d.)*

By the end of the 21st century, winters in the Republic of Moldova are projected to become wetter. The largest increase in winter precipitation, according to the SSP5 – 8.5 scenario, is expected to reach 13.3% in the northern region, while the southern region will experience the lowest increase, at 2.4%, by the year 2100. Throughout much of the year, a significant precipitation deficit was recorded across the territory of the Republic of Moldova. Agro-meteorological conditions during most of the 2021 growing season were generally unfavourable for the development of major-agricultural crop yields due to high temperatures and a lack of rainfall. This trend has been observed consistently across all three geographical zones – North, Centre, and South (Table 1).

According to the geographical region of the country, the amount of precipitation (Table 2) was distributed as follows: North: 402-614 mm (60-85% of the norm), Centre: 430-666 mm (60-90% of the norm), South: 352-490 mm (55-75% of the norm).

Table 1. *Average air temperature by year depending on the geographical zone, °C*

Geographical zone	Years				On average over 4 years
	2020	2021	2022	2023	
North	10.7	8.9	10.1	11.0	10.2
Centre	12.7	10.6	11.7	12.7	11.9
South	13.1	11.4	12.5	13.3	12.6
Average per country	12.17 ± 0.74	10.30 ± 0.74	11.43 ± 0.71	12.33 ± 0.69	11.6 ±0.73

Source: *National Bureau of Statistics of the Republic of Moldova (n.d.)*

Table 2. *The Amount of precipitation per year, mm*

Geographical zone	Years			
	2020	2021	2022	2023
North	614	605	402	458
Centre	562	666	444	430
South	460	490	352	389
Average per country	545.33 ± 45,23	587.33 ± 51.59	399.33 ± 26.59	425.67 ± 20.04

Source: *National Bureau of Statistics of the Republic of Moldova (n.d.)*

This distribution demonstrates the variability in precipitation across Moldova's regions, with the southern part receiving the least amount, which is a critical factor in the context of drought and agricultural productivity. At the same time, agricultural lands have low resilience to the increasing incidence of extreme weather conditions. The country faces several environmental issues, such as landslides, soil erosion, deforestation, the spread of pests and diseases, and the invasion of plants and animals into agricultural lands, among others. The growth of forage crops under high temperatures, drought, or floods can induce stress responses in green plants, potentially affecting not only their yield but also their composition and, consequently, their nutritional value for ruminants. For example, studies have shown that forage quality declines with rising temperatures. Therefore, to ensure future livestock productivity, the forage crop sector must consider environmental effects on both crop yields and quality parameters (Hart *et al.*, 2022). More efficient use of resources means more products and other ecosystem services are produced per unit of resource input when livestock systems are intensified sustainably (Dubeux *et al.*, 2024).

Climate change may lead to the deterioration of certain ecosystems in some parts of the country, with many species exhibiting reduced reproductive capacity and increased susceptibility to other factors. To mitigate the effects of drought in agriculture, irrigation is employed (irrigated land – 3,110 km^2), drought-resistant plant species are cultivated, and various agronomic systems are implemented to reduce water loss from the soil. Drought years with high temperatures recur approximately every 2-3 years in Moldova. According to statistical data regarding the sown area for root crops intended for feed, the most unproductive year was 2022, with an average area of 5.67 hectares across the three geographical zones. The situation improved in 2023, reaching an average sown area of 9.33 hectares, largely due to increased precipitation levels in 2023, which averaged 425.67 mm compared to 399.33 mm in 2022 nationwide. Table 3 indicates that the Southern region had the smallest sown area for corn, ranging from 520 to 1,499 hectares over the past four years, compared to the Northern region, which had sown areas of 1466 to 2,599 hectares, and the Central region, which ranged from 1,999 to 4,191 hectares (National Bureau of Statistics…, n.d.).

Table 3. *The area sown with agricultural crops in agricultural enterprises and farmer households by years*

Geographical zone	Root crops for fodder				Corn for silage, green mass and haylage			
	Years							
	2020	2021	2022	2023	2020	2021	2022	2023
North	2	2	7	12	2,599	1,466	2,153	1,570
Centre	19	33	10	11	4,191	1,999	2,412	2,705
South	152	80	-	5	1,499	520	1,122	575
Average per country	57.67 ± 47.4	38.33 ± 22.6	5.67 ± 2.9	9.33 ± 2.1	2,763.00 ± 781.4	1,328.33 ± 432.9	1,895.66 ± 393.9	1,616.66 ± 615.3

Source: *National Bureau of Statistics of the Republic of Moldova (n.d.)*

On average, the area of land sown with corn for silage, green mass, and hay has decreased compared to 2020, with reductions of 51.9, 31.4, and 41.5% in the years 2021, 2022, and 2023, respectively. Due to high temperatures in the Southern geographical zone, with an average of +12.6° cover the four reference years, the yield of root crops for feed was severely compromised, resulting in a productivity of only 66.3 quintals in 2021. This occurred despite higher precipitation (490 mm) and lower average temperature (11.4°C) in the Southern zone compared to other years. A similar trend was observed in this zone for corn yields for silage, green mass, and hay, which averaged 366.1 quintals per hectare. The least productive years for yields per hectare were 2020 and 2022, indicating a nationwide average productivity of root crops of 43.33 and 23.90 quintals per hectare, and 107.07 and 109.80 quintals per hectare for corn for silage, green mass, and hay. This decline was attributed to higher average temperatures (+12.17°C in 2020 and +11.43°C in 2022) and lower precipitation levels (545.33 mm and 399.33 mm, respectively) (Table 4).

Table 4. *Average harvest of agricultural crops in agricultural enterprises and farmer households by year, q/ha*

Geographical zone	Root crops for fodder				Corn for silage, green mass and haylage			
	Years							
	2020	2021	2022	2023	2020	2021	2022	2023
North	60.0	292.5	30.0	25.5	103.9	281.0	109.2	220.7
Centre	70.0	21.7	41.7	114.2	100.6	278.8	117.5	171.7
South	-	66.3	-	-	116.7	366.1	102.7	172.3
Average per country	43.33 ± 21.8	126.89 ± 83.8	23.90 ± 12.4	46.56 ±39.6	107.07 ± 4.9	308.63 ± 28.7	109.80 ± 4.2	188.23 ±16.2

Source: *National Bureau of Statistics of the Republic of Moldova (n.d.)*

Regarding the sown area for feed crops, the Central region prioritised with an area of 4,342 to 5,743 hectares, which is 22.0 and 92.3% more than the North and South regions in 2020; 19.3 and 59.6% more in 2021; 5.4 and 45.5% more in 2022; and 41.7 and 91.7% more compared to the North and South regions in subsequent years. Annual grasses are primarily cultivated in the North, with areas ranging from 241 to 421 hectares, which is 71.6 and 88.2% more compared to the Central and South regions in 2020; 46.9% more in 2021; 29.1 and 54.9% more in 2022; and 39.8 and 117.0% more in 2023 (Table 5).

Table 5. *The area sown on agricultural crops at agricultural enterprises and farmer households, ha*

Geographical zone	Forage crops				Annual herbs				Perennial herbs			
	Years											
	2020	2021	2022	2023	2020	2021	2022	2023	2020	2021	2022	2023
North	4,706	3,644	4,129	3,376	350	241	319	421	1,701	1,755	1,599	1,441
Centre	5,743	4,342	4,351	4,785	204	258	247	301	1,317	1,957	1,464	1,454
South	2,986	2,721	2,990	2,496	186	164	206	194	1,147	1,464	1,638	1,702
Average per country	4,478.33 ± 803.98	3,569.00 ± 469.44	3,823.33 ± 421.57	3,552.33 ± 666.63	246.66 ± 51.93	221.00 ± 28.91	257.33 ± 33.03	305.33 ± 65.56	1,388.33 ± 169.85	1,725.33 ± 143.09	1,567.00 ± 52.71	1,532.33 ± 84.91

Source: *National Bureau of Statistics of the Republic of Moldova (n.d.)*

However, the area sown with perennial grasses in the North has been declining over the monitored years, with a decrease of 15.3% in 2023 compared to the previous year. In 2020, the Southern region experienced a notable increase in the areas cultivated with perennial grasses, showing a rise of 48.4% in 2023 compared to 2020. The analysis of the presented data demonstrates a clear trend of declining forage crop cultivation across the Republic of Moldova, decreasing from an average of 4,478.33 hectares in 2020 to 3,552.33 hectares in 2023. The area under perennial grasses declined from 1,725.33 hectares to 1,532.33 hectares, whereas the area planted with annual grasses increased from 221 hectares to 305.33 hectares. The livestock sector will be impacted by the changing climate, but more indirectly. Lower humidity and higher temperatures will directly increase physiological stress and most likely have an impact on animal growth. Weather-related effects on fodder plants and grazing areas will be the indirect effect. Given their higher heat tolerance and capacity to survive on more drought-tolerant feed, it is probable that the population of goats and donkeys in the southern portion of the country will rise while that of cattle will decline. However, the northern part of the country can provide better development conditions for the animal's subsector (Agriculture and horticulture, n.d.).

The increased temperature conditions, low precipitation, and declining areas cultivated with forage plants have also led to a reduction in livestock numbers, including cattle and pigs. Both regionally and nationally, the number of beef cattle has noticeably decreased. In the North, the count dropped from 59,785 head in 2020 to 48,613 head in 2023; in the Central region, from 41.208 to 36.285 head; and in the South, from 16.367 to 12.013 head. A similar trend is observed in the number of dairy cows, with reductions of 16.7% in the North, 22.9% in the Central region, and 24.9% in the South in 2023 compared to 2020. The number of pigs has also decreased across all geographical regions of the Republic of Moldova over the past four years, with a notable decline in the North, where the livestock count dropped by 18.85% in 2023 compared to 2020. In the South, the pig population decreased by 12.18% up to 2022 but showed a slight increase of 2.9% in 2023 compared to 2020 (Table 6).

Table 6. *Livestock dynamics in farm of all categories, heads*

Specification	Years	Geographical zone			Average per country
		North	Centre	South	
Cattle for meat	2020	59,785	41,208	16,367	39,120.00±12,577.10
	2021	53,487	36,059	13,671	34,405.66±11,523.57
	2022	50,705	34,992	12,671	32,789.66±11,034.83
	2023	48,613	36,285	12,013	32,303.66±10,751.40
Dairy cows	2020	42,817	23,180	11,842	95,279.66±68,535.97
	2021	38,586	19,778	9,937	22,767.00±8,404.20
	2022	36,803	19,399	9,022	21,741.33±8,104.74
	2023	35,671	17,869	8,892	20,810.66±7,869.11

Table 6, Continued

Specification	Years	Geographical zone			Average per country
		North	Centre	South	
Pigs	2020	82,079	261,365	41,459	128,301.00±67,557.42
	2021	75,177	212,986	39,238	109,132.00±52,952.98
	2022	69,617	233,030	39,169	112,605.33±61,027.97
	2023	66,599	219,521	42,651	109,590±55,398.37
Sheep and goats	2020	158,260	164,029	223,332	181,873.66±20,795.96
	2021	147,865	146,599	203,005	165,823.00±18,594.59
	2022	136,407	139,250	194,018	156,558.33±18,747.80
	2023	141,018	139,385	185,854	155,419.00±15,224.80

Source: *National Bureau of Statistics of the Republic of Moldova (n.d.)*

On average, the number of sheep and goats has significantly decreased, showing declines of 8.8, 13.9, and 14.5% in 2021, 2022, and 2023, respectively, compared to 2020. Regionally, the largest decrease in the sheep and goat population occurred in the South, with a reduction of 16.8% in 2023; the Central region experienced a drop of 15.1% in 2022; and the North saw a decline of 13.8% in 2022, all compared to the reference year of 2020. After analysing the production of live weight meat, the Central region has the highest level of this indicator, ranging from 815,921 to 759,584 quintals, with a decrease of 6.9% in 2023 compared to 2020. In contrast, the Northern region recorded an increase of 14.9% in live weight production, while the Southern region saw a significant increase of 43.3% in 2023 compared to 2020 (Fig. 4). The production of cow's milk in the Republic of Moldova has increased significantly, from an average of 60,967.67 quintals in 2020 to 113,889 quintals in 2023, marking an overall increase of 86.8% (Fig. 5).

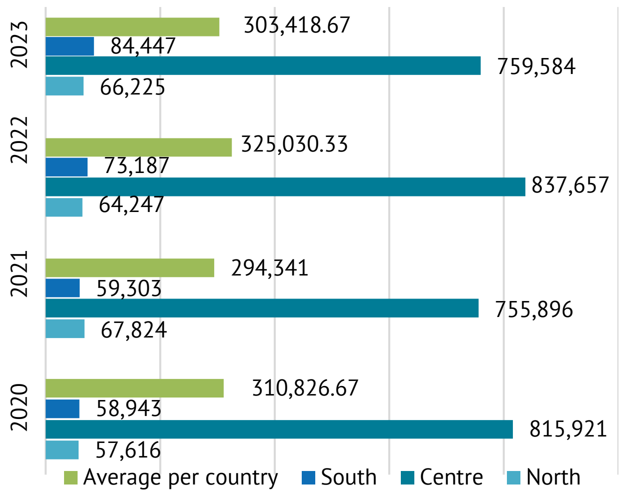

Figure 4. *Live meat production*
Source: *National Bureau of Statistics of the Republic of Moldova (n.d.)*

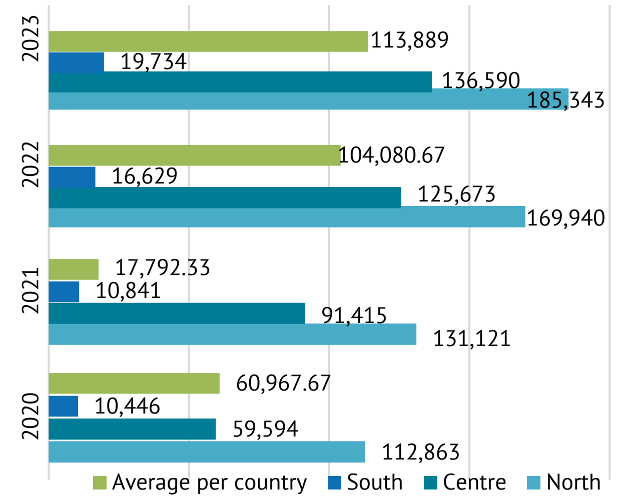

Figure 5. *Cow milk production*
Source: *National Bureau of Statistics of the Republic of Moldova (n.d.)*

The Northern region leads in this ranking, with cow's milk productivity rising from 112,863 quintals in 2020 to 185,343 quintals in 2023, representing a 64.2% increase compared to the reference year 2020. Notably, there has also been a significant increase in milk production in the Central region, with a rise of 129.2%, and in the Southern region, with an 88.9% increase in 2023 compared to 2020. The wool production in physical mass varies annually across the Republic of Moldova, with an average of 56.33 quintals in 2022 and a decline to 45.67 quintals in 2023. The Southern region is considered the leading area for wool production, with a yield ranging from 127 to 103 quintals, marking an 18.9% decrease in 2023 compared to 2020. In contrast, both the Northern and Central regions experienced increases in wool productivity up to 2022, followed by a sharp decline in 2023, showing decreases of 14.3% and 47.3%, respectively, compared to 2020 (Table 7).

Table 7. *Wool production (in physical mass) at agricultural enterprises and farmer households, q*

Geographical zone	Years			
	2020	2021	2022	2023
North	7	7	26	6
Centre	19	23	32	28
South	127	118	111	103
Average per country	51.00±38.16	49.33±39.64	56.33±27.39	45.67±29.36

Source: *National Bureau of Statistics of the Republic of Moldova (n.d.)*

Animal production based on grain crops may be less sensitive to climate change compared to ruminants that rely on conserved forage (hay and silage) and grazing (Orosz & Balogh, 2023; Tothi *et al.*, 2024). For cereal plants, which produce concentrated feed for animals, low temperatures reduce yields per unit area, or plants may fail to mature. High temperatures during the grain-filling stage led to deformed grains, reducing both yield and nutritional quality. Temperature and precipitation changes, as well as extreme weather and climatic conditions, already impact crop productivity and livestock production in Europe. In some regions of southern Europe, this may lead to the abandonment of agricultural lands affected by climate stress. Weather and climatic conditions also affect water resources needed for irrigation, animal watering practices, agricultural product processing, and transportation and storage conditions.

