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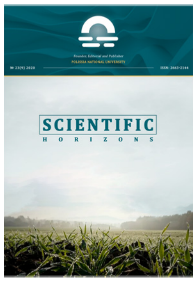

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Patterns of winter wheat ear productivity formation depending on the content of trace elements in the soil

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Abstract. The study of patterns of the formation of ear productivity depending on the content of potentially bioavailable Fe, Mn, Zn, Cu in the soil, the stochastic formalization of such patterns are important for a more profound understanding of the conceptual and mechanistic aspects of the dependence of yield development on the levels of nutrient supply of winter wheat under the conditions of environmentally friendly fertilization systems. The purpose of this study was to find statistically significant interdependencies, significant and relevant univariate or multivariate

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regression equations of the dependence of the mass of grains of ear^{-1} of winter wheat on the content of potentially bioavailable Fe, Mn, Zn, Cu in the soil, arguments and explanations of such subordinations under the conditions of environmentally friendly fertilization systems. The following methods were used in the study: field, laboratory-analytical, mass-spectrometric, mathematical-statistical (Student's *t*-test, *ANOVA*, correlational, single- and multivariate regression analyses). The applied green fertilization systems based on pea straw or pea straw + $N_{30}P_{45}K_{45}$, or $N_{60}P_{90}K_{90}$, only $N_{60}P_{90}K_{90}$ caused an increase in the weight of grains of one ear of winter wheat, the content of mobile forms of Fe, Mn, Zn, Cu in the grey forest soil under this culture (earing phase), compared to the control (without fertilizers). Substantial and significant Pearson correlation coefficients between the mass of grains of an ear of wheat and the content of mobile Fe, Mn, Zn, Cu in the soil, the corresponding contents of Mn and Zn, Cu and Zn, as well as the coefficients of partial correlation of the mass of grains of ear^{-1} of wheat – Cu, Mn – Zn testified to the complex structure of interdependencies between the traits under study. Reliable, relevant single- and multifactorial regression dependences of the mass of grains of ear^{-1} on linear combinations of products of independent variables (the content of mobile Fe, Mn, Zn, Cu in the soil) and/or such variables in indicators of natural powers 2-4 (fragments of the Kolmogorov-Gabor polynomial) were found. The coverage of regularities in the formation of the productivity of the ear of winter wheat depending on the content of potentially bioavailable microelements in the soil under the conditions of environmentally friendly fertilization systems will enable the theoretical substantiation and development of the latest strategies of mineral and ecological engineering of agricultural systems to maintain prominent levels and biological safety of the harvest of the specified crop

Keywords: ecological fertilization systems; winter wheat; trace elements; correlation; regression

INTRODUCTION

The problem of unbalanced management of soil resources, the use of intensive technologies without proper replenishment of nutrients and limitations of biological approaches has led to nutrient deficiencies and imbalances in soils of various genesis, as well as to stagnation of productivity in many countries. Special problems are observed in grey forest podzolized soils of Ukraine due to soil-forming processes that cause glaciation and leaching of trace elements. Solving these problems involves the development of "soft" approaches to increasing the efficiency of ecosystem services of agrophytocenoses using eco-friendly fertilizer systems (EFS). EFSs include moderate rates of mineral fertilizers with bio-effectors and/or trace elements to improve the yield of agricultural crops. Currently, it is important to investigate the patterns of formation of the final productivity of winter wheat depending on the content of mobile forms of essential microelements in the soil when using EFS on grey forest podzolized soils.

According to established ideas, conceptualized, specifically, by A.K. Shukla *et al.* (2018), the need of plants, including cereals, for micronutrients for optimal growth and development is undeniable, while the problem of deficiency of such chemical elements has been significant in many agricultural lands of the world for at least the last seventy years. According to the theoretical and methodological approaches that proceed from the above, A. Jalal *et al.* (2020) found that the number of days to flowering, productive shoots, plant height, wheat yield components were significantly dependent on the rates of application of $ZnSO_4 \cdot 7H_2O$ or $FeSO_4 \cdot 7H_2O$ to the soil (interactive effects occurred several days before flowering). However, in recent years, the frontier of scientific questions concerning the aspects of mineral nutrition of plants has shifted towards harmfulness and dualistic role (e.g., hormesis) of micronutrients in the life of plants, bioremediation, as stated, specifically, in the studies by E. Muszyńska and M. Labudda (2019), A. Rizvi *et al.* (2020). A considerable alternative to the above-listed areas of scientific research, as well as established organic, integrated agriculture, etc., are developed by German authors B. Zimmermann *et al.* (2021) approaches of Mineral-Ecological Cropping Systems (MECS), in which new and existing technologies are combined with agro-ecological practices to stimulate natural regulatory processes, non-chemical plant protection (generally, complete rejection of pesticides), as well as optimization of mineral fertilizer rates. It is advisable to casually apply the components of precision farming and/or treatment of soil, plants with bio-effectors, microelements with the specified set of measures. In this context, it is important to use microbiological fertilizers (e.g., soil inoculation), which contain cellulose-destroying (generally, biodegrading) microorganisms, with the aim of accelerated decomposition of crop residues (Yadav & Sarkar, 2019).

It is also known that the systematic involvement of various crop rotations in organic farming practices leads to increased inoculation of the root system with arbuscular mycorrhizal fungi (AMF), and the subsequent increase in the amount of absorption of nutrients by plants (AMF, as an alternative to chemical fertilizers) (Kaur & Purewal, 2019). It is appropriate to note the arguments of Y. Su *et al.* (2021) regarding the ambiguous influence of straw return on the accumulation of heavy metals and trace elements in soils. According to these authors, "dissolution effects" caused by a decrease or differential changes in soil pH, a transient decrease in the redox potential, and the formation of considerable amounts of dissolved organic matter (DOM) after the introduction of straw, as well as complex formation between DOM and metal ions, microbial methylation of metals in the soil lead to the release of macro- and microelements from the indicated plant residues, which can affect the physiological, biochemical, and biometric indicators of plants. The stated positions partially contradict the previous notion that the return of straw has the properties of mainly reducing the bioavailability of metals in the soil, however, it is consistent with the analysis performed by S.S. Dhaliwal *et al.* (2019) towards the ability of soil OM (SOM), namely plant residues, to increase the levels of mobility and bioavailability of trace elements. It is worth reminding that micronutrients and heavy metals can enter the soil from impurities contained in commercial mineral fertilizers (Ali *et al.*, 2020).

An alternative to the bioeffectors listed above in MECS, EFSs are biostimulants (BS), which, according to the du Jardin classification, include humic substances (HS), compositions of proteinogenic and non-protein amino acids (AA), growth stimulants (microorganisms or phytohormones), etc., which have properties aimed at increasing the level of plant tolerance to abiotic stress (Halpern *et al.*, 2015). Under the conditions of both applications to the soil and treatment of plants, HS cause a considerable improvement in the absorption of macro- and microelements (e.g., N, P, Fe, Mn, Zn, Cu) due to, among other things, an increase in their solubility, chelation, other signs of bioavailability, auxin-like activity of stimulating the development of root hairs, roots, including lateral ones (Halpern *et al.*, 2015). AA, which are part of BS, are often directly or indirectly involved in the regulation of the redox state of plants and play an important role in protecting the growth of these organisms from oxidative stress and detoxification of heavy metals (García-García *et al.*, 2020). Cytokinins (CK), which are part of BS or, e.g., biohumus, take part in many key events and functions at all levels of plant organization, specifically, activation of the cell cycle, the possibility of which depends on the level of providing plants with nutrients; also CKs play a crucial role in the control mechanisms of bacterial pathogenesis and contribute to mitigating the adverse effects of abiotic stress in plants (Wong *et al.*, 2020).

Thus, all the components, their combinations, based on which the ESFs proposed in this study are built, have real or potential properties towards changes in the levels of providing agricultural crops with macro- and microelements. However, the formation patterns of the final productivity of winter wheat depending on the content of the necessary bioavailable microelements in the substrates depleted by them under the conditions of EFSs, the corresponding mathematical and statistical formalizations and interpretations resulting from them, still lack coverage in the scientific literature.