C. Ringler *et al.* (2022), reports that access to sufficient, clean fresh water is essential for all life. This is particularly concerning as climate change will increasingly affect all aspects of food systems. Long-term consequences of climate change, mostly caused by human activity, pose a major threat to ecosystems, communities, and biodiversity. Research shows that there is frequently a nonlinear and region-specific link between precipitation and agricultural yields. (Mahadevan *et al.*, 2024). According to L.E. Sollenberger & M.M. Kohmann (2024) incorporating forage legumes into pastures is a recommended strategy for mitigating climate change, though the desired benefits from legumes depend on their resilience when exposed to climate change factors. To address the challenges posed by climate change and its multidimensional interactions, comprehensive strategies must be adopted. Smart agricultural management practices, water-efficient irrigation systems, encouraging climate-resilient crop varieties, enhancing soil conservation and enhancement strategies, putting into practice creative and sustainable fertiliser production plans, and workable water reuse and recycling solutions are a few examples (Wang *et al.*, 2018; Ahmad *et al.*, 2024).

R. Murabildayeva, *et al.* (2024) comes to the conclusion that the following suggested agricultural adaptation strategies and actions can be prioritised at the local and regional levels: management of crop varieties and land use change and innovative breeding techniques; management of water and soil, including agronomic practices; and training and knowledge transfer for farmers through research and development, including the creation of early warning systems. Given the threat of climate change and the anticipated effects on forage production in the future, it is also advised to continue research and extension on best practices to enhance livestock production using high-quality and high-yielding conserved forages that are adapted to the agroecological conditions of the particular regions (Tulu *et al.*, 2023). According to A. Maher *et al.* (2025), grasslands worldwide also face management issues brought on by both new and existing stressors, such as increased fire frequency and intensity, woody species expansion, annual grass invasion, recurrent grazing during the growing season, and climate change.

Although livestock systems based on grain crops show relatively greater resilience to climate variability, the forage- and pasture-dependent ruminant sector remains particularly vulnerable to the multifaceted impacts of climate change. The ongoing shifts in temperature, precipitation patterns, and water availability are already altering the agricultural landscape across Europe, including Moldova, with tangible consequences for crop productivity, forage quality, and animal performance. As climate extremes become more frequent, there is an urgent need to prioritise adaptive responses at both policy and farm levels. This includes the promotion of integrated crop-livestock systems, the development and dissemination of climate-resilient forage species, and the implementation of water- and soil-saving innovations. Only through coordinated action – encompassing research, technological innovation, farmer education, and region-specific strategies – can we ensure the long-term sustainability of livestock production and safeguard food security in the face of an increasingly unstable climate.

CONCLUSIONS

The conducted research confirms that climate change has a significant and growing impact on the forage base in the Republic of Moldova. Increasing temperatures, prolonged droughts, and irregular precipitation patterns have created unfavourable conditions for the cultivation and productivity of forage crops. The analysis of long-term data revealed a steady decline in both the total sown areas and the average yields of key forage species. These negative trends have led to a reduction in the volume and nutritional value of feed resources available for animal husbandry. As a consequence of the diminishing forage base, livestock production in Moldova has experienced a gradual downturn. Reduced availability of quality feed has limited the growth potential of ruminant and monogastric species alike, resulting in declining livestock populations. This, in turn, has led to a decrease in the output of animal-origin products such as milk, meat, and eggs. The reduction in these essential food commodities not only undermines the economic sustainability of the agricultural sector but also weakened the country's overall food security and negatively affects the livelihoods of rural communities that depend on livestock production.

The study highlighted the need for a fundamental shift toward more resilient and adaptive agricultural practices. In particular, there is a strong case for expanding the diversity of forage crops, adopting more efficient water management systems, and introducing technologies that enhance soil fertility and moisture retention. Equally important is the implementation of region-specific adaptation strategies that reflect the particular vulnerabilities and ecological conditions of Moldova's agro-climatic zones. In future research, it is planned to assess the potential of alternative and underutilised forage crops better adapted to arid conditions. Additionally, further studies will focus on evaluating the economic feasibility of innovative irrigation systems and forage conservation technologies. Particular attention will be given to the development of predictive models that integrate climate data to optimise forage crop planning and improve the resilience of livestock feeding systems under various climate scenarios.

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CONFLICT OF INTEREST

None.

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Анотація. Зміна клімату визнана зростаючою загрозою для розвитку людства та сталого існування природних екосистем, що має особливо серйозні наслідки для сільського господарства – основи існування сільських громад. Глобальні сільськогосподарські системи зазнали руйнівного впливу через підвищення температури на планеті, збільшення рівня CO_2 в атмосфері та зростання частоти екстремальних погодних явищ, таких як повені та посухи. У Республіці Молдова ці зміни створили все більші виклики для сектору кормів, який відігравав важливу роль у підтримці продуктивності тваринництва та забезпеченні національної продовольчої безпеки. У дослідженні оцінювали вплив зміни клімату на вирощування кормових культур, зосередившись конкретно на тому, як коливання температури та кількості опадів впливали на врожайність біомаси, поживну цінність та продуктивність тваринництва. Було застосовано мультидисциплінарний підхід, що включав аналіз довгострокових кліматологічних даних (1970-2020), огляд наукової літератури та узагальнення експериментальних даних, пов’язаних з фізіологією рослин та складом кормів в умовах абіотичного стресу. Результати показують постійне підвищення середніх температур та значну нерегулярність сезонних опадів, що призводить до зниження врожайності кормових культур на 15-30 % у роки екстремальної посухи. Підвищені температури прискорили дозрівання рослин, але зменшили співвідношення листя до стебла, що призвело до зниження вмісту сирого білка (на 10-20 %) і збільшення концентрації клітковини, особливо лігніну, що негативно вплинуло на перетравність. Ці зміни корелювали з помітним зниженням споживання корму жуйними тваринами і надоїв молока на 12 % у періоди високого стресу. Сукупним ефектом стало зниження ефективності систем тваринництва, що, в свою чергу, вплинуло на прибутковість ферм і стійкість продовольчого забезпечення. Результати дослідження підкреслили нагальну потребу в адаптивних стратегіях, таких як селекція посухостійких кормових культур, впровадження вдосконалених методів зрошення та перегляд національної сільськогосподарської політики. Дослідження пропонує важливі висновки для сільськогосподарських дослідників, тваринників та політиків, які прагнуть розробити стійкі до кліматичних змін системи управління кормовими культурами та тваринництвом у Молдові

Ключові слова: кліматичні умови; кормові культури; географічні райони; врожай; поверхня; кількість опадів

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Modern GIS technologies supporting land management in agricultural land consolidation

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Abstract. Ukraine has not conducted a comprehensive or systematic assessment of the effectiveness of spatial land consolidation processes, and the institutional framework supporting agricultural land integration remains limited. This study investigated the potential for rational land management through the application of agricultural land consolidation, focusing on the Liutenska and Petrivsko Romenska territorial communities. Geographic Information Systems (GIS) were employed to analyse spatial structure, land fragmentation, and opportunities for land-use optimisation. The methodological approach included geospatial analysis, systems analysis, graph-based generalisation, and normative-legal content analysis to evaluate fragmentation levels, ownership patterns, and spatial inconsistencies. The study found that land consolidation contributed to a reduction in land-use fragmentation, adjustments in land tenure structure, and improvements in the spatial configuration of agricultural areas. The integration of GIS tools supported spatial data analysis, enhanced transparency in decision-making processes, and facilitated the incorporation of ecological, economic, and social considerations. Parcel reallocation through equivalent exchange and consolidation planning supported more coordinated land cultivation, reduced transportation distances, and improved access to infrastructure. The findings suggested that spatial, legal, and institutional instruments need to be applied in combination to support land consolidation at the community level. These results can inform land management strategies for local authorities, agricultural producers, and stakeholders involved in rural development, particularly within the framework of ongoing land reform in Ukraine

Keywords: spatial optimisation; rural development; cadastral data; geoinformation analysis; sustainable agriculture; integration; fragmentation

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INTRODUCTION

The structure of agricultural land use in Ukraine remains highly fragmented and spatially inefficient. Historical processes of land distribution, partial reforms, and the long-standing moratorium on land sales have resulted in irregular and disjointed land holdings. These conditions impede the development of competitive agricultural production and hinder sustainable rural development. Land users often face limited access to tools that would allow them to plan, optimise, or consolidate land holdings, while institutional and technical frameworks for spatial land integration remain underdeveloped. In this context, Geographic Information Systems (GIS) present an opportunity for improving the spatial structure of land use, facilitating rational land management, and supporting more coordinated land reallocation processes at the local level.

Research by M. Malashevskyi & O. Malashevska (2022) focused on the modelling of land exchanges during the consolidation process. The authors developed a theoretical model for land plot reallocation based on the concept of spatial combinations, which provides the basis for optimising land parcel configurations during consolidation. In their study, the authors proposed a methodology for correcting land parcel boundaries to support consolidation efforts. They emphasised the need for accurate mapping and synchronisation with cadastral data, but did not address the practical implementation of GIS. A.M. Tretiak *et al*. (2025) analysed the consolidation of land shares (quotas) held by private owners, emphasising the need for legal clarity and a robust compensation mechanism to encourage voluntary participation in consolidation projects. Their findings suggest that transparent and legally secure frameworks are essential for stakeholder engagement. However, their research remains limited in terms of spatial or geoinformation modelling. N. Stoiko & O. Cherechon (2024) explored multipurpose land consolidation in the context of Ukrainian territorial communities. They examined how land integration could be used not only for agricultural optimisation but also to support environmental protection and infrastructure development. While their study offered a broad institutional perspective, it did not include spatial analysis or practical applications of GIS. A. Popov *et al*. (2020) introduced an alternative model to classical land consolidation, clustering agricultural lands according to production types. Their model was intended to improve the economic efficiency of land use, but the research did not include geoinformation technologies, and no case studies were provided to demonstrate practical outcomes.

J. Thomas (2023) provided a comprehensive handbook on rural land readjustment and consolidation in Germany, commissioned by the Federal Ministry of Food and Agriculture. The publication outlined institutional, legal, and organisational frameworks that have enabled the longterm success of consolidation programmes, with particular emphasis on compensation mechanisms, voluntary participation, and integration with rural development policies. The German experience demonstrates how consolidation can be embedded within a broader territorial development strategy, offering valuable insights for countries seeking to modernise their land management systems. P. Leń *et al*. (2024) introduced a novel method for determining the urgency of land consolidation, which incorporates market value alongside traditional spatial and legal indicators. Their approach allows for a more nuanced prioritisation of areas requiring intervention, ensuring that consolidation not only addresses fragmentation but also reflects economic efficiency and land market dynamics. The study demonstrated the potential of quantitative assessment methods to improve the planning and sequencing of consolidation projects, thereby enhancing their practical implementation. M. Bijandi *et al*. (2021) employed multi-objective particle swarm optimisation in their study on land consolidation. They incorporated landowner preferences and legal restrictions into their reallocation models, offering a rigorous quantitative and technical approach. However, the applicability of their model to Ukrainian conditions remains uncertain due to differing institutional structures. Y. Wei *et al*. (2020) utilised GIS tools to assess land suitability for agricultural development based on environmental criteria. The study demonstrated the effectiveness of integrating spatial data into land-use planning but did not address cadastral or legal data, which are essential for formal land consolidation processes. S.P. Tunalı & N. Dağdelen (2023) compared different land consolidation approaches in Turkey, concluding that mixed methods – combining legal, participatory, and spatial tools – were the most effective. Their methodology included spatial simulations and field validation, demonstrating the practical application of GIS in land reform. These findings may be relevant to the Ukrainian context, though institutional differences must be taken into account.

Despite these contributions, several critical aspects remain insufficiently explored. Few studies demonstrate how GIS tools are applied in real-life consolidation projects in Ukraine. Most studies focus on legal or theoretical frameworks without presenting empirical findings or spatial models. Additionally, there is limited research integrating cadastral, legal, and geospatial datasets for community-level consolidation planning. The practical role of land users, local institutions, and digital tools in land optimisation remains underrepresented in the literature. This study aimed to examine the potential for effective land management through the implementation of land consolidation in agricultural regions, using the Liutenska and Petrivsko-Romenska territorial communities as case studies. GIS technologies were applied to analyse the spatial structure, fragmentation, and land reallocation potential, with a focus on practical modelling and communitylevel integration.

MATERIALS AND METHODS

The research employed a multidisciplinary methodological framework to examine opportunities for rational land use through agricultural land consolidation, based on the case of the Liutenska and Petrivsko-Romenska rural territorial communities in the Myrhorod District, Poltava Region (Fig. 1). The approach integrated spatial, legal, and empirical methods to ensure analytical consistency and practical relevance.

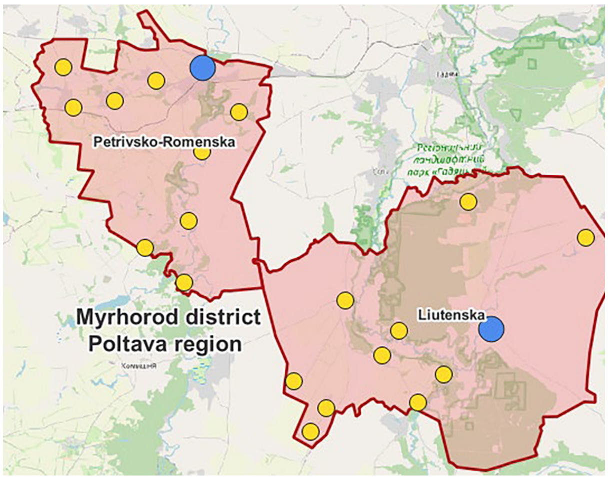

Figure 1. *Schematic map of the Liutenska and Petrivsko-Romenska communities, Myrhorod District, Poltava Region*
Source: *created by the authors using OSM map and QGIS*

The initial stage of the study involved a structural assessment of the land fund of the Liutenska and Petrivsko-Romenska communities, which cover 37,351.8 and 20,970 hectares respectively, as of 1 January 2025. Official cadastral records, archival materials, and land-use statistics were used to classify land by type (agricultural, forest, water bodies, wetlands, etc.) and by user category (households, enterprises, state institutions) (State Service of Ukraine…, n.d.). This classification allowed the identification of fragmentation patterns, ownership types, and spatial inconsistencies across village units. Geospatial analysis constituted the core of the research methodology. GIS platforms, including ArcGIS Engine and QGIS, were used to map the existing land parcel structure, overlay thematic layers, and simulate alternative configurations for land consolidation. These simulations were conducted using actual cadastral data sourced from the State Service of Ukraine for Geodesy, Cartography and Cadastre (n.d.). Key attributes such as parcel size, ownership form, land designation, and soil quality were analysed to model spatial optimisation scenarios. The resulting digital maps provided a basis for visualising fragmentation and designing reallocation strategies. The spatial analysis was supported by graph-based generalisation, a method used to aggregate and simplify spatial data for further processing. This enabled the identification of consolidated land blocks based on proximity and functional use, and the modelling of equivalent exchanges between fragmented plots. These models were generated within the ArcGIS environment using custom scripts designed to process topological relationships among land parcels.

A legal and normative content analysis was conducted in parallel to ensure that proposed consolidation scenarios aligned with existing Ukrainian legislation. The analysis covered the Land Code of Ukraine (amended as of 7 February 2025) (Law of Ukraine No. 2768-III, 2001), national land policy strategies (Resolution of the Cabinet of Ministers of Ukraine No. 695, 2020), and selected presidential (Decree of the President of Ukraine No. 722/2019, 2019) and governmental decrees (Law of Ukraine No. 552-IX, 2020). Key legal parameters, including land ownership rights, servitudes, and equivalence of compensation, were reviewed and integrated into the consolidation models (State Service of Ukraine…, n.d.). To examine the actual application of GIS tools by land users, an empirical component was incorporated. "Agrofirma 'Dovzhenko'" LLC (2023), which manages around 85% of agricultural land in the community, provided access to its ArcGIS Engine-based land management system. The system integrates data with the national cadastre and supports boundary monitoring, sowing control, and fertiliser application. Smaller enterprises such as "Agro-Kray" LLC (2025) and other farms used software, including FEODAL, which allows for parcel tracking and basic land monitoring. These cases demonstrated the real-world integration of spatial data into agricultural management.