The purpose of this study was to investigate the regularities of formation of (1) the productivity of the ear of winter wheat, (2) the content of potentially bioavailable Fe, Mn, Zn, Cu in the grey forest podzolized soil under these plants; to formalize the dependence of wheat traits (1) on soil properties (2) and to find relevant interpretations of such dependences using the methods of two- and multivariate statistics.

MATERIALS AND METHODS

The field experiment was conducted in 2019-2020 under the conditions of an experiment to investigate the productivity of crop rotations of the Institute of Agriculture of the Carpathian Region, Stavchany village, Lviv district, Lviv region. Micro-plot experiment, plot area – 1 m^2, distance between plots – 1 m, repetition – 6 times. The scheme of the field experiment was as follows: 1) control – without fertilizers; 2) pea straw; 3) pea straw + $N_{30}P_{45}K_{45}$; 4) pea straw + $N_{30}P_{45}K_{45}$ + BS (biological stimulator); 5) pea straw + $N_{30}P_{45}K_{45}$ + BS + HF (humus fertilizer); 6) pea straw + $N_{30}P_{45}K_{45}$ + BS + MF (microbiological fertilizer); 7) pea straw + $N_{30}P_{45}K_{45}$ + CF (chelated fertilizer); 8) $N_{60}P_{90}K_{90}$; 9) $N_{60}P_{90}K_{90}$+ BS; 10) $N_{60}P_{90}K_{90}$ + BS + manure (afteraction); 11) $N_{60}P_{90}K_{90}$ + BS + HF; 12) $N_{60}P_{90}K_{90}$ + BS + MF; 13) $N_{60}P_{90}K_{90}$ + HF. On the listed micro-plots, winter wheat (*Triticum aestivum* L.) of the Benefis variety was grown after field peas (*Pisum sativum* L.). Therefore, experimental fertilization systems were composed on the basis of pea straw, pea straw + $N_{30}P_{45}K_{45}$ (variants – var. 2, 3-7) or $N_{60}P_{90}K_{90}$ and $N_{60}P_{90}K_{90}$ with the addition of BS, HF, MF, CF (var. 8, 9-13).

The soil of the experimental plots was grey forest with a superficial glaciation, light loam. Physical and chemical and agrochemical parameters of the soil (depth 0-30 cm) before the experiment, characteristics of biological preparations, methods of their use were described earlier (Dubytskyi *et al.*, 2022).

Climatic conditions in the autumn of 2018 and 2019 were characterized by a uniform distribution of the sums of active temperatures (average – 0.3-0.5°C higher than the long-term annual average – LAA), precipitation amounts (PA; close to LAA). In April 2019, 2020, there was a 27-38% decrease in PA, in May – an increase of 1.3-1.6 times, compared to LAA. In the phase of earing and filling of grain, there was a 10-12% lack of moisture (2019) or overmoistening with temperatures, on average, 2.6°C higher, relative to LAA (2020). In general, the vegetation conditions ensured satisfactory growth and development of winter wheat.

The selection of soil samples (depth 0-30 cm) from experimental variants and their preparation for laboratory and analytical work was carried out pursuant to DSTU ISO 11464-2001 (2003) after the onset of the earing phase of winter wheat. The contents of mobile forms of trace elements MF-Fe, MF-Mn, MF-Zn, MF-Cu were determined according to DSTU 4770.6:2007

(2005): by extracting from air-dry soil with 1 M ammonium acetate buffer solution (AAB, pH 4.8), and in the following – measuring the absorption values of the obtained extracts at λ = 248.3, 279.5, 2 13.9, 324.7 nm, respectively, using a C-115M1 atomic absorption spectrophotometer (3 repetitions, 2 analytical parallels, *n*=6). The mass of ears of grain^{-1} per plant was determined in the phase of wax maturity (analytical balance Radwag AS 220/R2, Poland (±0.0001 g); 3 repetitions, 4 plants per repetition, *n*=12). The specified indicator was calculated according to certain principles of generally accepted approaches (Yeshchenko, 2014) and their specifications. The final values of each characteristic were obtained by averaging their values over 2 years of research (2019-2020).

Group analysis of statistical significance of differences in results was performed using *ANOVA* (α=0.05) in Excel 11.0.6560.0. In addition, in the specified program, estimates of the standard errors of the differences between the means (*SEDM*), Student's *t*-test, *df*, according to the formulas given in (Woodward, 2014), of the corresponding P values were calculated. Data were tested for normal distribution in Gretl 2021b. The Pearson correlation coefficients, partial correlation, and their significance levels were calculated in STATISTICA Version 10. The parameterization of linear univariate and multivariate regression equations using the method of ordinary least squares (OLS) (dependent variable y is the mass of grains per ear^{-1} per plant; independent variables x_1, x_2, x_3, x_4 are the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu, respectively, in soil), as well as principal component analysis (PCA, the *PC* number = number of independent variables) were performed in Gretl 2021b. OLS regression on *PC* (PCR), iterative Ridge regression methods (IRR, number of λ values = 100), ILASSO (Iterative Least Absolute Shrinkage Regression and Selection Operator, number of λ values = 100) on standardized x_{s_1}, ..., x_{s_4} were performed in the same program. To calculate the empirical OLS-regression coefficients ($b_{j(OLS\_PC)}$) from the PCR coefficients ($\beta_{j(PCR)}$), the authors of this study used the ratios of the corresponding matrices given by W.F. Massy (1965) and G. Sanchez and E. Marzban (2020). Briefly: the equation of the multiple regression of y_s on the standardized x_{s_1}, ..., x_{s_4} was substituted into the OLS regression expression of the standardized y_s on PC_1 in symbolic form, where the coefficients were the loads p_{11}, ..., p_{14} of the eigenvector P_1. – the algorithm according to K.O. Ekvall (2022). Grouping the terms in the last equation helped find expressions for $b_{j(OLS\_PC)}$.

The general expression of the Kolmogorov-Gabor polynomial (KGP) for the dependences of *y* on x_1, ..., x_4 was constructed according to R. Brito *et al.* (2016), H. Moosanezhad-Kermani *et al.* (2021):

$$y = b_0 + \sum_{i=1}^{n=4} b_i x_i + \sum_{i=1}^{n=4}\sum_{j=1}^{n=4} b_{ij} x_i x_j + \sum_{i=1}^{n=4}\sum_{j=1}^{n=4}\sum_{k=1}^{n=4} b_{ijk} x_i x_j x_k + \sum_{i=1}^{n=4}\sum_{j=1}^{n=4}\sum_{k=1}^{n=4}\sum_{l=1}^{n=4} b_{ijkl} x_i x_j x_k x_l, \quad (1)$$

where b_0, b_i, b_{ij}, b_{ijk}, b_{ijkl} are coefficients, *n*=4 is the number of independent variables. OLS-regression of *y* on fragments of the Kolmogorov-Gabor polynomial was performed according to the rules that determined the formation of *y* dependencies from: 1) 2nd-order interactions – sums of $b_{ij}x_ix_j$ + $b_{1234}x_1x_2x_3x_4$, both with and without x_i^2, x_j^2; 2) 3rd-order interaction – sums of $b_{1jk}x_1x_jx_k$, $b_{2jk}x_2x_jx_k$, $b_{3jk}x_3x_jx_k$; 3) 4th-order interaction – sums of $b_{11kl}x_1x_1x_{kxl}$, $b_{12kl}x_1x_2x_{kxl}$, $b_{13kl}x_1x_3x_{kxl}$; 4) $b_{1234}x_1x_2x_3x_4$; 5) sums of x_i and x_k or x_j and x_l, in which each variable was in natural powers 2-4; 6) dependence of *y* on only x_i^2, x_i^3, x_i^4. In items (2), (3) permutations with repetitions and x_{111}, x_{222}, x_{333}, x_{444}, x_{1111}, x_{2222}, x_{3333}, x_{4444} were excluded. The latter – because they caused a significant deterioration of the performance metrics of OLS-regression models.

The main performance metrics of OLS-regression models, specifically, the significance values of regression coefficients, factual F_a-ratios, standard errors of regressions (S), adjusted R^2 (R^2_{adj}), mean absolute percentage errors (*MAPE*), log-likelihoods, information criteria of Akaike, Schwarz, Hannan-Quinn (*logL*, AIC, BIC, HQC, respectively), Theil coefficients *U1*, *UM* displacement proportions, regressions *UR*, *UD* perturbations were obtained from Gretl 2021b. In addition, this program performed a typical set of analyses and tests for models for multicollinearity, leverage, linearity, heteroscedasticity, normal distribution of residuals, Chow test. The Durbin-Watson (*DW*) statistic was calculated according to O.I. Cherniak (2009), P. Turner (2020). The corresponding critical values (*dL*, *dU*, *P*=0.05) were obtained in Gretl 2021b. The presence or absence of autocorrelations was assessed according to a generally accepted algorithm (Cherniak, 2009). F_a-ratios and *MAPE* for PCR, IRR, ILASSO were calculated in Excel 11.0.6560.0 according to (Ahmadi & Rodehutscord, 2017) and (Levine *et al.*, 2019), respectively. The model was considered significant if F_a-ratio ⩾ *F* standard (*P*⩽0.05) and *MAPE*⩽5.0-6.0%.

RESULTS

The obtained results (Figure 1) showed an increase in the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu in the soil of variants 2, 8 by 2.3-12.2% and 16.7-24.1% (*P*<0.001), respectively, compared to the control (var. 1; earing phase of winter wheat). In addition, MF-Mn, MF-Zn experienced an increase in var. 3-7 by 12.7-22.6%, 4.8-10.8% and on var. 10-13 by 1.3-7.7%, 3.4-19.5% (*P*<0.001-0.01), relative to var. 2 and var. 8, respectively. Therewith, on var. 9, the content of MF-Zn in the soil was 1.1% (*P*<0.01) higher, while the content of MF-Mn did not differ significantly from the value of this indicator in var. 8. Ambiguous patterns of changes in MF-Fe, MF-Cu were found on var. 3-7, 9-13, relative to var. 2,

8. Admittedly, MF-Fe underwent growth on var. 3-5, 7 by 2.3-9.5%, while MF-Cu – on var. 5-7 – by 0.4-11.2% (*P*<0.001-0.01), compared to var. 3. Conversely, on var. 6, and var. 3, 4, a decrease in MF-Fe, MF-Cu by 1.3% and 1.1-2.2% (*P*<0.001-0.01) was noted, relative to var. 3. Furthermore, an increase in the values of MF-Fe was observed on var. 9 by 0.9%, and MF-Cu on var. 9-13 by 6.1-14.3% (*P*<0.001-0.05), compared to var. 8.

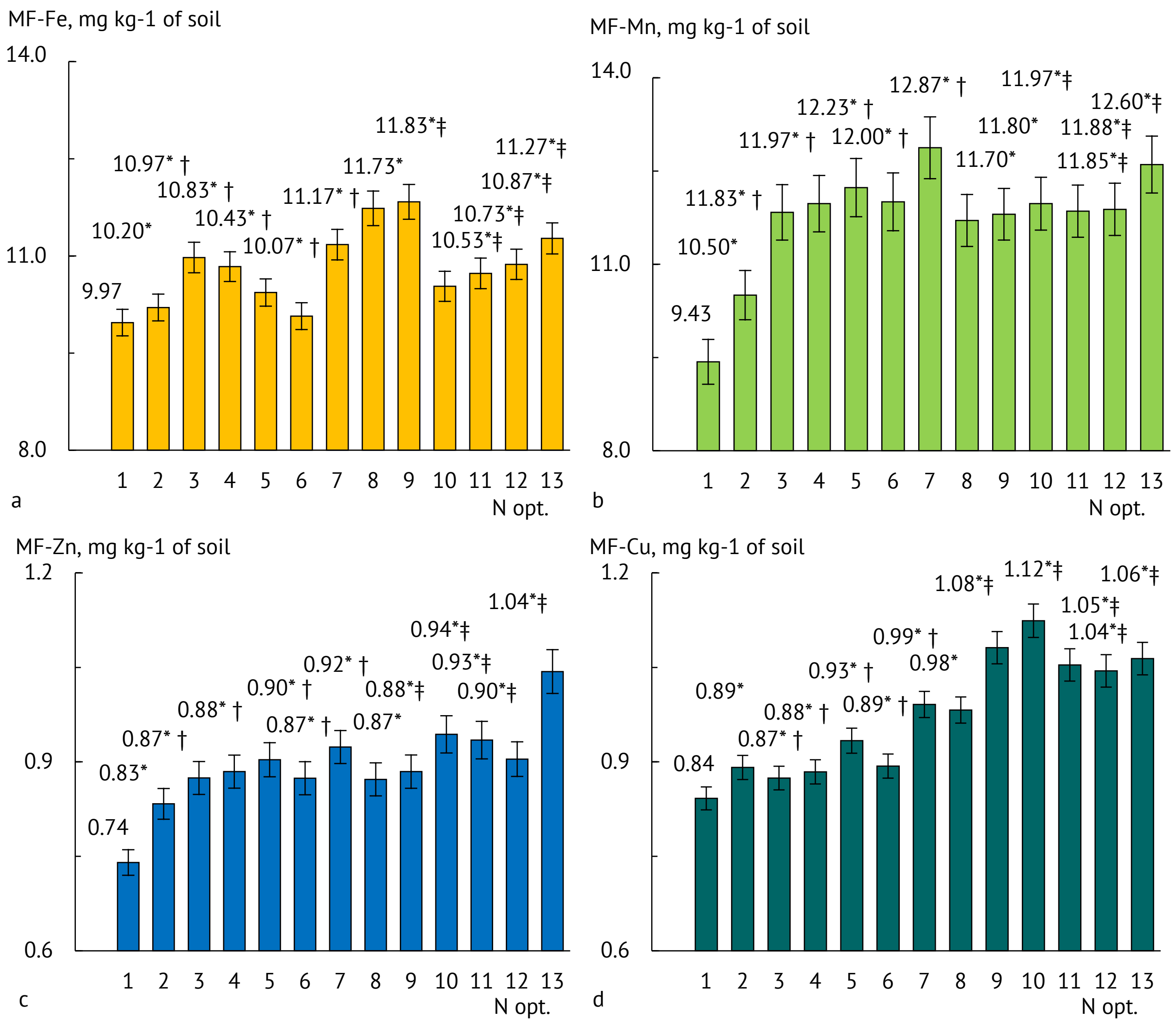

Figure 1. *Changes in the content of mobile forms of trace elements MF-Fe (a), MF-Mn (b), MF-Zn (c), MF-Cu (d) in the soil under winter wheat under the EFS conditions based on pea straw (var. 2), pea straw +* $N_{30}P_{45}K_{45}$ *(var. 3-7),* $N_{60}P_{90}K_{90}$ *(var. 9-13), including the control (var. 1 – without fertilizers) and solely* $N_{60}P_{90}K_{90}$ *(var. 8) (wheat earing phase, 2019-2020)*
Note: *For var. 1-13 significance levels of differences between means according to ANOVA data a, b, c, d – P<0.001, for var. 1-7 – P<0.01, P<0.001, P<0.001, P<0.001, var. 8-13 – P<0.001; Symbols *, †, ‡ – significance levels of differences (Student's t-test on means) relative to variants 1, 2, 8, respectively, P<0.001-0.05*
Source: *developed by the authors of this study*

Thus, EFS based on pea straw (var. 2), pea straw + $N_{30}P_{45}K_{45}$ (var. 3-7), $N_{60}P_{90}K_{90}$ (var. 9-13), and solely $N_{60}P_{90}K_{90}$ (var. 8) undoubtedly caused an increase in the content of mobile forms of Fe, Mn, Zn, Cu in the grey forest soil under winter wheat (earing phase), compared to the variant without fertilizers (var. 1). Therewith, the patterns of formation of MF-Fe, MF-Mn, MF-Zn, MF-Cu increments, relative to var. 1, 2, 8, significantly depended on the applied basic elements of fertilization systems (pea straw or $N_{60}P_{90}K_{90}$) and the type of particular fertilization system. To compare MF-Fe, MF-Mn, MF-Zn, MF-Cu with productivity, the pattern of changes in the mass of grains of ear^{-1} per one plant of winter wheat under the conditions of the fertilization systems under study was investigated (Fig. 2, waxy ripeness phase). On var. 2, 8 there was an increase in the specified indicator by 5.4%, 55.9% (*P*<0.01-0.001), respectively, compared to var. 1. The mass of grains of ear-1 increased on var. 3-7 by 19.4-35.7% and on var. 9-11, 13 by 4.8-11.0% (*P*<0.001-0.05), relative to var. 2 and var. 8, respectively. No significant differences were found between the values of this indicator for var. 8 and var. 12 (*P*=0.130).