Soil quality data were sourced from the Poltava branch of the State Institution "Institute for Soil Protection of Ukraine" (n.d.). Indicators such as pH, humus content, and available phosphorus, potassium, and nitrogen were used to assess agricultural suitability and potential for productivity improvement. These data informed the selection of parcels for modelling consolidation alternatives. The research process followed a structured sequence: collection and classification of spatial and cadastral data; GIS-based mapping and fragmentation analysis; scenario modelling for parcel reallocation using spatial optimisation techniques; normative-legal assessment of consolidation procedures; empirical validation through case studies of land users; and integration of soil quality data into consolidation planning. The selected methods reflect the need for a holistic perspective that combines technical, legal, and institutional dimensions of land consolidation. This methodological integration enabled the development of consolidation models tailored to local conditions and supported by empirical data and spatial analysis.

RESULTS AND DISCUSSION

As of 1 January 2025, the total land fund of the Liutenska territorial community was 37,351.8 hectares. Agricultural land accounted for 22,947.2 ha (61.4%), forest and forest-covered areas for 12,546.5 ha (33.6%), open wetlands for 783.9 ha (2.0%), built-up land for 690.6 ha (1.8%), water bodies for 329 ha (0.8%), and land without vegetation for 54.6 ha (0.1%) (Liutenska Village Council, n.d.). A detailed classification by village was conducted based on cadastral data (Table 1).

Table 1. *Distribution of land by villages in the Liutenska territorial community (as of 01.01.2025)*

Village	Total area, ha	Agricultural land	Forests and other forestcovered areas	Built-up land	Wetlands	Open wetlands	Barren land	Water bodies
Sosnivka	5,559.2000	2,960.2412	2,411.5024	106.7564	11.0600	19.1000	5.2000	56.4000
Rapynka	6,571.3000	5,648.2592	554.3000	113.8408	14.5920	144.2000	3.3000	107.4000
Lypivka	4,871.200	4,186.5231	379.8500	132.7269	40.6348	106.3000	4.9000	60.9000
Liutenka	20,350.100	10,152.2059	9,200.8681	337.2260	14.3940	514.3000	41.2000	104.3000
Total	**37,351.8**	**22,947.2294**	**12,546.5205**	**6,905.501**	**80,680.8**	**783.9000**	**54.6000**	**329**

Source: *compiled by the authors based on cadastral records*

The four villages – Sosnivka, Rapynka, Lypivka, and Liutenka – exhibited varied land-use distributions. In each case, agricultural land represented the dominant category, although forest land was particularly extensive in Rapynka and Liutenka (Fig. 2). The spatial structure was visualised using GIS-based land maps, and fragmentation patterns were analysed using overlay techniques and attribute data queries (Fig. 3). The analysis revealed inconsistencies in parcel size and shape, frequent separation of plots belonging to the same user, and limited access to agricultural infrastructure. These spatial patterns contributed to lower efficiency of agricultural operations.

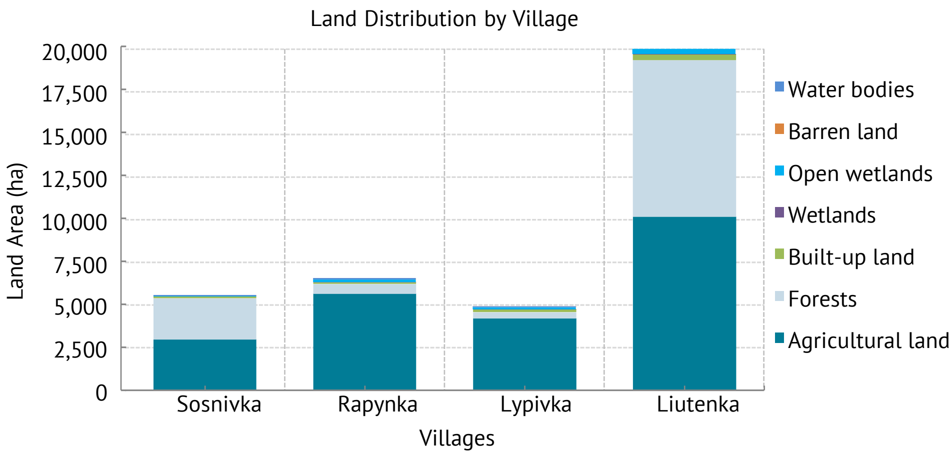

Figure 2. *Distribution of land types by village*
Source: *created by the authors using ArcGIS Engine and QGIS, based on cadastral data*

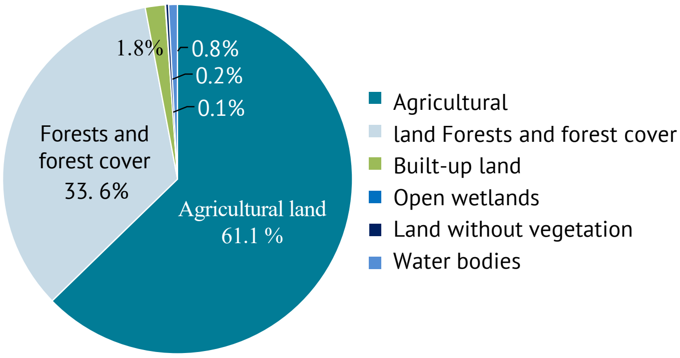

Figure 3. *Land distribution by category in the Liutenska community*
Source: *created by the authors using ArcGIS Engine and QGIS*

Soil quality analysis, based on data provided by the Poltava branch of the State Institution "Institute for Soil Protection of Ukraine" (n.d.), indicated that chernozem soils dominate the area. These soils have an average pH of 6.5, humus content of 3.08%, mobile potassium of 118.3 mg/kg, hydrolysable nitrogen of 112.7 g/kg, and phosphorus compounds of 117.1 mg/kg. These indicators confirm the potential for improved productivity under consolidated land use. The largest land user, "Agrofirma 'Dovzhenko'" LLC (2023), occupies around 85% of all agricultural land in the community and uses ArcGIS Engine for land parcel management. Smaller land users employ FEODAL software (Fig. 4), which offers limited functionality but supports basic monitoring and accounting tasks. The functionality of these systems was validated through structured interviews and software interface documentation.

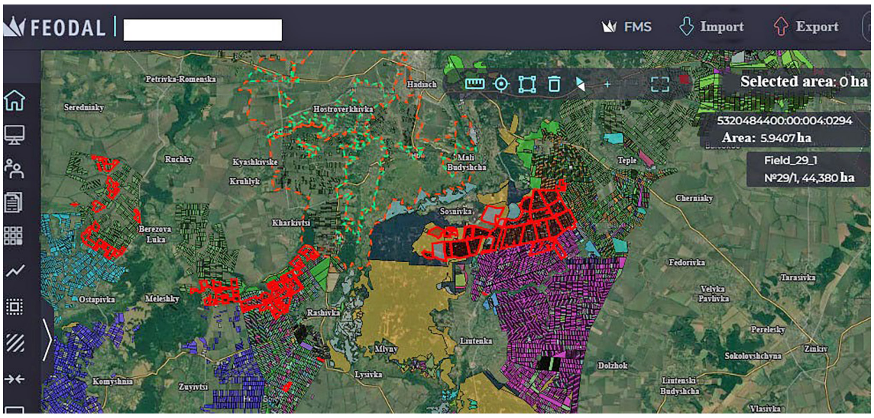

Figure 4. *FEODAL software in the territory of the Liutenska Village Council*
Source: *created by the authors using FEODAL software*

A significant share of the remaining land is managed by the farms Mayak LLC and Promin Farmer's Enterprise (FE). The rest of the land in the village districts and the community is held by small farming enterprises: Lypky FE, Sirius-Agro FE, Berus FE, Velykoobukhivske Agricultural Production and Processing Enterprise, and Hnyda Sole Proprietorship. Some lands are cultivated by individuals engaged in personal subsidiary farming. Addressing the problems in Ukraine's agricultural sector is linked to the completion of land reform, the abolition of the moratorium on the purchase and sale of agricultural land, the inclusion of land in economic circulation, and the recognition of land capital on a par with other means of production. This requires modern approaches to land management. As of 1 July 2021, the moratorium on the purchase and sale of agricultural land was lifted (Law of Ukraine No. 552-IX, 2020). This has contributed to strengthening and improving the financial standing of agricultural enterprises, as well as fostering effective ownership.

A fully functional land market is developing in Ukraine. Private individuals who own agricultural land plots have become sellers, but certain restrictions have been established on their purchase and sale. The law sets out restrictions for land plots owned by both individuals and legal entities. Land is considered in connection with joint ownership and shares in statutory capital, mutual investment funds, or legal entities whose participants are individuals. The abolition of the moratorium does not apply to land plots owned by state and communal authorities, nor to lands located in temporarily occupied territories. A list of persons who are not entitled to acquire land ownership has been established: legal entities whose participant or ultimate beneficial owner is a non-Ukrainian citizen; legal entities for which agricultural land plots in state or joint ownership are demarcated in kind; legal entities whose participant or ultimate beneficial owner is a citizen of a state recognised by Ukraine as an aggressor or occupier; legal entities belonging to terrorist organisations; legal entities to which special economic or other restrictive measures (sanctions) have been applied in accordance with the Law of Ukraine No. 552-IX (2020); legal entities created under Ukrainian law but which do not cooperate in combating the laundering of proceeds from crime; and legal entities controlled by individuals or legal entities registered in states included on the Financial Action Task Force list (Law of Ukraine No. 552-IX, 2020).

Ukraine is in the process of forming market relations to implement effective mechanisms for land integration, as well as considering the positive and negative experiences of various countries in integrating agricultural land under different land use models. This is crucial at the current stage of developing market-based land relations and in overcoming the fragmentation and parcellation of agricultural lands resulting from land share distribution and privatisation. Consolidation of agricultural lands is the process of amalgamating plots of land to address issues of irregular configuration, size, structure, location, and boundaries, thereby improving land use, increasing economic efficiency, and optimising production organisation (Lupenko *et al*., 2022). Land consolidation aims to eliminate obstacles associated with land ownership and land use that negatively affect agricultural organisation and the economics of agro-industrial complexes. This process unites the land of owners, farmers, and landholders, improves access to infrastructure and resources, and promotes their rational use. Land consolidation is considered the primary mechanism for rural land resource development, shaped by administrative-command methods such as nationalisation and artificial cooperation in plot amalgamation. At the core of the land consolidation procedure lies the principle of equal compensation for the plots whose boundaries are being demarcated. This principle stipulates that upon completion of the consolidation procedure, each owner should receive an equivalent value for their land plot or land use, matching the value of the land plot or land use they held before consolidation. During the land consolidation process, landowners receive compensation for the right of ownership or use of the land being consolidated or redistributed. The principle of equal compensation (equivalence) ensures that landowners do not incur financial losses after consolidation, and their rights to land resources are protected in accordance with their previous value and restored from the perspective of property rights and economic relations after the land integration procedure. Participants should not be placed at a disadvantage compared with others.

According to FAO (2023), in addition to sublease mechanisms, land consolidation is carried out either in accordance with a land management project for consolidation or under contractual terms of land integration and cooperation. The development of land management projects for land integration and consolidation may involve the following actions: transfer for use and extension of lease agreements, sublease agreements, and land servitudes, as well as the conclusion of such agreements for a new term; consideration of legal restrictions and encumbrances, including property rights and servitudes; prohibition of boundary changes; and restrictions on the use of land plots located within arrays of agricultural land. The community is authorised to manage territorial community land, issue notices for violations and administrative offences by individuals and legal entities, and enforce compliance with land and environmental legislation. Specialists from departments of land relations, communal property, and housing and communal services continuously monitor lease agreements and supplementary agreements, ensuring that enterprises and activities comply with statutory requirements. However, only strategic management of land development – through consolidation, integration, and clustering – will ensure progress in the community's land management and bring about qualitative improvements. GIS technologies are available for the management and rational use of agricultural land, significantly facilitating the work of agricultural enterprises.

The development of modern information technologies, particularly the integration of internet tools, geoinformation systems, organisational technologies, and mobile communication, has significantly reduced the perceived distance between remote locations, transforming the planet into a "visible" entity and making terrestrial objects and phenomena more "accessible". Rapid communication and the ability to analyse spatial information have become essential for many categories of IT users. A wide range of online web mapping services and GIS portals (ArcGIS Online, QGIS Cloud, Google Earth, Google Maps, OpenStreetMap (OSM), NASA Worldview, Sentinel Hub (EO Browser), Wikimapia, Bing Maps, Here Maps, MapQuest, Leaflet, Mapbox, etc.) are actively used not only in mobile navigation systems and GPS devices but also in everyday life by telecommunication users. Today, GIS tools are widely applied both to locate objects and phenomena on the Earth's surface and to analyse and select optimal routes across terrain. The evolution of GIS technologies, driven by the dynamic development of computer and internet technologies, is occurring at an extremely rapid pace, and even the boldest forecasts continue to hold true. While previously the development of such systems relied on a regulatory framework, today their use often extends into the online sphere, where, due to the lack of clear legal norms, user self-organisation is increasingly common.

Crowdsourcing is of great interest as a form of involving participants in the development of electronic or interactive maps. Thanks to the latest advances in cloud computing, GIS technologies are becoming accessible to an increasing number of users. GIS projects combine maps, photographs, crowdsourced data, social media resources, and other inputs. There is a shift from a geographically broad approach (aimed at accumulating information about geographical objects) to an analytically intensive approach, which involves expanding tools for processing spatial data and developing intelligent geoinformation systems. Digital knowledge is promising for the development of organisational technologies in agricultural land management. Large structures are managed using systems such as Material Requirements Planning (MRP), Manufacturing Resource Planning (MRP II), Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), Supply Chain Management (SCM), and others. Decision Support Systems (DSS) are also widely used within these frameworks. However, the design features of such systems do not always allow for the full utilisation of spatial information regarding the location or movement of large numbers of resources. Management information often contains spatial or geographical components that cannot be ignored during operational data processing. The development of information technologies has made it possible to create GIS systems that enable the collection, storage, processing, access, visualisation, and dissemination of spatial data, and are capable of solving a wide range of management tasks related to objects with spatial references.

Land users in the Liutenska community widely employ GIS software for agricultural land accounting. For example, the agricultural enterprise "Agrofirma 'Dovzhenko'" LLC (2023) uses ArcGIS Engine software, which allows the management of a large volume of related data within a single software database. In practice, the software makes it possible to track the farm's land plots, determine their spatial location, synchronise data with the state land cadastre, monitor cultivation boundaries, control sowing and harvesting, and apply plant protection products – among many other functions. The agricultural enterprise "Agro-Kray" LLC (2025) also uses ArcGIS software based on GIS technologies. The programme differs somewhat in its functional capabilities from ArcGIS Engine, but their core functions remain identical. Enterprises with a smaller land bank use FEODAL software. This programme offers more limited functionality but performs the main tasks of managing land resources and monitoring cultivation. New concepts for agricultural sector development should ensure balanced agricultural production, adapted as closely as possible to natural conditions. The implementation of these approaches requires measures for analysing land resources and organising rational land use in agricultural activity. It is necessary to transition to an adaptive development model that takes into account the ecological, social, and economic aspects of agricultural production. The organisation of the territory of agricultural enterprises plays a key role. The introduction of ecologically sound approaches to the organisation of territorial and land integration enhances land productivity, mitigates land degradation, improves crop yields, and ensures higher ecological and economic efficiency of production and economic activities.

Currently, four methodological approaches to the territorial organisation of agricultural enterprises, which take into consideration ecological and economic factors, require special attention: agroecological, agrolandscape, adaptive-landscape, and ecological-economic. The organisation of agriculture and agricultural territories, their combination and coordination with the natural elements of the agrolandscape, largely determine solutions to tasks concerned with effective and ecologically balanced land and nature management in the country's agricultural sector. Ensuring the balanced development of the agricultural sector is necessary for adaptation to the prevailing natural conditions of the territory and for adaptive landscape land management, within which the territory of a specific agricultural enterprise is implemented. In the course of organising the agricultural landscape of a territory, the land fund, which has significant natural resource potential, is transformed. During this process, a significant number of tasks related to the organisation of production processes are addressed: an institutional production system is organised, the economic direction of the enterprise is determined in the context of production sectors, the structure of sown areas of agricultural enterprises of various production types is outlined, a crop rotation system is organised, and land management design is performed.