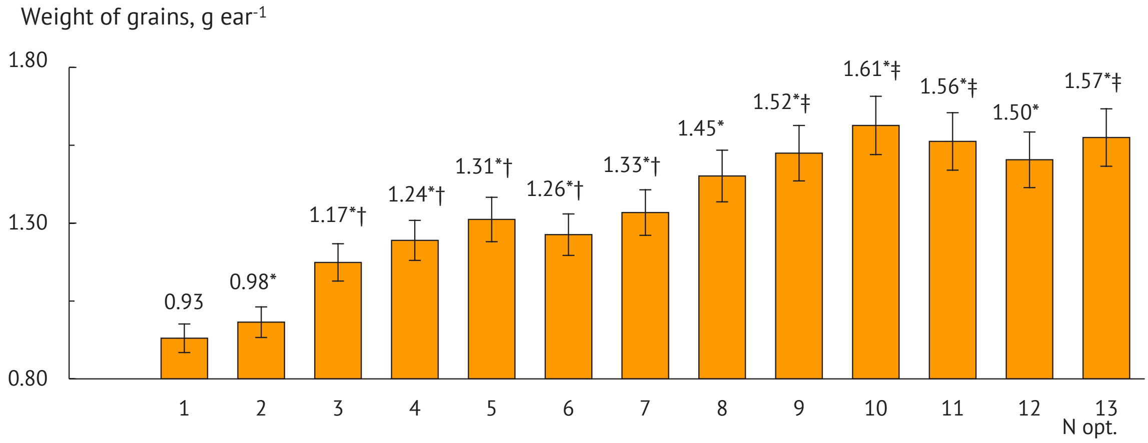

Figure 2. *Variation of the weight of ears of grain^{-1} based on one plant of winter wheat under the EFS conditions based on pea straw (var. 2), pea straw + $N_{30}P_{45}K_{45}$ (var. 3-7), $N_{60}P_{90}K_{90}$ (var. 9-13), including the control (var. 1 – without fertilizers) and solely $N_{60}P_{90}K_{90}$ (var. 8) (waxy ripeness phase, 2019-2020)*

Note: *For var. 1-13, 1-7, 8-13 significance levels of differences between means according to ANOVA data were P<0.001; Symbols *, †, ‡ – significance levels of differences (Student's t-test on means) relative to variants 1, 2, 8, respectively, P<0.001-0.05*

Source: *developed by the authors of this study*

It was established that the Pearson correlation coefficients *r* for the interdependencies between the mass of grains of ear^{-1} (*y*) and MF-Fe, MF-Mn, MF-Zn, MF-Cu (x_1, x_2, x_3, x_4, respectively) were 0.5837-0.9191 (*P*<0.001-0.05) (Table 1). Close two-dimensional correlations x_2-x_3, x_3-x_4 were also found: *r*=0.8347, 0.6989, *P*<0.001-0.01, respectively. Among the significant partial correlations were only the following: $r_{(yx4.x1x2x3)}$=0.8532, $r_{(x2x3.yx1x4)}$=0.6946, *P*<0.001-0.05. The fact that there was *r*>0.4, 0.7 ≈ *r*>0.7 among *r* between independent variables indicates the presence of multicollinearity between predictors. Since all partial correlation coefficients were smaller compared to the corresponding *r*, the effect of variable suppression was absent. Conversely, *y* and x_i depend on several unaccounted factors.

Table 1. *Pearson's correlation coefficients and partial correlation coefficients between the mass of grain ear^{-1} (per plant) of winter wheat and MF-Fe, MF-Mn, MF-Zn, MF-Cu*

			Pearson correlation coefficients		
	y	x_1	x_2	x_3	x_4
y					
x_1	0.5837ᵃ				
x_2	0.6936ᵇ	0.4998			
x_3	0.7957ᶜ	0.4296	0.8347ᶜ		
x_4	0.9191ᶜ	0.5160	0.4996	0.6989ᵇ	
			Partial correlation coefficients		
y					
x_1	0.1537				
x_2	0.4313	0.2773			
x_3	0.0509	-0.2482	0.6946ᵃ		
x_4	0.8532ᵇ	0.0859	-0.5282	0.2808	

Note: *y, x_1, x_2, x_3, x_4 are mass of grains of ear^{-1} based on one plant of winter wheat (g), MF-Fe, MF-Mn, MF-Zn, MF-Cu (mg kg^{-1} of soil); partial correlations y-x_i were calculated under the conditions of invariance x_j, x_l, x_k, partial correlations x_i-x_j – under the conditions of invariance y, x_l, x_k; indices a, b, c are the significance level of the correlation coefficient P<0.05, P<0.01, P<0.001, respectively*

Source*: developed by the authors of this study*

Given the significant $r>0$ between y and each of x_1-x_4 (Table 1), a search was made for univariate OLS regression models among the following specifications: linear, semi-logarithmic, linearized exponential, power, modified sigmoid logistic $ln((2\cdot 1/y) - 0) = b_0 + b_1 x_{1i}$, modified lognormal $ln(10\cdot 1/y) = b_0 + b_1 ln x_{1i}$ (0, 2, 10, and 1 were empirical constants selected "by hand" using OLS and y_{max}, respectively; for a general derivation of the last 2 functions, see, e.g., (Yahya *et al.*, 2019)), as well as power polynomials. No equations were found that were characterized by both sufficient levels of significance of F_a-ratios, *MAPE* values, on the one hand, and adequate test scores, on the other hand, or relevantly significant F_a-ratios in combination with significant equation coefficients; obtaining models with $b_0>0$ was also problematic ($b_0 \leqslant 0$ contradicts the definition of ear productivity).

Notably, the samples y, x_1, x_4 were characterized by a normal distribution (*ND*) of the data according to the Doornik-Hansen test, Shapiro-Wilk *W*-statistics, Lilliefors, Jarque-Bera tests, while x_2 were characterized significant deviations from the *ND*; x_3 was normally distributed according to the second and fourth criteria, and deviated from *ND* according to the remaining tests applied. Data were not logarithmised, given the generally satisfactory values of the correlation coefficients and their significance. In addition, deviation of regression residuals from *ND* among the specifications listed above occurred only once.

Considering the results of the correlation analysis, it is reasonable to assume multivariate dependences of y on x_1-x_4. The following OLS models were created and analysed:

factoring in partial correlations

$$y = -0.833^{**} + 1.704^{**} x_4 + 0.049^{*} x_2 x_3, \tag{2}$$

multivariate additive regression model (MAM)

$$y = -1.483^{**} + 0.021 x_1 + 0.068 x_2 + 0.108 x_3 + 1.740^{**} x_4, \tag{3}$$

sequential exclusion of variables from MAM

$$y = -1.348^{**} + 0.078^{*} x_2 + 1.818^{**} x_4, \tag{4}$$

semi-logarithmic modification of the latter

$$y = 0.571^{**}\, ln\, x_2 + 1.900^{**}\, ln\, x_4. \tag{5}$$

Here "**", "*" – $P<0.01$-0.05. Corresponding F_a-ratios – 22,956-2592,530 > *F* standard ($P<0.001$), R^2_{adj} – 0.880-0.907, *MAPE* – 3.43-3.95%. Evidence of strong multicollinearity was found (Adkins *et al.*, 2015) for the first three models: 2 condition numbers (*CN*)>10 (first), 4 and 1 *CN*>30 (second and third), corresponding variance proportions (*VP*) – 0.999, 1.000, 0.999-1.000. It is possible that multicollinearity is the reason for the insignificance of b_1-b_3 in the second model (Thompson *et al.*, 2017), and $b_0<0$ in the first three equations (Adeboye *et al.*, 2014). In the fourth among these models, $b_0=0$.