In addition to the land management works related to the formation of land plots through their consolidation, it is also necessary to include land redistribution measures, because consolidated territories may contain land plots with different owners, different land uses, and different designated purposes. Land consolidation involves reducing the number of landowners and reducing the number of land plots. Amalgamation to form land plots is possible only if the designated purpose is preserved, but during land consolidation, situations often arise in which the designated purpose of a land plot changes. Even if the first four methods of land demarcation (Law of Ukraine No. 2768-III, 2001) are used for land redistribution, such a procedure requires the preparation of separate land management documents (land management projects and/or technical documentation for land management) for each individual case, which is a costly and lengthy process. A comparative case study was conducted for Berezova Luka Village (Petrivsko-Romenska community), where spatial reorganisation was modelled through land parcel consolidation. The area was characterised by elongated, narrow, and non-contiguous land plots, which led to increased transport time and inefficient field operation planning (Fig. 5).

Following spatial modelling based on equivalent land value exchange, consolidated blocks were formed to reduce fragmentation (Fig. 6). GIS analysis demonstrated reductions in the number of parcels per user and increased plot contiguity.

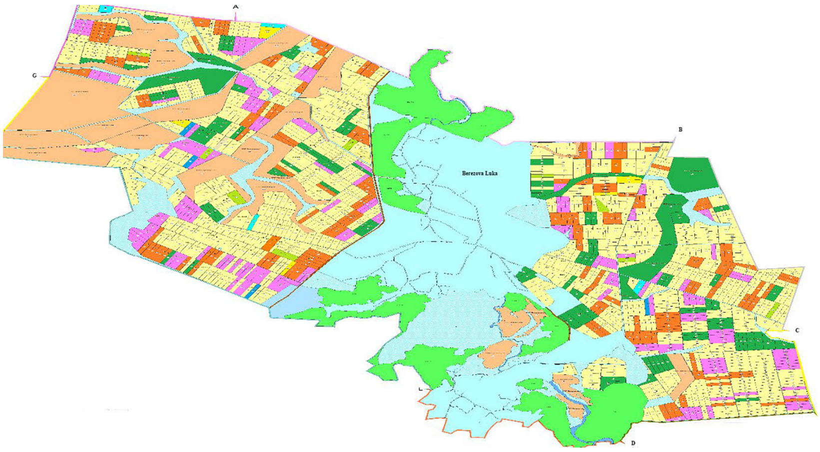

Figure 5. *Plan of Berezova Luka (Petrivsko-Romenska community) before land consolidation*
Source: *created by the authors using an ArcGIS-based simulation*

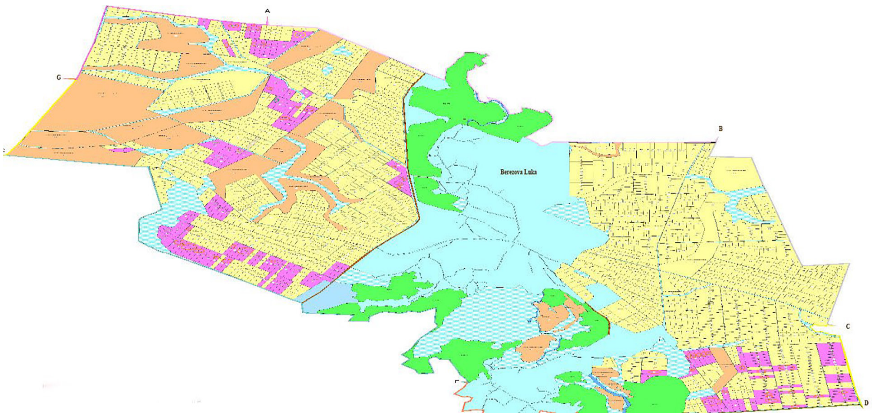

Figure 6. *Plan of Berezova Luka (Petrivsko-Romenska community) after parcel reorganisation for one user*
Source: *created by the authors using an ArcGIS-based simulation*

The application of GIS tools enabled precise measurement of changes in parcel boundaries, verification of ownership continuity, and assessment of potential impacts on agricultural accessibility. These results support the operational feasibility of consolidation under the current legislative framework. In summary, this research constituted a scientific inquiry into methods and approaches for rational land management through land consolidation, examined ways to improve spatial consolidation, and defined land use structures through legal and land management mechanisms.

The simulated reorganisation in Berezova Luka further confirmed that consolidating disjointed parcels into contiguous blocks can significantly improve the efficiency of agricultural operations. The presented research aligns closely with recent investigations exploring the technical and practical benefits of land consolidation. For instance, the study of Z. Zhang *et al*. (2025) in the hilly and mountainous regions of China reinforces these findings by demonstrating that arable land consolidation is crucial for mitigating land fragmentation, particularly in facilitating the use of modern agricultural machinery. The elongated and narrow plots observed in Berezova Luka before the simulated reorganisation present precisely the kind of spatial inefficiency that hinders mechanisation. GIS-based modelling, which resulted in more compact and accessible land blocks, provides a practical validation of these principles. Similarly, the research by Y. Yang & T. Cao (2023), which utilised GIS for the optimal zoning of agricultural land, corroborates this methodological approach. Their focus on using geoinformation technologies to optimise regional land use mirrors the application of ArcGIS Engine and QGIS in this study for analysing land categories, soil quality, and ownership patterns to design effective consolidation scenarios. This parallel underscores that GIS is not merely a mapping tool but a critical analytical system for strategic land management, a conclusion strongly supported by the findings of this study.

The central role of digital technologies in contemporary land management, as highlighted in this study through the use of software such as ArcGIS Engine and FEODAL by local enterprises, is further elaborated by A. Koshel & D. Koshel (2024). Their analysis of modern digital tools in land resource management systems affirmed that the integration of spatial data is fundamental to improving administrative efficiency and production outcomes. The case study of "Agrofirma 'Dovzhenko'" LLC, which leverages its GIS to synchronise with the state cadastre and manage cultivation, serves as a concrete example of the advanced application described by these authors. However, the use of less functional software, such as FEODAL, by smaller farms indicates a digital divide that could hinder the universal adoption of sophisticated consolidation practices, highlighting a need for scalable solutions.

While the technical benefits are clear, the successful implementation of land consolidation is fundamentally dependent on a robust legal and institutional framework. The conclusion that spatial, legal, and institutional instruments must be applied in concert finds strong support in Ukrainian legal scholarship. B. Derevyanko & O. Turkot (2024) explored the benefits and contradictions of current legislative drafting for land consolidation in Ukraine, pointing to the legal complexities that must be navigated. This study complemented their legal analysis by providing an empirical case of how these laws could be applied at the community level, emphasising the principle of equivalent compensation as a cornerstone for ensuring fairness and landowner participation. This principle is also a central tenet in broader European practice, as outlined in the FAO legal guide by T. Veršinskas *et al*. (2023). Their guide, based on regulatory practices across Europe, advocated legal frameworks that are flexible and participatory, aligning with the findings of this study on the need to integrate stakeholder interests. A comparison with the established land management system in Germany, as described by U.E. Chigbu *et al*. (2023), also shows that although the historical and legal context may differ, the main goal remains the creation of economically viable and environmentally sustainable land structures.

The broader socio-economic implications of the findings are reinforced by research from other post-Soviet nations. J. Looga *et al*. (2023) framed land consolidation in Estonia as an innovation policy instrument capable of stimulating rural economies, particularly for small agricultural farms. This perspective aligns with the conclusion that consolidation is a primary mechanism for rural development, capable of improving agricultural productivity and, by extension, the financial standing of agricultural enterprises. Furthermore, the study by W. Krupowicz *et al*. (2020) on implementing crowdsourcing initiatives in land consolidation procedures in Poland introduced an innovative participatory dimension. While the study focused on data from official cadastres and enterprises, the Polish experience suggests that engaging a wider community through crowdsourcing could enhance the accuracy of spatial data and foster greater transparency and public trust in the consolidation process, a key element highlighted in this research. The connection between rational land tenure and economic health was also underscored by N. Kantsedal & O. Leha (2022), who identified institutional stability as a prerequisite for the investment attractiveness of Ukraine's agricultural sector. By creating more orderly and efficient land holdings, the consolidation measures demonstrated in this study directly contribute to building this stability and making agricultural land a more secure and profitable asset.

Ultimately, the approaches and outcomes detailed in this research are in harmony with globally recognised best practices. The FAO (2023) generic master's course curriculum on land consolidation promotes an integrated approach that combines technical skills in spatial planning with a deep understanding of legal frameworks, stakeholder engagement, and sustainable development goals. This study, by integrating GIS-based spatial modelling, normative-legal analysis, and empirical data from local land users, exemplifies this holistic methodology. The successful reorganisation of parcels to reduce transport costs, improve infrastructure access, and enable more coordinated cultivation directly supports the sustainable development goal of enhancing agricultural productivity and farmer incomes. The study confirms that GIS-supported land consolidation is not merely a theoretical exercise but a practical and effective strategy for advancing land reform in Ukraine, offering a replicable model for local authorities to overcome the legacy of land fragmentation and foster sustainable rural development.

The findings confirm that the integration of GIS-based modelling, normative-legal frameworks, and empirical validation provides an effective foundation for advancing agricultural land consolidation in Ukraine. The application of GIS tools has enabled precise measurement of changes in parcel boundaries, verification of ownership continuity, and assessment of potential impacts on agricultural accessibility. These results support the operational feasibility of consolidation under the current legislative framework. This study constitutes a scientific inquiry into methods and approaches for rational land management through land consolidation, the exploration of ways to improve spatial consolidation, and the determination of land use structure through legal and land management mechanisms. The findings demonstrate that the application of modern GIS technologies is a crucial instrument for supporting agricultural land consolidation in Ukraine, leading to reduced fragmentation, enhanced spatial optimisation, and more rational land management within the Liutenska and Petrivsko-Romenska territorial communities.

CONCLUSIONS

This study has shown that the integration of modern GIS technologies is an effective tool for resolving the problem of agricultural land fragmentation in Ukraine, which arose from the land-sharing process. Unlike general assertions, this research has yielded concrete results that confirm the practical effectiveness of the proposed approaches. The analysis of the Liutenska and Petrivsko-Romenska territorial communities, with total areas of 37,351.8 ha and 20,970 ha respectively, revealed significant spatial disparity and inefficiency in the existing land use. It was established that in the Liutenska community, agricultural land accounts for 61.4% of the territory. Approximately 85% of this land is cultivated by a single large agricultural enterprise, which uses advanced ArcGIS Engine software, whereas smaller farms employ less functional systems such as FEODAL. This finding indicates a digital divide that could hinder the comprehensive implementation of consolidation.

A key result of this research was the modelling of spatial reorganisation using the example of Berezova Luka village. The simulation, conducted based on equivalent land value exchange, clearly demonstrated the benefits of consolidation: a transition from inefficient, elongated, and fragmented plots to the formation of compact, functionally integrated blocks. This resulted in a reduction in the number of parcels per user, the optimisation of their configuration and, consequently, a decrease in transport costs and an increase in the efficiency of agricultural operations. Further scientific research should be directed towards several areas. It is necessary to develop scalable and accessible GIS solutions for small and medium-sized farms to overcome the identified technological divide. Pilot projects should be conducted to implement the developed consolidation models in practice, in order to verify their economic efficiency and social acceptance at the community level. Another promising area is the analysis of the adaptability of the proposed methodology to other regions of Ukraine, taking into account their unique agricultural landscapes and socio-economic characteristics.

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Сучасні ГІС-технології для підтримки управління земельними ресурсами при консолідації сільськогосподарських земель

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Анотація. Україна не проводила комплексну або систематичну оцінку ефективності процесів просторової земельної консолідації, а інституційна база, що підтримує інтеграцію сільськогосподарських земель, залишається обмеженою. Це дослідження вивчало потенціал раціонального землекористування шляхом застосування сільськогосподарської земельної консолідації, зосереджуючись на територіальних громадах Лютенська та Петрівсько-Ромська. Для аналізу просторової структури, фрагментації земель та можливостей оптимізації землекористування було використано географічні інформаційні системи (ГІС). Методологічний підхід включав геопросторовий аналіз, системний аналіз, узагальнення на основі графіків та нормативно-правовий контент-аналіз для оцінки рівнів фрагментації, моделей власності та просторових невідповідностей. Дослідження показало, що укрупнення земельних ділянок сприяло зменшенню фрагментації землекористування, коригуванню структури землеволодіння та поліпшенню просторової конфігурації сільськогосподарських територій. Інтеграція інструментів ГІС сприяла аналізу просторових даних, підвищенню прозорості процесів прийняття рішень та полегшила врахування екологічних, економічних і соціальних аспектів. Перерозподіл ділянок шляхом еквівалентного обміну та планування укрупнення сприяли більш скоординованому обробітку землі, скороченню транспортних відстаней та поліпшенню доступу до інфраструктури. Результати дослідження свідчили про необхідність комплексного застосування просторових, правових та інституційних інструментів для підтримки земельної консолідації на рівні громади. Ці результати можуть бути використані для формування стратегій управління земельними ресурсами місцевими органами влади, сільськогосподарськими виробниками та зацікавленими сторонами, що беруть участь у розвитку сільських територій, зокрема в рамках поточної земельної реформи в Україні

Ключові слова: просторова оптимізація; розвиток сільських територій; кадастрові дані; геоінформаційний аналіз; стале сільське господарство; інтеграція; фрагментація

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Application of comprehensive integrated indices of breeding boars in DanBred breeding programmes

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Abstract. Breeding programs for pigs involve a comprehensive assessment of productive and reproductive traits in purebred lines through the use of individual breeding indices, which allows for an effective increase in the genetic potential of both crossbred animals for industrial production and subsequent generations of breeding stock. This approach differs from traditional methods that are limited to evaluating individual traits and slow down genetic progress. The aim of the study was to determine the feasibility of using an individual integral evaluation of boars and to establish the influence of their age and individual breeding index on reproductive and productive qualities. The study involved 304 Duroc sows, which were inseminated with semen from four boars differing in age, belonging to either the breeding nucleus or the reproductive group, and their comprehensive breeding value index, calculated according to the DanBred system (at least 130 points for the "breeding nucleus" and 105 points for the "reproductive group"). It was found that the individual comprehensive index and age of the boars significantly affected the reproductive performance of the sows. The best results in reproductive indices (sow reproductive quality index – 84.8; viability – 99.1%; reproductive index – 34.8; litter uniformity – 0.90) were obtained from sows inseminated with semen from young boars (12-18 months) with high indices. Older boars or those with lower breeding value indices showed poorer results. It was also established that young boars with high indices demonstrated better semen quality (ejaculate volume – 332.6 ml; concentration – 499.2 million/ml; motility – 8.7 points), although older boars produced more insemination doses per ejaculate (32.8). These findings confirm the feasibility of implementing boar index evaluation technology to improve the efficiency of breeding programs in Ukrainian pig production

Keywords: breeding programs; reproductive qualities; pig farming; cluster evaluation; semen quality

INTRODUCTION

Optimisation of the reproductive ability of pigs is an important prerequisite for achieving sustainable and economically efficient pork production. In the field of artificial insemination in pigs, the role of breeding boars is undoubtedly key, as they are an integral factor in the genetic potential of breeding enterprises and in raising pigs for fattening in commercial farms. Therefore, understanding and improving the reproductive capacity of boars is important for maintaining high-quality pork production and adapting to market demands.

Artificial insemination is the most common assisted reproductive technology in animal husbandry. This process begins with obtaining fresh ejaculate from selected boars, which are kept in specially equipped facilities (i.e., a breeding station) that also have a laboratory where semen quality is evaluated, and the ejaculate is

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processed into artificial insemination doses. Afterward, all obtained data are entered into specialised programs and automatically processed, and based on them, breeding programs are developed (Althouse, 2024). Commercial pig farming is systematic and focused on processing breeding data. Both integrated and independent systems include software packages that allow the collection and monitoring of a wide range of performance indicators, including reproductive parameters. Based on these data, comprehensive breeding indices are formed for each animal. Based on this breeding index, animals are individually selected for mating. An example of such data processing can be seen in enterprises that work with a software package within the DanBred pig breeding system. Each week, an individual breeding index is calculated for every breeding animal. This cluster index reflects the expected breeding and economic value of the animal, considering all key breeding traits: meat traits – live weight and its absolute, average daily, and relative gains, meatiness coefficient, and meat yield; fattening traits – age at reaching 100 kg live weight, fattening duration, feed cost per unit of production, and feed conversion index; reproductive traits – prolificacy, piglet weight at birth, litter weight at weaning, number of functional teats, viability, and piglet survival. For breeding boars, a number of semen productivity indicators are also taken into account – average volume of filtered ejaculate, sperm concentration, sperm motility, number of insemination doses, fertilising ability, ejaculation index, and others (DanBred, n.d.).

In addition, A. Lykhach *et al*. (2023) studied the relationship between behavioural manifestations and semen productivity of boars of modern and local breeds, which can be used as a basis for cluster evaluation and the formation of individual indices in breeding programs. During the individual selection of boars for breeding work, both in pedigree and commercial herds, particular importance is given to qualitative semen indicators – ejaculate volume and its storage ability. Although these indicators are strictly individual for each boar, breed-specific features of semen productivity, which are important in the organisation of artificial insemination, should also be taken into account. The hereditary potential of a breeding boar is also of great importance, in particular the total number of sperm, their motility, semen concentration, and ejaculate volume. Thus, the breeding index is formed based on a set of sub-indices (clusters), each of which reflects the genetic value of a certain trait. Weighting the clusters according to their economic significance makes it possible to form an integrated overall breeding value index, which is the criterion for selecting breeding stock (Tsheten & Penjor, 2024). According to J. Gu *et al*. (2023), methods of comprehensive cluster selection have improved animal breeding by increasing the accuracy of predicting breeding values, especially for traits that are difficult to measure and have low heritability, as well as shortening generation intervals. In addition, the authors proposed a method of selecting pigs based on a relatedness index, which determines the ideal individual with information about useful genotypes for the target trait. Thus, the basis for evaluating selection decisions is the useful genotypic similarity between the candidate and the ideal individual. That is, the relatedness index can overcome the need to establish genetic reference groups and continuously determine the phenotype.

Also, according to V.I. Khalak & B.V. Gutyj (2023), the issue of finding effective breeding methods for integrated evaluation of pig productivity traits, taking into account their genotype and interbreed differences in some complex indicators or integral indices, remains relevant, as this will simplify the selection and mating process. According to H. Reyer *et al*. (2024), morphological characteristics of sperm and so-called "stress tests" are more informative for assessing reproductive performance, based on which one of the main clusters of sperm quality – the sperm motility index – is calculated. Assessment of sperm motility, as part of the integral index, helps to evaluate fertilisation ability and sperm resistance to environmental changes. Sperm motility under stress conditions varies between normal and abnormal sperm groups, as well as during sperm aging. When evaluating boar semen, these data can help not only in compiling a comprehensive breeding index but also in predicting the fertilisation potential of the ejaculate by assessing sperm resistance to thermal stress, which can also be assessed as a separate index. Testing sperm motility after prolonged exposure to +38°C simulates the duration of sperm in the female reproductive tract. This makes it possible to draw conclusions about their fertilisation ability and functional metabolism. The stress test at low temperatures, i.e., +6°C, models an optimal storage regime that limits bacterial growth and can also affect semen quality. Testing sperm motility using index evaluation makes it possible to detect even small differences between high-quality ejaculates, and the sperm quality index, based on various measurements and assessments, accurately reflects the requirements of artificial intelligence and contributes to fertility prediction.

As breeding experience showed, the transmission of hereditary potential from the breeding herd to commercial herds occurs mainly through male individuals, i.e., boars. Accordingly, the success of breeding improvement of the herd is ensured by the correct individual selection of a boar based on a set of integral qualities.

This prompted interest in studying the influence of integral cluster indices on the productive qualities of breeding boars. Considering that a successful combination of parental pairs in breeding work has a fundamental impact on the breeding and productive qualities of their offspring, the purpose of the study was to demonstrate the effectiveness of using an integrated evaluation of Duroc boars, taking into account their age, individual breeding value selection index, and usage.

MATERIAL AND METHODS

The study was conducted on a commercial farm in Denmark using Danish-bred Duroc pigs during the period 2022-2023. Animal handling procedures fully complied with European legislation (Council Directive 98/58/EC, 1998; Nalon & Stevenson, 2019). The research protocol was approved by the bioethics committee in accordance with good clinical practice standards for the protection and humane treatment of experimental animals. A total of 304 Duroc sows were included in the study and inseminated with semen from four different boars. Semen was collected using an automated semen collection system – IMV Collectis (France) and evaluated using a portable CASA-type mobile analyser for rapid assessment of motility, concentration, and sperm morphology directly at the animal. The boars differed in several parameters: membership in the nucleus breeding herd or reproductive group, age category (12-18 months vs. over 18 months), and their comprehensive breeding value index. All animals were maintained under identical feeding and housing conditions. The experimental design and formation of groups are presented in Table 1.

Table 1. *Grouping Scheme of Experimental Pigs*

Index	Boar Class			
	Reproductive group		Nucleus herd	
	No. 1	No. 2	No. 3	No. 4
	18 months and ⩾	12-18 months	18 months and ⩾	12-18 months
Total Index, points	105	125	130	140
Number of sows (head)	85	75	70	83

Source: *compiled by the author*

Boars were evaluated using a comprehensive integral breeding index, which was calculated by a computer program within the DanBred pig breeding system. According to the breeding data calculations, the integral breeding index should be at least 130 points for nucleus herd boars and at least 105 points for boars of the reproductive group. The program takes into account the individual characteristics of boars and sows, and automatically selects sows for each specific boar, which resulted in a different number of sows included in the study. Sows were evaluated for maternal qualities using reproductive performance evaluation indices. To determine the comprehensive indicator of sows' reproductive traits, the formula by V.A. Kovalenka was used (Stavetska & Piotrovych, 2015):

$$CIRT = 1.1X_1 + 0.3X_2 + X_3\ 0.35X_4, \qquad (1)$$

where *CIRT* is a comprehensive indicator of reproductive traits; X_1 – litter size, heads; X_2 – maternal milk yield, kg; X_3 – number of piglets at weaning, heads; X_4 – litter weight at weaning, kg.

For the calculation of the Selection Index of reproductive traits of sows, the formula of D.A. Baranovskyi (Stavetska & Piotrovych, 2015) was used:

$$SRQI\ =\ 6X_1 + \frac{9{,}34X_2}{X_3}, \qquad (2)$$

where *SRQI* is a selection index of reproductive traits in sows; X_1 – number of piglets at birth, heads; X_2 – litter weight at weaning, kg; X_3 – weaning age, days.

For the determination of the viability index, the algorithm by V.P. Kovalenko was used as the basis (Harmatiuk, 2022):

$$V_i = X_1 / X, \qquad (3)$$

where V_i is a viability index; X_1 is an individual litter size of the sow, heads; X – an average number of piglets at birth, heads.

The methodology of V.P. Kovalenka was used for calculating the reproductive traits index (Harmatiuk, 2022):

$$RQI = A + 2 \times B + 35\sigma, \qquad (4)$$

where *RQI* is a reproductive quality index; *A* – litter size, heads; *B* – number of piglets at wearing, kg; *σ* – an average daily gain of one piglet from birth to weaning, g; 35 – constant coefficient.

V.P. Kovalenka's algorithm forms the basis for calculating the litter uniformity index (Harmatiuk, 2022):

$$LU = (X_{max} - X_{min}) / X, \qquad (5)$$

where *LU* is a litter uniformity; X_{max} – maximum live weight of a piglet in the litter at birth, kg; X_{min} – minimum live weight of a piglet in the litter at birth, kg; *X* is an average live weight of a piglet in the litter at birth, kg.

In addition, using evaluation indices, an index assessment of boar sperm productivity was conducted. The ejaculation index was calculated based on the formula by A.V. Kvasnytsky (Sheremeta & Opanasenko, 2012).

$$E_i = n_{cd} / t_E, \tag{6}$$

where *Ei* is an ejaculation index; n_{cd} – number of semen doses obtained from one ejaculate; t_E – duration of the ejaculation reflex in the boar, minutes.

The sperm productivity index of boars was calculated using the algorithm by H.D. Sviatovets (Melnyk *et al.*, 2022):

$$SPI = (O \times K \times A) / 10, \tag{7}$$

where *SPI* is a sperm productivity index of boars, billion; *O* – ejaculate volume, ml; *K* – sperm concentration in the ejaculate, billion/ml; *A* – sperm motility, points; 10 – number of ejaculates evaluated.

RESULTS AND DISCUSSION

With a short production cycle, rapid cash turnover, the implementation of modern feeding and housing technologies, and the use of contemporary animal breeding programs, pig farming has high potential and opportunities for efficiently increasing meat production. The growth in profitability of the pig farming sector is largely driven by the use of highly productive lines, breeds, and crosses in the breeding process, both within purebred breeding and through crossbreeding and breed-line hybridization. The quality of breeding stock largely depends on the hereditary potential of appropriately matched parental forms – sows and, primarily, boars (von Keyserlingk *et al.*, 2024). Calculations of reproductive performance data for sows (Table 2), inseminated by different boars, confirmed that the individual selection index of the boars has a direct impact on the reproductive qualities of the sows.

Table 2. *Reproductive qualities of sows depending on the class and age of boars*

Index	Boar Class			
	Reproductive group		Nucleus herd	
	No. 1	No. 2	No. 3	No. 4
	18 months and ≥	12-18 months	18 months and ≥	12-18 months
Overall index, points	108	136	131	139
Number of Sows, heads	83	71	69	81
Farrowing rate, %	62.4	84.6	60.8	86.4
Number of piglets at birth, heads	9.0 ± 0.15	10.5 ± 0.28	8.8 ± 0.13	11.4 ± 0.15*
Birth weight of piglet, kg	1.20 ± 0.02	0.97 ± 0.04	0.88 ± 0.04	1.1 ± 0.05
Milk yield, kg	57.0 ± 3.4	55.4 ± 2.0	53.4 ± 2.7	56.6 ± 3.4
At 35 days weaning				
Number of piglets, heads	7.8 ± 0.32	8.2 ± 0.58	7.0 ± 0.05	7.9 ± 0.44
Total Litter weight, kg	64 ± 2.1	60.8 ± 3.4	59.0 ± 5.1	63.2 ± 4.8
Piglet weight, kg	8.85 ± 0.27	8.70 ± 0.21	8.0 ± 0.18	8.3 ± 0.47
Survival rate, %	64.4 ± 1.8	68.3 ± 4.6	84.7 ± 3.5***	69.7 ± 7.1

Note: * – $P < 0.05$; ** – $P < 0.01$; *** – $P < 0.001$
Source: *compiled by the author*

Breeding boars were evaluated based on an integral comprehensive breeding value index, which was at least 130 points for the segment – breeding nucleus, and for boars of the reproductive group, it had to be no less than 105 points. Analysis of the obtained results showed that the studied sires met the established requirements for this indicator. At the same time, the highest index among boars in the reproductive group was recorded in boar No. 2 which was 136 points, while among animals of the breeding nucleus, the best result was demonstrated by boar No. 4 which was 139 points, which, according to the integral index, corresponded to the requirements of the reproductive group class. These same production groups were also characterised by the highest farrowing rates which were 84.6% and 86.4%, respectively. Among sows of the breeding nucleus group, the highest reproductive performance was demonstrated by those inseminated with semen from a boar with a breeding value index of 136 points. Their litter size was 10.5 piglets, and piglet survival to weaning was 68.3%, which exceeded the respective indicators of the first group (9.0 piglets and 64.4%). At the same time, due to lower litter size, sows inseminated with semen from an older boar over 18 months with a selection index of 108 had higher results for indicators such as piglet birth weight, litter weight at birth, and, accordingly, total litter weight and average live weight of one piglet at weaning.

Analysis of the reproductive ability of sows established that the highest comprehensive integral index was observed in animals of the breeding nucleus in the fourth group – 139 points. Sows of this group had significantly better reproductive performance compared to other experimental groups. In particular, the number of piglets at birth was at the level of 11.4 ± 0.15 piglets, which was statistically significant compared to the indicators of other groups by 15-23% ($P \leqslant 0.05$). Regarding piglet birth weight, sows of the fourth group were second only to sows of the first group, in which this indicator was 1.20 kg and was 0.1 kg higher. In contrast, in the second and third groups, birth weight was lower compared to the fourth: 0.97 ± 0.04 kg and 0.88 ± 0.04 kg, respectively, versus 1.1 ± 0.05 kg in the fourth group. A similar trend was observed for milk production: sows of the fourth group, despite high litter size, were second only to animals of the first group of the "breeding nucleus" class, which, however, had lower litter size indicators. The suckling period at the enterprise lasts up to 35 days of age. During this time, the number of weaned piglets in the third and fourth groups was 7.0 and 7.9 head, respectively, which corresponded to survival rates of 84.7% ($P \leqslant 0.001$) and 69.7%, respectively. The average weight of one piglet at 35 days among sows of the first segment was significantly lower compared to animals of breeding use, although the difference was not statistically confirmed. In addition, the conducted studies showed that the class and age of the boar significantly affect the maternal qualities of sows (Table 3). In particular, evaluation by the *RQI* in the breeding nucleus class established that the advantage was observed in sows inseminated with semen from boar No. 3 with a comprehensive breeding value index of 131 points. In contrast, in the "reproductive group" class, the opposite trend was observed: the highest indicators were recorded in sows inseminated with semen from a young boar No. 4 with the maximum comprehensive index – 139 points.

Table 3. *Maternal qualities of sows based on reproductive evaluation indices depending on the class and age of boars*

Index	Boar Class			
	Reproductive group		Nucleus herd	
	No. 1	No. 2	No. 3	No. 4
	18 months and ⩾	12-18 months	18 months and ⩾	12-18 months
Overall index, points	108	136	131	139
CIRT, points	64.8 ± 3.88	62.4 ± 2.74	61.7 ± 4.93	65.9 ± 4.21
SRQI, points	70.6 ± 2.13	79.4 ± 4.02	68.1 ± 4.84	84.8 ± 4.48**
Viability index, %	65.8 ± 7.04	72.2 ± 6.18	59.4 ± 2.56	99.1 ± 5.08***
Reproductive performance index, points	31.9 ± 2.31	33.06 ± 2.08	31.1 ± 1.44	34.8 ± 1.85
Litter uniformity	0.19 ± 0.003	0.33 ± 0.008***	0.36 ± 0.005***	0.90 ± 0.003***

Note*:* ** – $P < 0.05$; ** – $P < 0.01$; *** – $P < 0.001$; CIRT is a comprehensive indicator of reproductive traits; SRQI is sow reproductive quality index*
Source: *compiled by the author*

At the same time, the comprehensive indicator of reproductive qualities in the experimental groups showed no significant differences and ranged between 61.7 and 65.9 points. Analysis of the *SRQI* revealed a wider variation among the groups, from 68.1 to 84.8 points. In the "reproductive group" class, higher *SRQI* values were observed in sows inseminated with semen from young boars aged 12-18 months and received 79.4 points, which exceeded the same indicator in sows mated with older boars (70.6 points). Similarly, in the "breeding nucleus" class, higher values of this index were recorded in sows inseminated with young sires which was 84.8 points. These animals exhibited the highest SRQI among all experimental groups, significantly surpassing other groups ($P \leqslant 0.01$). The viability index of piglets across the studied groups showed a similar trend, indicating its dependence on both the comprehensive breeding value index and the age of the boar. However, the viability index was not associated with the production class of the sire; the highest value was recorded in group 4, where the boar had an individual comprehensive index of 139-99.1%, which significantly exceeded the values of other groups by 27.7-42.4% ($P \leqslant 0.001$). Conversely, the lowest viability index was observed in sows from the reproductive group inseminated by an older boar with the lowest individual breeding value index which was 59.4%. In the "breeding nucleus" class, a similar dynamic was observed: sows inseminated with semen from young boars with higher indices demonstrated a higher piglet viability index which was 72.2%, whereas the use of older sires with lower individual indices resulted in only 65.8%.