According to existing ideas, to minimize or eliminate the effects of multicollinearity between endogenous variables in MAM, it is advisable to use regularized multiple regression methods (Çankaya *et al.*, 2019). However, PCR, IRR, ILASSO performed in this study were not successful in the parameterization of the equation $y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4$. The obtained regression coefficients were as follows: 1) PCR (by the first component) – -14.796, 0.398, 0.322, 4.367, 2.880; 2) IRR – $-8.135\cdot 10^{-18}$, 0.097, 0.198, 0.149, 0.610; 3) ILASSO – $-5.872\cdot 10^{-18}$, 0.056, 0.273, 0.033, 0.730, respectively. The values of *t*-Student, *P* for these coefficients were not calculated, since the models were insignificant and, therefore, could not be used for a full interpretation of the multivariate dependences of y on x_1-x_4. Corresponding F_a-ratios – 2.011-2.255<*F* standard = 3.838 ($P=0.05$), *MAPE* – 111.195-244.783%. For all these regressions, the inequalities *SSR*>*SST*, *MSE*>*MST* were true, which made it impossible to calculate R^2 (Levine *et al.*, 2019), and therefore R^2_{adj}. Due to the insignificance of the PCR equation, as well as to save space, the details of this approach are not given.

The features of the above OLS-multifactor models, PCR, IRR, ILASSO testify, most likely, in favour of the opinion that the considered specifications, namely, simple MAM for the dependences of y on x_1-x_4 are irrelevant and/or ineffective. It is possible that the considered multivariate system of variables can be described by the above-unanalysed nonlinear dependences of y on each x_i or x_1-x_4 (OLS for linearized specifications or nonlinear least squares methods). However, the authors of this study did not find any assumptions about the form of such dependencies in the scientific literature. In this regard, the possibilities of presenting this multidimensional system of variables with OLS-regression models on fragments of the Kolmogorov-Gabor polynomial (KGP) were implemented. The latter includes standard additive and multiplicative models as partial cases, nonlinear terms of higher order. This makes it expedient to solve, using KGP, the tasks of formal and comparative structural-parametric identification of individual models of multifactor evaluation (Skakalina, 2018). For this, the group method of data handling (GMDH) was used according to genetic and several other algorithms (Stepashko, 2018). In this study, the model of the dependences of y on x_1-x_4 was specified as fragments of the KGP, which included partial cases of interactions of factor variables separately of the 2nd, 3rd, and 4th orders, as well as additive combinations of x_1, x_3 or x_2, x_4, in which each variable was raised to powers of 2, 3, 4, the dependence of y on x_i^2, x_i^3, x_i^4. The following were the most relevant (namely, $b_0>0$, significant values of performance metrics, adequate estimates for all tests, absence of autocorrelations, uncertainty intervals), among such OLS-parameterized models, or their improved versions (logarithmisation of independent variables, transformation into a linearized modified lognormal dependence).

$$y = 1.148^{*} - 0.231^{*}x_1 + 0.007^{*}x_1x_2 + 0.164^{**}x_1x_4\,, \quad (6)$$

$$y = 0.793^{**} + 0.033^{*}x_1^2x_2 - 0.470^{*}x_1^2x_3 + 0.014^{**}x_1^2x_4 - 0.031^{*}x_1x_2^2 + 0.421^{*}x_1x_2x_3\,, \quad (7)$$

$$y = 0.399^{**} - 0.086^{*}x_2x_3^2 + 0.171^{**}x_2x_3x_4\,, \quad (8)$$

$$y = 1.491^{**} + 0.834^{**}\,ln(x_3x_4^2), \quad (9)$$

$$y = 0.943^{**} + 0.003^{*}x_1^3x_2 - 0.049^{*}x_1^3x_3 + 0.001^{**}x_1^3x_4 - 0.003^{*}x_1^2x_2^2 + 0.044^{*}x_1^2x_2x_3, \quad (10)$$

$$y = 0.527^{**} + 0.007^{**}x_1x_2x_4^2, \quad (11)$$

$$y = 0.580^{**} - 0.100^{*}x_1x_3^3 + 0.181^{**}x_1x_3^2x_4\,, \quad (12)$$

$$ln(100 \cdot 1/y) = 5.479^{**} - 0.505^{**}x_1x_4^3, \quad (13)$$

$$y = 0.471^{**} + 0.008^{**}x_1x_2x_3x_4\,, \quad (14)$$

$$y = 20.660^{**} - 1.056^{**}x_2^2 + 0.127^{**}x_2^3 - 0.004^{**}x_2^4 + 4.680^{*}x_4^3 - 3.075^{*}x_4^4\,, \quad (15)$$

$$y = 1.410^{**} + 1.073^{**}\,ln(x_4^2)\,. \quad (16)$$

In equations (6)-(16), the symbols "*", "**" indicate the significance of coefficients P<0.05, P<0.01, respectively; in (13) the numbers 100, 1 are the empirical coefficient selected "manually" using OLS, y_{max}, respectively. Individual performance metrics of OLS regression models (6)-(16) are presented in Table 2. Clearly, the best among these models are characterized by equations (15), (10), (7) (the largest R^2_{adj}, combined with sufficiently low levels of *S*, *MAPE*, *U1*, and optimally high *DW*); the worst among them are (14), (16) (smallest R^2_{adj}, combined with high levels of *S*, *MAPE*, *U1*) (Table 2). This quality classification is consistent with the values of *logL*, AIC, BIC, HQC for these models. Admittedly, for (15), (10), (7) the specified characteristics were 21.816-29.071, -46.840–-28.243, while for (14), (16) – 13.416-14.170, -24.572–-21.703, respectively. Strong evidence of multicollinearity of OLS regression models (6), (7), (8), (10), (12), (15) was found: 1-5 *CN*>10, 1-3 *CN*>30, *VP*=0.625-1.000; for (6), (8), (10), (12) Variance Inflation Factor (*VIF*)=2.882-12.401, for the rest among these equations *VIF*>1000. However, sufficient levels of significance of such models, their coefficients, high R^2_{adj}, low *S*, *MAPE*, *U1*, adequate evaluations by all tests, strongly suggest that the corresponding dependencies are close to the variables really existing in the system under study. An overestimation of ear productivity under conditions corresponding to b_i=0 in models (13), (15), and, probably, (6), (9), (16) is not excluded; the above calls into question the use of such dependencies for extrapolations.

Table 2. *Numerical values of efficiency metrics of OLS regression models (6)-(16)*

Number of equation	F_a	R^2_{adj}	*S*	*MAPE*	*U1*	*UM*	*UR*	*UD*	*DW*
6	31.118*	0.883	0.076	3.65	0.023	0	0	1	2.756
7	29.831*	0.923	0.062	2.88	0.017	0	0	1	2.297
8	47.318*	0.885	0.075	4.08	0.024	0	0	1	2.640
9	97.836*	0.890	0.074	4.26	0.025	0	0	1	2.266
10	30.277*	0.924	0.061	2.79	0.017	0	0	1	2.254
11	87.469*	0.878	0.077	4.76	0.026	0	0	1	2.188
12	34.326*	0.847	0.087	5.32	0.028	0	0	1	1.667
13	54.142*	0.816	0.076	1.30	0.008	0	0	1	1.303
14	56.391*	0.822	0.094	5.27	0.032	0	0	1	2.391
15	93.951*	0.975	0.035	1.50	0.010	0	0	1	3.171

Table 2, Continued

Number of equation	F_a	R^2_{adj}	*S*	*MAPE*	*U1*	*UM*	*UR*	*UD*	*DW*
16	64.675*	0.841	0.088	5.75	0.030	0	0	1	1.574

Note: *F_a, R^2_{adj}, S, MAPE, U1, UM, UR, UD, DW – factual F_a-ratio, adjusted coefficient of determination, standard error of regression, mean absolute percentage error, Theil coefficient, bias proportions, regressions, perturbations, Durbin-Watson statistics, respectively; * – the level of significance of the factual F_a-ratio (> F standard) P<0.001*
Source: *developed by the authors of this study*

Thus, the OLS-regression models represented by equations (6)-(16) proved the presence of dependences *y* (mass of grain ear^{-1} of winter wheat; waxy ripeness phase) on linear combinations of factor variables x_1, x_2, x_3, x_4 (content, respectively, of MF-Fe, MF-Mn, MF-Zn, MF-Cu in grey forest soil; earing phase), each of which is included in a nonlinear mathematical expression. Specifically, in equations (6), (14) or (15), (16), the specified regularities were implemented due to the inclusion, respectively, of products of independent variables or such variables in indicators of natural powers 2-4, while in models (7)-(13) – products of factor variables, some of which are in indicators of natural powers 2-4. Notably, most of the OLS regression models (6)-(16) include x_i^2 and/or x_i^3 and/or x_i^4 in the absence of corresponding x_i (power index = 1). Such forms of equations can be interpreted as the dependence of an exogenous variable on unidentified factors that affect y simultaneously with x_i, and this influence is integrated at the level of the formation of subordination of *y* to the values of x_i^2 and/or x_i^3, and/or x_i^4 with the simultaneous levelling of dependencies on x_i (corresponding b_i=0), namely, according to semi-logarithmic or modified lognormal regularities (for partially similar, but mathematical explanations, see, e.g., (Aguilar *et al.*, 2020).

DISCUSSION

In podzolized, specifically grey forest soils, to which the substrate used in this study belongs, the typical redistribution of the silty fraction leads to the leaching of trace elements from the upper eluvial horizons and their accumulation in the illuvial ones. In turn, the depth of such processes depends on the intensity of podzolization (Fatiiev & Pashchenko, 2003). In general, low total concentrations of microelements, typical for podzolic soils, cause a deficiency of one and/or several elements in these soils. In addition, glaciation, as a result of imperfect drainage under conditions of clay enrichment and, therefore, the development of high adsorption capacity of such soils lead to Mn, Cu, Zn deficiency in the soil (Alloway, 2013). Clearly, the ability to increase the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu in the grey forest surface-glazed soil revealed in this study is an important positive feature of the applied fertilization systems.

According to the existing ideas given in the studies of Schulin *et al.* (2010), partially expanded by Vatansever *et al.* (2017), the conditions of insufficient or excessive supply of plants with trace elements have the properties to substantially change the intensity and direction of several physiological and biochemical processes, morphological features, life cycle, etc., and therefore, the values of the components of the productivity of agricultural crops. It is appropriate to assume that the improvement of the conditions of provision of mobile forms of trace elements can lead to an increase in the level and quality of the final productivity of agricultural crops. An increase in the application rate of $ZnSO_4 \cdot 7H_2O$ caused an increase in Zn-DTPA (diethylenetriaminepentaacetic acid) in the soil, optimization of the distribution of Zn in the roots, an increase in the concentration of Zn in shoots and grain, an increase in yield, elements of wheat productivity (field, vegetation experiments) (Liu *et al.*, 2017). Applying $ZnSO_4$ to the soil led to an increase in the number of ears, thousand kernel weight (TKW), yield, while foliar application of $MnSO_4$ – TKW of wheat during some years of the study (Pahlavan-Rad & Pessarakli, 2009). In the same study, significant interactive effects of Zn and Fe ($FeSO_4$, foliar feeding) caused an increase in the number of grains in the ear, TKW. Application of fertilizers containing Fe-EDDHA (ethylenediamine-N,N′-bis (2-hydroxyphenylacetic acid)), $ZnSO_4 \cdot 7H_2O$, $MnSO_4 \cdot H_2O$, $CuSO_4 \cdot 5H_2O$ caused a significant increase in grain yield, straw yield, TKW, number of seeds per ear of wheat (Ziaeian & Malakouti, 2001). DTPA-extracted micronutrients were identified as, among others, the most likely to explain the variability of wheat grain quality in artificial neural network (ANN) for hilly regions of western Iran (Ayoubi *et al.*, 2014). A significant positive correlation was found between Fe-DTPA and total yield, grain yield, TKW, Cu-DTPA and TKW, Mn-DTPA and total yield, TKW of wheat (*r*=0.21-0.61, *P*<0.01-0.05) (Ajami *et al.*, 2020).

Therewith, the scientific literature holds ambiguous assessments of the interdependencies between the content of mobile forms of micronutrients in the soil and the signs of productivity of grain crops. Admittedly, Menna (2022) documented no significant correlations between soil available Cu, Mn, Fe, Zn concentrations and total aboveground biomass or wheat grain yield. It was demonstrated that chitosan nanoparticles in a complex with Zn caused an increase in the content of Zn in grain, without affecting grain yield, protein content, the number of ears in an ear, TKW, etc. Furthermore, H. Liu *et al.* (2017) found that Fe and Zn concentrations in grain were significantly and negatively correlated with wheat grain yield. It was suggested that interdependencies between productivity and concentrations of mineral elements in the body of agricultural plants can be positive on soils depleted of mineral elements (Gregorio *et al.*, 2002). There are no potential obstacles to formulating assumptions about the presence of interdependencies between the content of mobile forms of trace elements in substrates depleted by them, specifically the considered soil, and signs of the final productivity of winter wheat grown under such conditions.

The coefficients of two-dimensional and partial correlations obtained in this study revealed a complex structure of interdependencies between exogenous (the mass of grains in ear^{-1} of winter wheat; waxy ripeness phase) and endogenous variables (the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu in the grey forest soil; earing phase), the presence of the subordination of the listed variables to factors not considered in this study. in addition, the analysed regression models, including those specified as fragments of KGP equations (6)-(16), proved that the development of winter wheat ear productivity does not depend linearly on the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu as such, in the grey forest soil, taken both separately and in the form of additive combinations. On the other hand, the indicated feature of plants is largely determined by linear combinations of interactions of trace elements among themselves (products of independent variables), as well as a number of predictors not identified in this study (independent variables in indicators of natural powers 2-4). Among other things, the latter may include several soil characteristics (pH, content of mineral components, dissolved and solid phases of organic matter, etc.), components of the rhizosphere, namely the root system of plants.

The formulated assumptions are, at least partially, consistent with experimental results and corresponding concepts existing in the scientific literature. It is known that after entering the soil system, specifically through weathering of primary minerals, trace elements are first absorbed during initial reactions, then slowly adsorbed and, thus, undergo transformations and redistribution into numerous chemical forms with different mobilities, toxicity, and bioavailability (Ali *et al.*, 2020). Some factors, including pH, ORP (Oxidation Reduction Potential), total metal concentrations, properties of trace elements, soil structure, concentrations of complexing agents (organic and inorganic), competing cations, content of organic matter (OM), etc., can affect solubility, bioavailability, uptake by plants, and movement of trace elements in the soil profile (Shukla *et al.*, 2018). Furthermore, soil pH and OM (SOM) have properties to change the direction and depth of metal ion speciation processes in the environment (Schulin *et al.*, 2010).

Partitioning between the solid and liquid phases of the soil environment may be accompanied, among other things, by competition between complexation with dissolved organic matter (DOM) and sorption/deposition, particularly of Cu and Zn, in the solid phase. In addition, ions of trace elements and common metals (e.g., Fe and K) can compete for adsorption sites (Liao *et al.*, 2021). It is known that in soils with a low Zn content (high pH and low Zn) complexation with DOM, controlled by humic and fulvic acid fractions (HA and FA), is important for the formation of available forms of this element (Klinkert & Comans, 2020). This is consistent with the predictions obtained in the same study (NICA-Donnan multisurface model) regarding the preferential binding of Zn to dissolved HA in the soil solution. Typically, Fe and Mn form poorly or insoluble oxides in soil that serve as adsorption surfaces, and yet the aforementioned Fe, Zn, and especially Cu can interact relatively easily with DOM or SOM. Therewith, Zn often stays more "soluble" than Cu (Zahedifar *et al.*, 2017). Controlling the processes of sorption/deposition, the SOM cycle has a positive effect on the solubility of trace elements, namely Fe, Mn, Zn, Cu, the ratio of water-soluble and exchangeable Fe, amorphous and crystalline Fe oxides, specifically adsorbed inorganic Mn oxide. In addition, the cycle of SOM and DOM, playing a key role in the distribution of metal ions between solid particles and the soil solution, contributes to increasing the content of available forms of trace elements, during the decomposition of the first and accumulation of the second among the indicated fractions (Zaragüeta *et al.*, 2021). It is interesting that the bioavailability of Fe, Mn, Zn, Cu correlated positively and significantly with the content of silt, clay, OC, but negatively and significantly with sand, $CaCO_3$, soil pH. Notably, for the interactions of Fe, Mn, Zn, Cu, Mg, in the context of the growth and formation of productivity of agricultural crops, antagonism occurs much more often than synergism (Rietra *et al.*, 2017). At least in part, this can be explained by competition between cations in comparable uptake mechanisms involving root cell transport systems. However, both antagonism and Liebig-synergism can occur between N and certain elements that improve symbiotic nitrogen fixation in plants, specifically Cu. Synergism of macroelements-Zn on calcareous soils, N NH_4-fertilizers-Mn under conditions of Mn-deficiency was also revealed, while the introduction of N-, S-fertilizers stimulated the production of phytosederophores and caused an increase in Zn, Fe in wheat (Rietra et al., 2017).