The sow reproductive performance index showed minimal variability, ranging from 31.1 to 34.8 points, following the overall trend of dependence on boar age and individual comprehensive index. The highest values were recorded in sows of groups No. 2 and No. 4, while groups No. 1 and No. 3 had slightly lower scores. It is also important to note significant differences in litter uniformity. The highest score of 0.90 was observed in sows of group No. 4, which statistically exceeded the corresponding indicators of other groups ($P \leqslant 0.001$). The lowest litter uniformity was found in sows of group No. 1 which has got only 0.19 points. In breeding programs and the individual selection of boars for both pedigree and commercial herds, semen quality, its quantity, and storability are of particular importance. All these indicators have pronounced individual variability; however, there are also interbreed differences in semen quality, which must be considered when implementing artificial insemination (Karpovsky *et al.*, 2020). Genetic factors also play a crucial role, including total ejaculate volume, total sperm count, sperm concentration, and semen density. In this regard, the effect of the individual comprehensive breeding value index and boar age on semen production characteristics was studied. Among boars belonging to the "breeding nucleus" class, the mean ejaculate volume of 332.6 ± 30.2 mL was significantly higher, which exceeded that of boars from group No.1 – 299.4 ± 24.3 mL ($P \leqslant 0.05$) (Table 4). In the "reproductive group" class, the advantage was observed in boar No. 4 – 257.6 ± 25.1 mL, although the difference compared to boar No. 1 was not statistically significant. The lowest ejaculate volume of 229.4 ± 24.3 mL was recorded in boar No. 3, which belonged to the older age category, significantly lower than the values in group No. 1 ($P \leqslant 0.01$). A high level of variation was observed in sperm concentration, which ranged from 312.3 to 499.2 million/mL.

Table 4. *Effect of boar class and age on semen productivity parameters*

Index	Boar Class			
	Reproductive group		Nucleus herd	
	No. 1	No. 2	No. 3	No. 4
	18 months and ⩾	12-18 months	18 months and ⩾	12-18 months
Overall Index, points	108	136	131	139
Average Volume of Filtered Ejaculate, ml	299.4 ± 24.3	332.6 ± 30.2*	229.4 ± 23.6**	257.6 ± 25.1
Sperm Concentration, million/ml	404.5 ± 35.5	499.2 ± 28.4*	312.3 ± 52.2**	457.6 ± 18.8
Sperm Motility, points	7.5 ± 1.9	8.7 ± 2.5	7.1 ± 3.1	8.0 ± 1.1*
Number of Semen Doses, pcs	32.8 ± 5.6	27.7 ± 1.7**	24.4 ± 10.2	29.6 ± 2.8*

Note*: * – $P < 0.05$; ** – $P < 0.01$; *** – $P < 0.001$*
Source: *compiled by the author*

Among the studied population, regardless of production class, the highest values were observed in young boars aged 12-18 months with high individual comprehensive indices: 499.2 ± 28.4 million/mL in boar No. 2 and 457.6 ± 18.8 million/mL in boar No. 4. In contrast, older boars No. 1 and No. 3 showed lower sperm concentration values of 404.5 ± 35.5 and 312.3 ± 52.2 million/mL, respectively ($P \leqslant 0.01$). Sperm motility also demonstrated a dependence on the age of the animals: young boars under 18 months exhibited higher scores have got 8.7 points in boar No. 2 ("reproductive group") and 8.0 points in boar No. 4 ("breeding nucleus") ($P \leqslant 0.05$). Older boars (over 18 months) had lower motility scores which have got 7.5 and 7.1 points, respectively. The cumulative criterion for semen quality is the number of insemination doses obtained from a single ejaculate. By this indicator, unlike the previous ones, boar No. 1 of the "reproductive group" class had an advantage – 32.8 doses, which significantly exceeded the corresponding values of other groups ($P \leqslant 0.01$). Similar values were noted in boars No. 2 and No. 4 – 27.7 and 29.6 doses, respectively, with varying degrees of statistical significance. Additionally, boars were evaluated for their fertilising ability (Table 5). The highest level of this indicator was found in young boars No. 4, which also had the highest comprehensive index 86.4%. High fertilisation ability was also observed in young boars of the "reproductive group" class, specifically No. 2 and valued at 84.6%. In contrast, older boars, regardless of breeding purpose, showed lower values of 62.4% and 60.8%, respectively.

Table 5. *Influence of boar class and age on fertilising ability*

Index	Boar Class			
	Reproductive group		Nucleus herd	
	No. 1	No. 2	No. 3	No. 4
	18 months and ⩾	12-18 months	18 months and ⩾	12-18 months
Overall Index, points	108	136	131	139
Sows, heads	83	71	69	81
Fertility rate, %	62.4	84.6	60.8	86.4
Number of Piglets at Birth, heads	9.0 ± 0.18	10.5 ± 0.32	8.8 ± 0.21	11.4 ± 0.11*

Note*: * – $P < 0.05$; ** – $P < 0.01$; *** – $P < 0.001$*
Source: *compiled by the author*

A similar age-related pattern was also observed for sow prolificacy. Sows inseminated with semen from younger boars exhibited higher prolificacy – 11.4 and 10.5 piglets – compared to 9.0 and 8.8 piglets in sows inseminated by older boars. Modern high-tech and profitable pig production requires comprehensive, objective, and reliable evaluation of both genetic traits and the reproductive capacity of boars. This process begins at an early age with selection and targeted rearing, as well as assessment based on individual growth performance, sexual behaviour, expression of mating reflexes, and semen production characteristics (Balogun & Stewart, 2021). Therefore, the need arises to complement traditional methods of semen quality evaluation with more advanced approaches involving a comprehensive assessment of boars using various evaluation indices. Analysis and calculation of the ejaculation index revealed that the best values were characteristic of young boars under 18 months of age in Groups 2 and 4 – those animals with the highest individual integral breeding value indices, regardless of their breeding status or category (Table 6). The ejaculation index values were 4.20 ± 0.024 ($P \leqslant 0.001$) and 4.06 ± 0.017 ($P \leqslant 0.001$), respectively.

Table 6. *Assessment of Boars of Different Classes and Ages Based on Index Values*

Index	Boar Class			
	Reproductive group		Nucleus herd	
	No. 1	No. 2	No. 3	No. 4
	18 months and ⩾	12-18 months	18 months and ⩾	12-18 months
Overall index, points	108	136	131	139
Ejaculation Index	3.97 ± 0.077	4.20 ± 0.024***	2.91 ± 0.032***	4.06 ± 0.017***
Semen Productivity Index, billion	276.4 ± 5.76	345.1 ± 8.92	233.4 ± 4.98***	379.2 ± 5.68***

Note*: * – $P < 0.05$; ** – $P < 0.01$; *** – $P < 0.001$*
Source: *compiled by the author*

Conversely, older boars (over 18 months) showed significantly lower ejaculation index values are 3.97 ± 0.077 and 2.91 ± 0.032 with a statistically proven difference ($P \leqslant 0.001$). A similar age-related dependence was observed for the sperm production index. Boars younger than 18 months recorded the highest values of 345.1 billion and 379.2 billion sperm cells, respectively – with a highly significant advantage ($P \leqslant 0.001$). In older boars, this indicator was considerably lower – 276.4 billion and 233.4 billion, respectively ($P \leqslant 0.001$). According to V.I. Khalak *et al.* (2024), innovations in breeding were necessary to obtain animals that were both productive and adapted to a wide range of local conditions and diverse systems. Breeding strategies to advance agroecological systems are similar across animal species. However, current practices differ for ruminants, pigs, and poultry. Ruminant breeding remains an open system, where farmers continue to select their own breeds and strategies. In contrast, pig and poultry breeding is largely dominated by international breeding companies that supply farmers with hybrid animals. Therefore, breeding strategies must be adapted for different species. Pig breeding programs using artificial insemination have greatly benefited from the integration of advanced techniques and the application of cluster-based integral assessment of boar potential. While traditional selection methods are based solely on the sire's phenotype – such as growth rates and conformation – modern selection increasingly relies on comprehensive indices supplemented by phenotypic traits. Cluster indices serve as critical indicators of boar reproductive capacity. They help identify individuals with high fertility and detect potential fertility problems at an early stage, enabling proactive strategies in breeding programs (Vaishnav *et al.*, 2025).

Pig breeding programs such as DanBred have significantly expanded the number of traits used for boar selection. This system allowed ranking of breeding stock based on two groups of indices – comprehensive integral breeding value indices. The first group of cluster indices focused on growth and terminal line traits, based on growth performance and sperm production indicators. The second group was concentrated mainly on maternal line development, evaluating sow reproductive traits and considering litter size and its main characteristics (González-Diéguez *et al.*, 2020). Semen quality is a key biomarker for assessing boar reproductive capacity, encompassing a wide range of parameters such as morphology, motility, sperm concentration, and ejaculate volume. These parameters collectively reflected the functional competence of spermatozoa, enabling the identification of ejaculates that do not meet minimum quality requirements. Although most biomarkers have limited informativeness individually, they provided data on quantitative and qualitative sperm characteristics and serve as the basis for forming complex integral or cluster indices of sperm production. S. Jang *et al.* (2022) noted that most commercial pigs in swine production result from crossing maternal-line sows with pooled semen from terminal sires. Therefore, it was reasonable to assume that the true genetic value of most commercial boars for reproductive traits remains unknown. These animals represented a population subjected to limited selection for male reproductive traits, requiring cluster-based integral assessment of each sire across a set of characteristics, combined with semen pooling based on similar cluster index scores.

S.P. Turner *et al.* (2024) recommended that commercial pig breeding programs based on integrated selection indices should also incorporate new phenotyping methods and genetic methodologies that expand the range of welfare traits. Specifically, separate individual welfare indices should be developed to exert selection pressure on welfare traits, improving animal well-being and contributing to economic and environmental benefits. Additionally, one of the sub-indices within a cluster index may include an inbreeding index, which helps prevent inbreeding issues in breeding herds. The effective size of these herds or populations is generally small, increasing the risk of reduced adaptability and viability in pigs (Kramarenko *et al.*, 2023). Inbreeding index data enabled new approaches to breeding programs and help avoid negative inbreeding consequences. As noted by R. Ausejo-Marcos *et al.* (2024), analysis all components of the overall integral index were essential for understanding its relationship with fertility and prolificacy, providing insights into reproductive success and assisting the industry in distinguishing among boars used in breeding programs. Integrating this information into a simplified form – through cluster aggregation – is necessary for better ejaculate quality assessment. H.H. Salgado *et al.* (2021) developed a new feeding behaviour index that integrates multiple components of pig feeding behaviour during fattening, consolidating these into a single parameter and accounting for changes over time. This index better illustrates individual feeding patterns, identifies the impact of production factors on feeding behaviour and growth, and improves productivity. Moreover, this index may serve as one of the components or sub-indices of an individual comprehensive breeding value index. Other researchers have indicated that genomic information on purebred animals before selection allows better prediction of commercial performance. They work with large datasets based on imaging, sensors, and sound data, complicating animal selection processes. Therefore, it is recommended to use integral indices that include behavioural and welfare indicators (Howard, 2019).

In the studies by S. Kramarenko *et al.* (2019), analysis of microsatellite locus polymorphism in meat-type pigs revealed associations between specific alleles and reproductive traits, an important prerequisite for forming selection indices. The authors emphasised the effectiveness of genetic markers for evaluating boar breeding value and recommended integrating them into breeding programs using comprehensive breeding value indices. A statistically significant effect of boar breed on stillbirth rates was also established. Specifically, offspring of Duroc boars exhibited substantially higher stillbirth rates (15.0%) compared to other breeds (10.0-10.1%). These results confirmed the importance of considering boar breed characteristics when calculating comprehensive breeding value indices aimed at improving piglet viability and reducing reproductive losses in commercial breeding programs. Chinese researchers S. Ye *et al.* (2020) suggested including a breed fixation index based on allele composition in the integral index evaluation of boars, which can be useful for distinguishing breeds, lines, or specific crosses. Consequently, predicting breeding value using cluster assessment based on individual comprehensive integral indices holds potential for improving selection efficiency, reducing costs, and creating a platform that integrates approaches to enhance pig productivity, advance biological discoveries, and increase the economic profitability of the industry.

CONCLUSIONS

The reproductive performance of sows is influenced by the individual comprehensive breeding value index and the age of the boars. The highest fertility rate (86.4%), litter size at birth (11.4 piglets), and number of weaned piglets (7.9 piglets) were observed in sows inseminated with semen from boars with the highest individual integral indices in the "nucleus breeding" production class. Meanwhile, the highest piglet survival rate (68.3%) was recorded in sows inseminated with semen from young boars of the "reproductive group" with an individual breeding value index of 136. Overall, for most reproductive traits, sows inseminated with semen from young boars aged 12-18 months demonstrated superior performance. A clear relationship was confirmed between the age and class of the boar, as determined by the comprehensive breeding value index, and the maternal traits of sows according to reproductive assessment indices. Specifically, the highest values for most reproductive indicators were observed in sows inseminated with semen from young boars aged 12-18 months with the highest individual comprehensive index. SRQI values included 84.8 points, piglet viability index was 99.1%, reproductive traits index was 34.8 points, and litter uniformity was 0.90 points. Conversely, the use of older boars or animals with lower individual integral indices was associated with decreased reproductive performance in sows.

The influence of age and the individual comprehensive selection index of boars on semen productivity indicators was confirmed, regardless of their breeding purpose. In particular, young boars with high individual integral selection indices showed higher values of ejaculate volume is 332.6 ml, sperm concentration is 499.2 million/ml, and sperm motility is 8.7 points. At the same time, the number of semen doses obtained from a single ejaculate was higher in older boars, amounting to 32.8 doses. A correlation was also established between the age, individual integral breeding value index of boars, and both fertility and litter size in sows. Sows inseminated with semen from young boars had higher values for these traits is 86.4% fertility and 11.4 piglets per litter. A clear trend of the effect of age and the comprehensive selection index of boars on semen quality parameters was confirmed. Young boars with high comprehensive indices exhibited higher ejaculate index values – 4.20 and 4.06 points, respectively, as well as sperm productivity index values is 345.1 billion and 379.2 billion spermatozoa. In contrast, boars older than 18 months had lower values for these indices, indicating an age-related decline in semen quality.

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CONFLICT OF INTEREST

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Застосування комплексних інтегральних індексів кнурів-плідників в програмах розведення системи DanBred

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Анотація. Програми розведення свиней передбачають комплексну оцінку продуктивних і репродуктивних ознак у чистопородних лініях за допомогою індивідуальних племінних індексів, що дозволяє ефективно підвищити генетичний потенціал як помісних тварин для промислового виробництва, так і наступних поколінь племінного поголів'я. Такий підхід відрізняється від традиційних методів, які обмежуються оцінкою окремих ознак і уповільнюють генетичний прогрес. Метою дослідження було визначити доцільність використання індивідуальної інтегральної оцінки кнурів та встановити вплив їх віку та індивідуального селекційного індексу на репродуктивні та продуктивні якості. У дослідженні брали участь 304 свиноматки породи Дюрок, яких запліднювали спермою чотирьох кнурів різного віку, що належали до племінного ядра або репродуктивної групи, та їхнім комбінованим індексом племінної цінності, розрахованим за системою DanBred (не менше 130 балів для «племінного ядра» та 105 балів для «репродуктивної групи»). Було встановлено, що індивідуальний комплексний індекс та вік кнурів значно впливали на репродуктивну продуктивність свиноматок. Найкращі результати за репродуктивними показниками (індекс репродуктивної якості свиноматок – 84,8; життєздатність – 99,1 %; репродуктивний індекс – 34,8; однорідність приплоду – 0,90) були отримані від свиноматок, запліднених спермою молодих кнурів (12-18 місяців) з високими показниками. Старіші кнури або кнури з нижчими показниками племінної цінності показали гірші результати. Також було встановлено, що молоді кнури з високими показниками демонстрували кращу якість сперми (об'єм еякуляту – 332,6 мл; концентрація – 499,2 млн/мл; рухливість – 8,7 балів), хоча старші кнури давали більше доз для запліднення на еякулят (32,8). Ці результати підтверджують доцільність впровадження технології оцінки показників кнурів для підвищення ефективності селекційних програм в українській свинарській галузі

Ключові слова: селекційні програми; репродуктивні якості; свинарство; кластерна оцінка; якість сперми

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Establishment of effective chemical means of weed control in amaranth crops

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Abstract. The widespread introduction of amaranth into agricultural production in Ukraine, particularly in the sufficiently moist conditions of the Western Forest-Steppe, is hampered by a number of technological difficulties, one of the key ones being weed infestation of crops. The purpose of the study was to identify effective herbicides for weed control in amaranth crops in the conditions of the Western Forest-Steppe of Ukraine. Field studies to determine effective herbicides – promethrin (500 g/ha); clomazone (480 g/ha); fenmedifam (60 g/ha) + desmedifam (47 g/ha) + ethofumesate (75 g/ha) + lenacil (27 g/ha); fenmedifam (320 g/ha); triflusulfuron (500 g/ha); clopyralid (750 g/ha) on amaranth crops were conducted during 2021-2023 on the experimental field of the Department of Plant Growing Technologies of Lviv National University of Natural Resources under conditions of sufficient moisture. Control – variant with biological methods of weed control. It was found that all the herbicides studied were effective in controlling weeds. The lowest number of weeds was found in the variant using the herbicide prometrin (500 g/ha) – 1.6 pcs/m2, and the lowest weed weight was found when using the herbicide clopyralid, 750-108 g/m2. All herbicides under study had a suppressive effect on amaranth plants, as evidenced by the parameters of the crop structure. In particular, the panicle length was the longest in the control (64 cm) and decreased to 49-56 cm in the variants with herbicide application, the height was 32-52 cm shorter, and the weight of 1,000 seeds decreased to 0.68-0.80 g. All the herbicides under study also caused a decrease in amaranth yield by 0.40-1.37 t/ha due to the stress effect on the plants. The highest amaranth yield was obtained in the variant with biological weed control methods – 3.21 t/ha. In the variants using herbicides, the highest yield (2.81 t/ha) was provided by the pre-emergence herbicide prometrin at an application rate of 2 l/ha

Keywords: yield; herbicide; weight of 1,000 seeds; prometrin; Western Forest-Steppe

INTRODUCTION

Amaranth (*Amaranthus spp.*) is a highly productive crop with extremely valuable agronomic and biochemical properties, which is increasingly attracting the attention of Ukrainian farmers as a source of high-quality protein, oil, feed, and biomass. A particular feature of amaranth is its thermophilic nature and slow initial growth, which makes it especially vulnerable to weed competition during the first 3-5 weeks of the growing season. Yield losses due to weed infestation can reach 30-50%, especially in years with excessive spring rainfall. Weeds not only reduce yields but also hinder harvesting, degrade seed quality, and contribute to the

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development of diseases and pests. Therefore, there is an urgent need to identify the most effective and crop-safe herbicides that can provide reliable control of a wide spectrum of weeds without phytotoxic effects on amaranth. Given this context, research on herbicide protection in amaranth crops is of significant practical importance for developing effective cultivation technologies, reducing manual weeding labour, increasing yield stability, and enhancing the overall profitability of the crop.