Considering the above, in general, the authors of this study consider it reasonable to assume that all applied fertilization systems affected the rate of SOM circulation in the grey forest surface-glazed soil under winter wheat in the earing phase. In turn, this led to changes in pH, solubility of microelements, ratios in the accumulation of Fe, Mn, Zn, Cu complexes with DOM, SOM, fine and coarse clay and silty minerals, suspended particles, etc., as well as interactions between themselves, a number of other micro- and macroelements in the soil, transport systems of root cells, rhizosphere microorganisms. Interdependencies of trace elements with the listed and probably several other soil characteristics formed a multidimensional system of predictors of the soil environment in the earing phase, which did not linearly affect the formation of the final productivity of winter wheat, levelling the expected response to the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu as such. In the future, it is advisable to investigate the regularities of the formation of winter wheat productivity depending on the simultaneous influence of the listed trace elements and some agronomically important soil characteristics, specifically, potential, exchangeable, hydrolytic acidity, the degree of saturation with bases, the content of exchangeable Ca^{2+}, Mg^{2+}, easily hydrolyzable N, available P, K, water- and NaOH-soluble labile OC, etc. in the earing phase, and during spring tillering – waxy ripeness.

CONCLUSIONS

The studied ecological fertilization systems based on pea straw, pea straw + $N_{30}P_{45}K_{45}$, $N_{60}P_{90}K_{90}$, as well as solely $N_{60}P_{90}K_{90}$ led to a significant increase in the mass of grains of ear^{-1} of winter wheat (waxy ripeness phase), the content of mobile forms of Fe, Mn, Zn, Cu (earing phase) in grey forest surface-glazed soil under this culture, compared to the control (without fertilizers). There were significant Pearson correlation coefficients between mass of grains of ear^{-1} of wheat and the content of mobile forms of Fe, Mn, Zn, Cu in the soil, the corresponding contents of Mn and Zn, Cu and Zn (0.5837-0.9191, P<0.001-0.05), as well as reliable coefficients of partial correlation between the mass of grains of ear^{-1} – Cu, Mn, Zn (0.6946-0.8532, P<0.001-0.05). There is a number of strong evidences regarding the presence of complications for the presentation of the dependence of mass of grains of ear^{-1} on the content of mobile forms of Fe, Mn, Zn, Cu in the soil by meaningful and/or appropriate single- and multivariate linear and linearized nonlinear (method of least squares) or regularized least squares regression equations. As a result of the specification of such dependencies as fragments of the Kolmogorov-Gabor polynomial, their subsequent parameterization using the method of least squares, reliable, relevant one- and multifactorial regressions of the mass of grains of ear^{-1} on linear combinations of products of independent variables and/or such variables in indices of natural powers 2-4 were found. Therewith, the linear and additive subordination of mass of grains of ear^{-1} to the values of the content, as such, of mobile forms of Fe, Mn, Zn, Cu in the grey forest soil were levelled. The obtained results were interpreted as the dependence of the productivity of the ear of winter wheat on linear combinations of interactions of microelements with each other and/or unidentified in this study predictors in the multidimensional space of soil characteristics under the conditions of eco-friendly fertilization systems. In the future, it is expedient to cover the regularities of the formation of the productivity of the ear of winter wheat depending on the content of trace elements, as such, in combination with the soil characteristics not considered in this study, formed by the actions of the specified fertilization systems.

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None.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Закономірності формування продуктивності колоса пшениці озимої залежно від вмісту мікроелементів у ґрунті

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Анотація. Вивчення паттернів формування продуктивності колоса залежно від вмісту потенційно біодоступних Fe, Mn, Zn, Cu у ґрунті, стохастична формалізація таких закономірностей є важливими для поглибленого розуміння концептуальних і механістичних аспектів підпорядкованостей розвитку урожайності рівням забезпечення пшениці озимої поживними речовинами за умов екологізованих систем удобрення. Мета роботи полягала у віднаходженні статистично достовірних взаємозалежностей, значущих і релевантних одно- або багатофакторних регресійних рівнянь залежності маси зерен колос$^{-1}$ пшениці озимої від вмісту потенційно біодоступних Fe, Mn, Zn, Cu у ґрунті, аргументаціях та роз'ясненнях таких підпорядкованостей за умов екологізованих систем удобрення. У дослідженнях використано такі методи: польові, лабораторно-аналітичні, мас-спектрометричний, математико-статистичні (*t*-тест Стьюдента, *ANOVA*, кореляційний, одно- та багатофакторний регресійний аналізи). Застосовані екологізовані системи удобрення на основі *соломи* гороху *або* соломи гороху + $N_{30}P_{45}K_{45}$, або $N_{60}P_{90}K_{90}$, лише $N_{60}P_{90}K_{90}$ *викликали збільшення маси зерен колос*$^{-1}$ *пшениці озимої, вмісту рухомих форм* Fe, Mn, Zn, Cu у сірому лісовому ґрунті під цією культурою (фаза колосіння), порівняно з контролем (без добрив). Істотні й значущі коефіцієнти кореляції Пірсона між масою зерен колос$^{-1}$ пшениці й *вмістом рухомих* Fe, Mn, Zn, Cu у ґрунті, відповідними вмістами Mn і Zn, Cu і Zn, а також коефіцієнти часткової кореляції маса зерен колос$^{-1}$ – Cu, Mn – Zn засвідчили складну структуру взаємозалежностей між вивченими ознаками. Віднайдено достовірні, релевантні одно- й багатофакторні регресійні залежності маси зерен колос$^{-1}$ від лінійних комбінацій добутків незалежних змінних (вміст *рухомих* Fe, Mn, Zn, Cu у ґрунті) і/або таких змінних у показниках натуральних степенів 2-4 (фрагменти полінома Комогорова-Габора). Розкриття закономірностей формування продуктивності колоса пшениці озимої залежно від умісту потенційно біодоступних мікроелементів у ґрунті за умов екологізованих систем удобрення дозволить теоретично обґрунтувати і розробити новітні стратегії мінерально-екологічного інжинірингу систем землеробства з метою підтримання високих рівнів і біологічних безпек урожаю зазначеної культури

Ключові слова: екологізовані системи удобрення; пшениця озима; мікроелементи; кореляція; регресія

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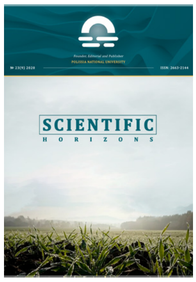

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Transgressive variation in productivity traits in F_2 naked oat hybrids

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Abstract. One of the most effective methods for increasing yield and resistance to abiotic and biotic factors in the environment is genetic selection and improvement of varieties. Solving these tasks is possible using positive transgressions, which are of great practical importance at this stage of selection. The aim of the research was to determine the coefficient of heritability in the broad sense (H^2) and the degree and frequency of transgressions for productivity traits in second-generation hybrids of naked oat, created by crossing based on the eco-geographical principle and selection of economically valuable biotypes for further breeding work. During 2021, research