As noted by E.V. Torres *et al*. (2024), amaranth has the potential to be a multipurpose crop of high value to the agro-industrial sector, serving as a source of protein, dietary fibre, antioxidants, and functional compounds for the food, pharmaceutical, and cosmetic industries. Particular attention was given to its agronomic traits, such as adaptability to adverse growing conditions, drought tolerance, and high biomass accumulation and grain yield. In the study by B. Mukuwapasi *et al*. (2024), amaranth was presented as a high-yielding, nutritious, and climate-resilient crop. Among its agronomic advantages are a short growing period, efficient water use, and resistance to biotic and abiotic stresses. The researchers emphasised that despite its adaptability to drought, high temperatures, and poor soils, and its exceptional nutritional value (high levels of protein, lysine, iron, and calcium), amaranth remains underutilised in agriculture across Africa, Asia, and other developing regions.

Ukrainian researchers T.I. Hoptsii *et al*. (2022) also highlighted the high potential of amaranth under climate change conditions, its drought tolerance, adaptability to light and moderately fertile soils, and the unique nutritional quality of its grain. Research conducted in the Poltava Oblast showed that domestically bred varieties provide grain yields of 2.1-2.7 t/ha, with high protein content (14-17%) and a favourable biomass ratio. T.I. Yaniuk & N.V. Grünwald (2022) stated that amaranth offers a promising alternative to traditional cereal crops in Ukraine due to its agronomic properties (resistance to temperature stress, high yield potential, and biological productivity) and nutritional benefits. Field studies of the influence of the characteristics of domestic varieties on the productivity of grain amaranth were conducted in the conditions of the Western Forest-Steppe of Ukraine. According to the studies, significant differences between the varieties were established in terms of biometric parameters of plants and grain yield. The varieties Kharkivskyi 1 and Lera demonstrated higher adaptability, greater biomass accumulation, and increased grain yield (over 2.5 t/ha) in the region under study (Tyrus & Lykhochvor, 2021).

However, the large-scale adoption of amaranth in agricultural production in Ukraine, particularly under the moderately humid conditions of the Western Forest-Steppe, is hindered by several technological challenges, among which weed infestation is one of the key issues. As a niche and relatively uncommon crop for industrial cultivation, no herbicides are currently registered for use on amaranth crops in either Ukraine or globally. According to N.I. Dudka (2020), weed control in amaranth fields primarily relies on biological methods, such as multiple shallow tillage operations before sowing, post-emergence harrowing, inter-row cultivation, and manual weeding. Mechanical weed control was also recommended by B. Melander & M.R. McCollough (2021). Given the botanical similarity between amaranth and sugar beet, the use of herbicides registered for sugar beet crops is suggested. These include Aramo 45, Betanal MaxxPro, Dual Gold, Caribou, Lontrel Grand, Pyramin Turbo, Frontier Optima, Fusilade Forte, etc. As of 2025, there were no registered herbicides for use in amaranth cultivation in Ukraine, therefore, the purpose of the study was to determine effective herbicides for weed control in amaranth crops under the conditions of the Western Forest-Steppe of Ukraine without negatively affecting the growth, development, and productivity of the crop.

MATERIALS AND METHODS

The research was conducted in 2021-2023 at the experimental field of the Department of Plant Production Technologies of Lviv National University of Life and Environmental Sciences. For the field trial, the preparations were taken that were experimentally established as the most tolerant to amaranth among 36 variants and provided positive results. The research scheme (Table 1) presented the most tolerant herbicides to amaranth, with the optimal application rate, established experimentally among 36 variants, and were appropriate for controlling the number of weeds.

Table 1. *Features of herbicide application in the experiment*

No.	Herbicide (Active ingredients, g/l; kg/ha)	Application rate	Due dates
1	Control	Two inter-row cultivation and manual weeding.	
2	Phenmedipham, 60 + Desmedipham, 47 + Etofumesate, 75 + Lenacil, 27	1.25 l/ha	After germination of amaranth in the cotyledon phase in weeds (BBCH 10)

Table 1, Continued

No.	Herbicide (Active ingredients, g/l; kg/ha)	Application rate	Due dates
3	Phenmedipham, 320	1.0 l/ha	2-6 leaves of amaranth (BBCH 12)
4	Prometrin, 500	2.0 l/ha	Immediately after sowing (BBCH 01)
5	Clomazone, 480	0.10 l/ha	Immediately after sowing (BBCH 01)
6	Triflusulfuron-methyl, 500	0.02 kg/ha	4-5 leaves of amaranth (BBCH 13)
7	Clopyralid, 750	0.1 kg/ha	4-5 leaves of amaranth (BBCH 13)

Note: *BBCH – system for uniformly coding phenologically similar stages of plant growth*
Source: *developed by the author*

The research compared the effectiveness of different herbicides by determining the residual weediness. The survey was carried out in the third ten days of July during the period of development of the largest mass of weeds. The soil of the experimental plot was dark grey podsolised with a humus content of 2.5%. The content of easily hydrolysed nitrogen was 78-84 mg, mobile forms of phosphorus and potassium (according to the Chirikov method) – 88-90 mg and 94-98 mg per 1 kg of soil, respectively. The reaction of the soil solution was close to neutral; the pH of the salt extract – -5.9-6.0 (DSTU 4115:2002, 2003). When analysing hydrothermal conditions over the study period, deviations from the long-term average were observed. The general trend was characterised by higher temperatures and increased precipitation. In 2021, there was sufficient moisture, but April was marked by temperatures below the long-term average. The following months – May, June and July – created favourable conditions for the emergence and development of amaranth seedlings. The weather conditions in 2022 were characterised by a cold April and a moisture deficit during the spring and summer period covering April, May, and June. In 2023, April was also marked by low temperatures, and May was characterised by insufficient rainfall. The situation changed significantly in the summer months, when in June and July, the average long-term precipitation rate was recorded by 24.4 and 31.7 mm above the long-term average, respectively. The experimental area was 10 m^2, the replication of the experiment was four-fold. Plots were placed systematically. 7 variants of weed control were investigated on the variety Kharkivskyi 1.

The amaranth's predecessor was winter wheat. After harvesting the predecessor, the field was disked and autumn ploughing was carried out and phosphorus and potash fertilisers – $P_{60}K_{120}$ were applied. At the first opportunity to enter the field, closed the moisture with the following two cultivations. Pre-sowing soil cultivation was carried out to the depth of seed placement, using the combined tool "Compactor" (Profi Stan). Nitrogen fertiliser (N_{160}) was applied in the spring for pre-sowing tillage. Seeds were sown in a row method to a depth of 2 cm in the third ten days of April in all three years of research. The seeding rate was 0.4 million/ha. A Horsch Pronto 4 DS seed drill was used. Harvesting of amaranth was carried out in two stages: mowing – in the phase of full seed ripeness in the lower and middle parts of the panicle, after drying the panicles of amaranth were threshed. The statistical data were processed through analysis of variance (ANOVA) in the Statistica 13 software. Comparisons between data sets were performed using the Tukey test. Differences among samples were deemed statistically significant at $p < 0.05$. The tabulated data were presented as arithmetic means accompanied by standard deviations ($x \pm$ SD). Correlation analysis based on Pearson correlation coefficients was conducted to test statistical hypotheses concerning the functional relationships between the experimental indicators. The strength and direction of relationships between variables were interpreted according to the standard scale ($r = \pm 0.1$-0.3 – weak; ± 0.3-0.7 – moderate; ± 0.7-1.0 – strong). Regression equations and statistical models of the relationship between dependent and independent variables were created using "Statistica 13" software. The ethical guidelines for treating plants were followed during experimental research, including gathering plant material. The Convention on Biological Diversity (1992) provisions were met by the authors.

RESULTS AND DISCUSSION

In the conditions of sufficient moisture in the Western Forest-Steppe, the problem of weed infestation arises annually. The nature of weed infestation determines the ratio between the main biological groups of weeds, and the degree of weed infestation determines the number of weeds (pcs/m^2) and their weight (g/m^2). It should be borne in mind that a larger number of weeds per unit area with a small mass causes less damage to amaranth plants than a large mass of weeds even at a significantly lower density. In this study the number of weeds in the amaranth crops was low. The lowest number of them was in the variant with the use of the herbicide prometrin 1.6 pcs/m^2 (Fig. 1).

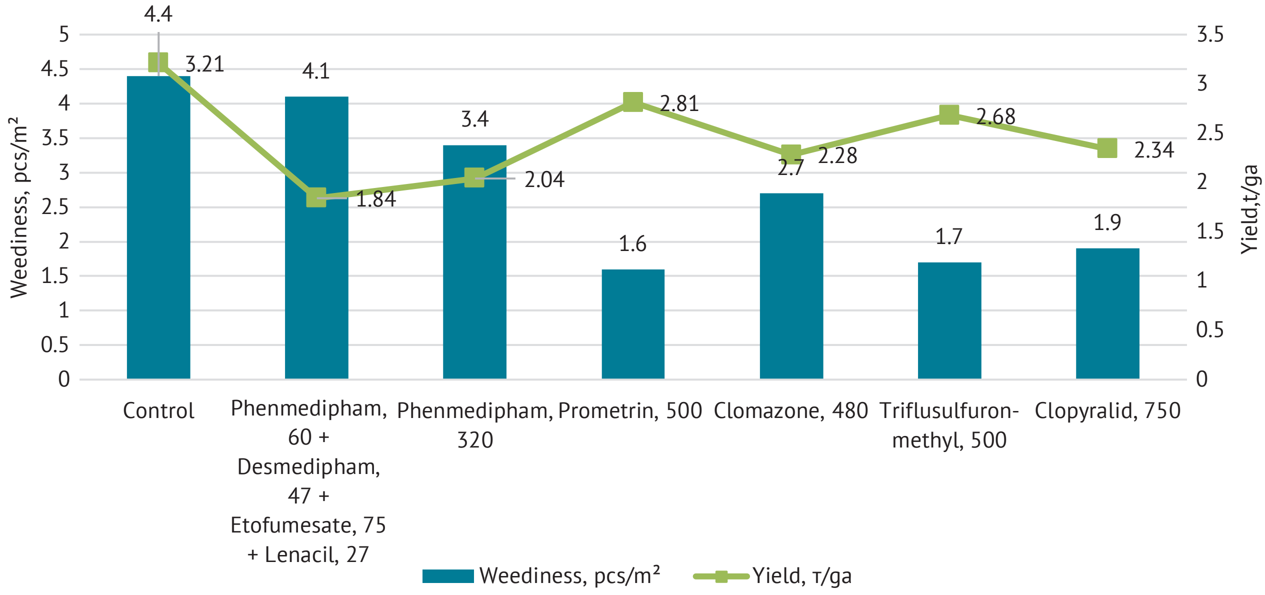

***Figure 1.** Effect of herbicide on weediness and yield of amaranth variety Kharkivskyi 1*

***Source:** developed by the author*

The statistical analysis revealed a strong inverse relationship between the number of weeds and the herbicide, with a correlation coefficient of $r = -0.91$ (Fig. 2). This pattern can be represented by a regression equation:

$$Weediness,\ g/m^2 = 228.00 - 19.43 * Herbicide, \quad (1)$$

the coefficient of determination: $R2 = 0.83$.

This can be explained by the good effectiveness of herbicides in the first 40 days of the amaranth's vegetation. In addition, amaranth has a high ability to compete with weeds when it reaches the 10-leaf stage. The rapid development of sufficient optical density of amaranth crops allows reliably controlling the emergence of plants of repeated summer weeds. Herbicides of the betanal group in the second and third variants less effectively controlled the level of weeds and significantly suppressed amaranth plants. The weed weight was also lower when prometrin was applied (113 g/m^2), and the lowest when clopyralid was used (108 g/m^2) (Table 2).

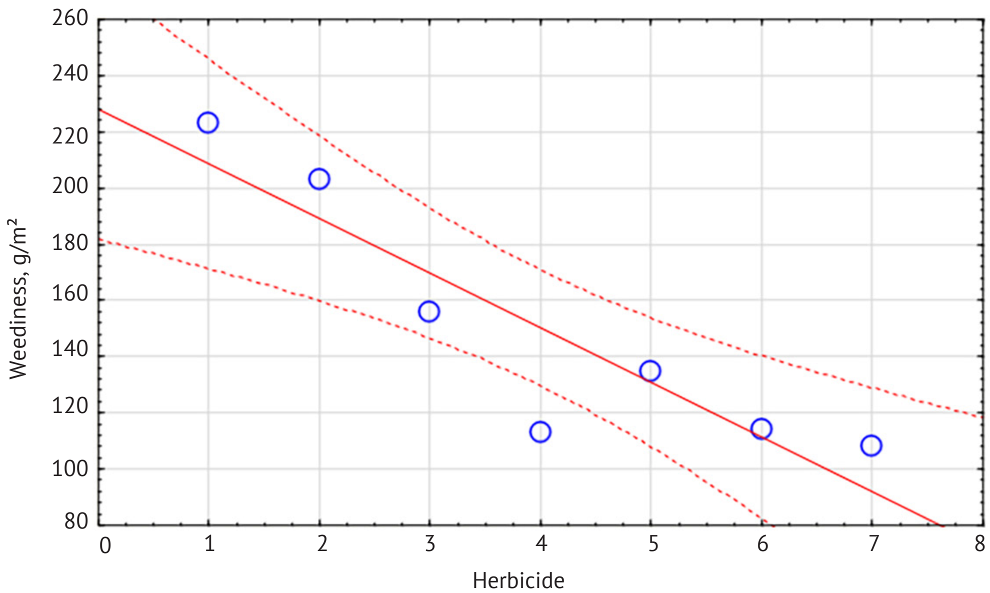

***Figure 2.** Statistical model of the herbicide effect on weed infestation of amaranth crop*

***Source:** developed by the author*

Table 2. *Level of weed infestation in amaranth crops depending on herbicide, average for 2021-2023*

Types of weeds	No. 1	2	3	4	5	6	7
Chenopodium album L.	0.5/30	0.1/16	0.8/32	-	0.1/14	-	0.3/24
Galium aparine L.	0.3/15	0.2/10	0.2/12	0.1/14	-	0.2/11	0.2/14
Thlaspi arvense L.	0.3/15	0.1/14	-	-	-	-	0.3/18
Sinapis arvensis L.	0.3/18	0.1/10	0.2/10	-	0.1/10	0.1/12	0.4/19
Tripleurospermum inodorum L.	0.5/25	0.4/21	0.6/24	0.1/10	0.2/12	0.1/12	-
Cirsium arvense L.	0.4/28	0.4/26	0.5/23	0.3/20	0.4/20	0.4/20	-
Sonchus oleraceus L.	0.4/22	0.3/19	0.3/21	0.2/16	0.2/17	0.3/18	-
Polygonum persicaria L.	0.4/18	1.4/40	0.2/14	0.2/20	0.5/19	0.1/12	0.2/15
Polygonum convolvulus L.	0.5/21	0.3/18	0.4/17	0.3/15	0.6/23	0.3/15	0.3/18
Polygonum scabrum Moench.	0.8/31	0.8/29	0.2/15	0.4/18	0.6/20	0.2/14	-
Total	4.4/223	4.1/203	3.4/156	1.6/113	2.7/135	1.7/114	1.9/108

Note: *numerator – pcs/m2, denominator – g/m2*
Source: *developed by the author*

The control was the weediest, with 4.4 plants per m^2 and a weight of 223 g/m^2. Notably, in the studies conducted there is no direct correlation between the weight and number of weeds and the yield of amaranth grain. Analysis of the elements of the yield structure clearly shows the suppressive effect of herbicides on amaranth plants. This was especially evident in the height of the plants. On the control without chemical weed control, the height of plants was much higher (220 cm) compared to other variants (Table 3).

Table 3. *Crop structure elements depending on herbicide, average for 2021-2023*

Herbicide	Plant height, cm	Panicle length, cm	Weight 1,000 seeds, g	Seed weight 1 plant, g
Control	220 ± 5.77a	64 ± 1.83a	18 ± 0.32a	0.84 ± 0.016a
Phenmedipham, 60 + Desmedipham, 47 + Etofumesate, 75 + Lenacil, 27	168 ± 3.65bcf	49 ± 0.82bcfg	10 ± 0.22b	0.68 ± 0.016bf
Phenmedipham, 320	170 ± 4.08cef	51 ± 0.82bcfg	12 ± 0.26c	0.73 ± 0.014cfg
Prometrin, 500	188 ± 4.4dg	56 ± 1.15de	16 ± 0.34de	0.80 ± 0.018de
Clomazone, 480	178 ± 3.74efg	56 ± 1.41de	16 ± 0.36de	0.78 ± 0.018dfg
Triflusulfuron- methyl, 500	171 ± 3.65bceg	51 ± 1.15bcfg	14 ± 0.34fg	0.70 ± 0.008bcef
Clopyralid, 750	180 ± 3.92gdef	51 ± 0.82bcfg	14 ± 0.36fg	0.74 ± 0.016ceg

Note: *values that have at least one identical letter within a table column do not differ when using the Tukey test ($p < 0.05$)*
Source: *developed by the author*

Thus, the difference between the control and the variant with the application of phenmedipham + desmedipham + etofumesate + lenacil herbicide was 52 cm. When using the herbicide prometrin, which was relatively tolerant to amaranth, the height of the plants was also 32 cm less. The length of the panicle was also the longest in the control (64 cm), and decreased to 49-56 cm in the variants with herbicides. The weight of grain per plant varied in a significant range and had a strong relationship with yield, as evidenced by the correlation coefficient $r = 0.87$. While in the variant without herbicide application, the grain weight was 18 g per plant, this figure decreased to 10 g with phenmedipham + desmedipham + etofumesate + lenacil due to the severe herbicide stress for amaranth plants. Herbicides also had a negative effect on the weight of 1,000 seeds. In the control, it was 0.84 g, and in the variants with chemical weed control, it decreased to 0.68-0.80 g. The reduction of all elements of the crop structure led to a natural decrease in the yield of amaranth grain, despite the fact that the level of weeds was lower when herbicides were applied. This was confirmed by the results of statistical analysis: a strong relationship was found between plant height, panicle length, weight of 1,000 seeds, and yield, where the correlation coefficient was $r = 0.84$, $r = 0.81$, $r = 0.76$, respectively. The herbicide phenmedipham + desmedipham + etofumesate + lenacil provided a certain control of weeds, but simultaneously, this variant had the lowest yield (1.84 t/ha) in the experiment (Table 4).

Table 4. *Grain yield of amaranth variety Kharkivskyi 1 depending on herbicide, t/ha*

No.	Herbicide	Years			Average for years, t/ha	Increase to control	
		2021	2022	2023		t/ha	%
1	Control	3.22±0.068a	3.35±0.048a	3.06±0.078a	3.21	-	-
2	Phenmedipham, 60 + Desmedipham, 47 + Etofumesate, 75 + Lenacil, 27	1.84±0.050b	1.92±0.054b	1.76±0.042bc	1.84	-1.37	-42.7
3	Phenmedipham, 320	2.12±0.047c	2.16±0.051c	1.84±0.068bc	2.04	-1.17	-36.4
4	Prometrin, 500	2.87±0.065d	2.91±0.071df	2.65±0.057df	2.81	-0.40	-12.5
5	Clomazone, 480	2.27±0.048eg	2.34±0.060e	2.23±0.050eg	2.28	-0.93	-29.0
6	Triflusulfuron-methyl, 500	2.71±0.056f	2.79±0.063fg	2.54±0.051df	2.68	-0.53	-16.5
7	Clopyralid, 750	2.39±0.056eg	2.43±0.039fg	2.20±0.104eg	2.34	-0.87	-27.1

Note: *values that have at least one identical letter within a table column do not differ when using the Tukey test ($p < 0.05$)*
Source: *developed by the author*

The herbicide phenmedipham + desmedipham + etofumesate + lenacil is widely used in sugar beet cultivation and is recommended in many recommendations for use in amaranth crops, but in studies it suppressed the crop plants and did not provide proper weed control. Visually, there was no burning of amaranth plants from the application of herbicides in any variant. However, the plants slowed down for some time in all variants compared to the control, which indicates that they were exposed to herbicide stress. The use of phenmedipham resulted in a sharp decrease in yield compared to the control by 1.17 t/ha, and it also proved to be quite stressful for amaranth. Prometrin herbicide proved to be the most tolerant to amaranth plants. The yield after its application was 2.81 t/ha. The highest yield (3.21 t/ha) was obtained in the control without the use of herbicides. The biological method of weed control was almost as effective as the chemical method, and the amaranth plants did not suffer from herbicide stress. The results of field experiments have shown that weeds can be effectively controlled using biological methods even in conditions of sufficient moisture. This allows producing environmentally friendly products with a much higher price and increasing the profitability of amaranth cultivation.

Amaranth had attracted growing attention as a promising crop due to its high nutritional value and adaptability to diverse environmental conditions. Despite its potential, the cultivation of amaranth faced a number of agronomic challenges, among which weed competition remained one of the most critical. However, there are a number of scientific papers on the resistance of Amaranthus weeds to several classes of herbicides. In particular, G.B.P. Braz & H.K. Takano (2022) conducted research focusing on the mechanisms of multiple resistance observed in Amaranthus species in different regions of the world and analysed the effectiveness of contemporary herbicides and combinations of active ingredients. Particular attention is paid to ways of reducing selective pressure on weeds, recommendations for herbicide rotation and integrated control methods. The review emphasised the importance of a comprehensive approach to managing resistant Amaranthus biotypes in agricultural systems, particularly in Brazil, where the problem is widespread. The study by X. Guo *et al.* (2024) investigated the effects of long-term use of the herbicide fomesafen on weeds, particularly *Amaranthus retroflexus* L. (common pigweed), in fields in China. The results showed that the systematic use of fomesafen led to the accumulation of *A. retroflexus* seeds in the soil, and a significant increase in its resistance to this active ingredient. Biological tests demonstrated that new generations of this weed had reduced sensitivity to fomesafen, indicating the development of resistance at the population level. The results of a study conducted by C.W. Beiermann *et al.* (2022) in the United States showed that post-emergence treatment (imazamox + bentazon) provided poor control of Palmer amaranth and did not result in a sustained reduction in Palmer amaranth density and biomass compared to the untreated control. Data on the presence of acetolactate synthase (ALS) inhibitor and glyphosate-resistant Palmer amaranth have been confirmed in Nebraska and are widespread in several counties (Mausbach *et al.*, 2021).

The study by D.I. Chaudari *et al.* (2019) presented results on the impact of integrated weed management on productivity development in grain amaranth (*Amaranthus hypochondriacus* L.) under conditions of South Gujarat, India. The field experiment included the use of pendimethalin (1.0 kg/ha a.i.) as a pre-emergence herbicide and quizalofop-p-ethyl (50 g/ha a.i.) as a post-emergence herbicide, combined with hand weeding. The highest grain yield (1,650 kg/ha) and net profit were achieved with the treatment involving pendimethalin followed by hand weeding on the 30th day after sowing. There is a significant lack of research on herbicide resistance in amaranth. Findings by P. Kudsk *et al.* (2012) demonstrated that amaranth is highly sensitive to herbicides targeting broadleaf weeds. Among the herbicides tested, amaranth tolerated only the active ingredients clomazone, clopyralid, phenmedipham, and triflusulfuron. Application of clomazone in the early post-emergence phase, instead of pre-emergence, ensured full crop tolerance even at the highest application rates. The post-emergence herbicides phenmedipham and triflusulfuron caused less crop injury at the 4-6 leaf stage compared to the 2-4 leaf stage, whereas clopyralid remained selective at both growth stages. J.S. Desai (2021) evaluated the effectiveness of integrated weed management in grain amaranth (*Amaranthus hypochondriacus* L.) at the experimental farm of Sardarkrushinagar Dantiwada Agricultural University. The results showed that the most effective approach was a combination of strategies, particularly inter-row cultivation 20-30 days after sowing along with the use of the herbicides pendimethalin and oxyfluorfen. This approach resulted in the lowest weed density and the highest grain yield (~1.5-1.7 t/ha). The researcher emphasised the value of an integrated method as a balance between effective weed control and reduced chemical load on the agroecosystem.

The effectiveness of biological weed control methods was confirmed by research conducted by scientists from various countries and soil-climatic zones. In a study by S. Deryło & Ł. Chudzik (2015), the impact of different primary soil tillage methods on the yield of cultivated amaranth (*Amaranthus hypochondriacus* L.) was investigated in Poland. The results showed that some fewer intensive methods, particularly shallow and disc tillage, can provide stable yields and help preserve soil moisture. Field experiments conducted in 2018 and 2019 in central Italy, which compared several mechanical weed control practices in grain amaranth (*Amaranthus cruentus* L.), demonstrated that selecting the optimal plant density and proper row spacing is also crucial for effective mechanical weed management (Casini & Biancofiore, 2020; Casini *et al.*, 2022). A field experiment conducted by J.S. Desai *et al.* (2023) at the Agricultural College Farm of SDAU compared 10 weed management strategies in grain amaranth (*Amaranthus hypochondriacus* L.), including herbicides (pendimethalin, oxadiargyl, oxyfluorfen), mechanical inter-row cultivation at 3-4 weeks after sowing, combined approaches, and weed-free control. The lowest weed density (4.07 plants/m²) and minimum weed dry biomass (4.81 g/m²) were recorded with oxyfluorfen (50 g/ha) combined with inter-row cultivation at the 4th week. Although the weed-free treatment was the most effective, the combination of herbicide and cultivation provided comparable efficacy with reduced labour input. This approach was deemed optimal under conditions of labour scarcity.

The benefits of combining chemical and mechanical weed control for increased productivity and profitability of grain amaranth under subtropical conditions were further supported by K. Patidar *et al.* (2024). The highest plant biomass, grain yield, and net returns were achieved with an integrated system: pre-sowing application of pendimethalin (1.0 kg/ha) + inter-row cultivation on day 30. While manual weeding was also effective, it required significantly more labour input. The study by S.R. Anand *et al.* (2025) examined the effect of different weed control methods on the growth and yield of grain amaranth (*Amaranthus hypochondriacus* L.) in North Indian conditions (Faizabad, Uttar Pradesh). The experiment included a comparison of hand weeding, inter-row cultivation, mulching and herbicide options. The highest yield and biomass were obtained when combining two-time hand weeding (20 and 40 days after sowing) with inter-row loosening. The results confirm the effectiveness of mechanical methods as an environmentally safe alternative to herbicides for amaranth.

CONCLUSIONS

All herbicides tested phenmedipham (60 g/ha) + desmedipham (47 g/ha) + etofumesate (75 g/ha) + lenacil (27 g/ha) (post-emergence); phenmedipham (320 g/ha) (post-emergence); prometrin (500 g/ha) (pre-emergence); clomazone (480 g/ha) (pre-emergence); triflusulfuron-methyl (500 g/ha) (post-emergence); clopyralid (750 g/ha) (post-emergence) were effective in controlling weeds. The lowest number of weeds was observed in the variant using the herbicide prometrin (500 g/ha) – 1.6 pcs/m^2. The weight of weeds was also lower when prometrin (500 g/ha) was applied – 113 g/m^2, and lowest when clopyralid herbicide was used, 750-108 g/m^2.

All the herbicides under study had a suppressive effect on amaranth plants, as evidenced by the yield structure parameters. In particular, the panicle length was the greatest in the control (64 cm) and decreased to 49-56 cm in the variants with herbicide application, while the height was 32-52 cm lower. Herbicides also had a negative effect on the weight of 1,000 seeds. In the control, it was 0.84 g, and in the variants with chemical weed control, it decreased to 0.68-0.80 g. In the variant without herbicides, the grain weight was 18 g per plant, while with the use of phenmedipham, 60 + desmedipham, 47 + etofumesate, 75 + lenacil, 27, this indicator was the lowest in the experiment – 10 g due to severe herbicide stress on amaranth plants. All the herbicides under study also caused a decrease in amaranth yield by 0.40-1.37 t/ha due to the stress effect on the plants. The highest yield of amaranth was formed in the variant without the use of herbicides with biological methods of weed control – 3.21 t/ha. In the variants with the use of herbicides, the highest yield (2.81 t/ha) was provided by the pre-emergence herbicide prometrin (500 g/ha) at an application rate of 2 l/ha. There is a need to continue investigating the specifics of herbicide use in amaranth crops, in particular, to clarify the active ingredients, rates, and timing of their application.

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Встановлення ефективних хімічних засобів регулювання чисельності бур'янів в посівах амаранту

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Анотація. Широке впровадження амаранту у сільськогосподарське виробництво в Україні, зокрема в умовах достатнього зволоження Західного Лісостепу, стримується низкою технологічних труднощів, серед яких одним із ключових є забур'яненість посівів. Метою дослідження було визначення ефективних гербіцидів для боротьби з бур'янами в посівах амаранту в умовах Західного Лісостепу України. Польові дослідження з встановлення ефективних гербіцидів – прометрин (500 г/га); кломазон (480 г/га); фенмедіфам (60 г/га) + десмедіфам (47 г/га) + етофумезат (75 г/га) + ленацил (27 г/га); фенмедіфам (320 г/га); трифлусульфурон (500 г/га); клопіралід (750 г/га) на посівах амаранту проводили впродовж 2021-2023 рр. на дослідному полі кафедри технологій у рослинництві Львівського національного університету природокористування в умовах достатнього зволоження. Контроль – варіант з біологічними методами боротьби з бур'янами. Встановлено, що всі досліджувані гербіциди були ефективні щодо контролю бур'янів. Найменша кількість бур'янів була на варіанті з використанням гербіциду прометрин (500 g/ha) – 1,6 шт/м^2, а найнижча маса бур'янів за використання гербіциду клопіралід, 750-108 г/м^2. Всі досліджувані гербіциди виявляли пригнічувальну дію на рослини амаранту, про що свідчать параметри структури врожаю. Зокрема, довжина волоті була найбільша на контролі (64 см), і зменшувалася до 49-56 см на варіантах із застосуванням гербіцидів, висота була меншою на 32-52 см, маса 1000 насінин знизилась до 0,68-0,80 г. Всі досліджувані гербіциди внаслідок стресового впливу на рослини амаранту також спричинювали зменшення його врожайності на 0,40-1,37 т/га. Найвища врожайність амаранту формувалась на варіанті з біологічними методами боротьби з бур'янами – 3,21 т/га. На варіантах з використанням гербіцидів вищу урожайність (2,81 т/га) забезпечив препарат досходовий гербіцид прометрин за норми внесення 2 л/га

Ключові слова: врожайність; гербіциди; маса 1000 насінин; прометрин; Західний Лісостеп

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