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was conducted on 15 intervarietal hybrids. F_2 and parental components were analysed for traits such as plant height, spike length, number of spikelets per spike, number of grains per spikelet, and grain weight per spikelet. Field research methods (phenological observations), laboratory methods (structural analysis of the material under study), and mathematical-statistical methods (objective evaluation of the experimental data obtained) were used. A prominent level of the coefficient was observed for the trait "grain weight per spikelet", ranging from 0.66 to 0.88 in hybrid populations OM 11-3007/Abel, OM 2803/Abel, Percy Can/Inermis, Percy Can/Abel. The analysis of the second-generation F_2 intervarietal hybrids of naked oat allowed the identification of transgressions for all the studied traits. The highest number of positive transgressions was found for the following productivity traits: spike length (*Tf* 31.82 – 59.09%, *Td* 7.53 – 15.49%); number of spikelets per spike (*Tf* 27.30 – 54.50%, *Td* 8.85 – 26.49%); number of grains per spikelet (*Tf* 45.50 – 77.27%, *Td* 16.63 – 27.62%); and grain weight per spikelet (*Tf* 63.64 – 81.80%, *Td* 18.12 – 25.36%). The selection-genetic analysis of studying the nature of heritability, frequency, and degree of transgressive variation in spikelet productivity traits of F_2 naked oat hybrids allowed the identification of a considerable number of transgressive forms, in which productivity elements vary widely, indicating successful selection work in creating promising high-yielding breeding material

Keywords: naked oat; productivity traits; hybrid combinations; parental components; heritability, transgression

INTRODUCTION

Naked oat is a relatively new grain crop that is currently perceived as niche. However, with each passing year, the demand for products made from naked oat is increasing, as more people seek to consume quality and healthy food. The rising demand for healthy food products, such as organic, bio, fitness, and farmer's products, produced in limited quantities, has been observed (Tinker *et al.*, 2022). L.O. Udova (2018) also confirms this trend in Ukraine.

Nevertheless, it remains a tradition to primarily cultivate hulled oats, while naked oat occupies insignificant areas in production. However, this makes naked oat a unique crop in its own way. Some opinions attribute the limited use of naked oat in modern production to its insufficient study, higher demands for cultivation conditions, and certain biological drawbacks that ultimately affect its yield and quality (Hoptsiy & Kravchenko, 2023).

According to Necheporenko and Orlov (2020), increasing oat yield through selection is the most challenging task. T.P. Lozinska (2019) believes that addressing this challenge, along with enhancing resistance to abiotic and biotic factors, is possible through genetic and selective improvement of varieties, which, in turn, depends on the availability of suitable starting material with valuable breeding traits (Bilyavska & Rybalchenko, 2020). Incorporating valuable genotypes into the breeding process to create new varieties allows for the combination of valuable agricultural traits in hybrids, improves grain quality, and ultimately enhances the economic efficiency of oat cultivation (Haleem *et al.*, 2022). To achieve this goal, breeders employ various selection methods, but interspecific hybridization remains the most effective method (Lozinsky *et al.*, 2021). According to Nimbala Anisa and Neik Rudra (2021), the creation of hybrids should be purposeful, and knowledge of the patterns of trait "heritability" enables more efficient selection, elimination of low-value forms, and preservation of promising genotypes.

The use of positive transgressions is common in the creation and improvement of self-pollinating plants (Shchuts, 2019; Rauf *et al.*, 2020). Researchers emphasize the significance of transgressions and consider positive transgressions to be the most effective approach in working with breeding materials. Positive transgressions resulting from recombination of different economically valuable traits are particularly valuable in breeding (Tomaszewska & Kosina, 2019; Lozinsky *et al.*, 2021).

Tromsiuk and Bugayov (2021) highlight the importance of obtaining positive transgressions through the application of the ecogeographic principle in selecting parental pairs for hybridization. However, in their studies, Koroluk *et al.* (2022) pointed out that the genetic divergence of parental components can yield both positive and negative results. On one hand, it allows obtaining hybrid populations with certain traits that significantly exceed those of the parental forms. On the other hand, the hybrids may not conform to the desired model.

The analysis of breeding and genetic research shows that scientists have achieved some results in understanding the occurrence of transgressive variability to some extent. However, there is still no unified theory of trait transgression and adequate explanations for this genetic phenomenon (Lekhman, 2019; Lozinsky, 2021). Therefore, the question of the heritability of productivity elements and their transgressive variability in F_2 hybrids of naked oat remains relevant, as its resolution can enhance the selection value of hybrid combinations and contribute to the development of promising genotypes. Hence, this study was conducted to determine the coefficient of heritability and the frequency and degree of transgression for key productivity elements in F_2 hybrid generation of naked oats.

MATERIALS AND METHODS

The research was conducted from 2018 to 2021 at the Scientific-Educational Production Centre "Experimental

Field" of V.V. Dokuchaev Kharkiv National Agrarian University (since September 2021, State Biotechnological University). The soil cover of the experimental field consisted of typical chernozem, slightly eroded, low humus content, heavy loamy on forest loam. According to the Department of Soil Science at V.V. Dokuchaev Kharkiv National Agrarian University, the humus content in one soil layer (according to Turin) was 5.0%.

During 2018, the collection samples of naked oat obtained from the National Plant Genetic Resources Centre were studied and analysed for key agronomic traits. Based on the analysis, nine varieties were selected: Skarb Ukrainy, Inermis, Pushkinskyi, Holz, Vandrounik, Marafon, Samuel, Percy Can, Abel, and four inbred lines: OM 11-3007, OM 28-03, TR 12-115, and w/o No. Ren Nuda, of naked oat from domestic and foreign breeding, were selected for hybridization. Parental components for crossing were selected based on the level of expression of key agronomic traits and the ecological-geographical principle, which formed three groups: 1) hybridization of varieties and inbred lines of domestic origin among themselves; 2) hybridization of varieties and inbred lines of domestic origin with varieties from different ecological-geographical groups (foreign origin); 3) hybridization of varieties from different ecological-geographical groups (foreign origin) among themselves.

In 2019, hybridization was conducted through mechanical castration of flowers of the maternal plant, followed by forced pollination after 2 days using the Shishlov method. Plant isolation was ensured with paper bags. Based on the selected parental material, 15 hybrid combinations were created and studied in the hybrid nursery in 2020. In the F_1 hybrids, the level of phenotypic dominance, true and hypothetical heterosis were determined.

In 2021, the second-generation hybrid populations were studied to establish the coefficients of heritability and the frequency and degree of transgressive variation for key productivity elements. The sowing of F_2 hybrid population seeds and parental forms was carried out in the second decade of April in the hybrid nursery using the "parental form – F_2 – parental form" scheme with a row width of 15 cm. Throughout the vegetation period, phenological observations were conducted. Plant harvesting was done at full maturity, with all oat plants harvested with their roots. Structural analysis of hybrid plants and parental forms was conducted individually for traits such as spike length, number of spikes and grains per spike, grain weight per spike, and plant height.

The coefficient of heritability in the "broad sense" (H^2) was determined in F_2 using A.A. Zhuchenko's formula (1980), which is considered a quantity that reflects the real situation and can be used for the effective selection of transgressive forms. According to O.Ya. Ala's classification (1976), the coefficients of heritability were divided into: high – H^2=0.66-1.00; medium – 0.33-0.65; low – 0.00-0.32. The degree (*Td*) and frequency (*Tf*) of transgression were calculated using the Voskresenska-Shpot method (1967).

During the research, the meteorological conditions in 2021 were favourable for the growth and development of the obtained oat hybrids, although there were certain deviations in some periods both in terms of air temperature and precipitation. For instance, May to June, the period when productive stems and the number of grains in the spike are actively formed, characterized by an adequate amount of precipitation with slight deviations from the monthly norm. The amount of precipitation in April was 37.3 mm, in May – 52.1 mm, and in June – 82.0 mm (compared to the long-term norms of 34.9 mm, 43.7 mm, and 65.7 mm, respectively). The air temperature was also close to the average long-term indicators. However, July and August were dry months, with air temperatures of +24.5°C and +24.1°C, and precipitation of 26.6 mm and 12.9 mm, respectively.

RESULTS AND DISCUSSION

Special attention was paid to analysing the investigated F_2 populations, focusing on the manifestation of positive transgressive forms of productivity traits. Understanding the mechanisms of their heritability can lead to the creation of valuable parental material for future new cultivar development.

Regarding the length of the panicle, the manifestation of positive transgression was observed in 12 (80%) F_2 combinations (Table 1). However, their frequency and degree varied significantly. The frequency of transgressions ranged from 4.55% to 59.09%, while the degree of transgression ranged from 1.41% to 15.49%. Three combinations showed no transgression. The most promising populations were as follows: Samuel/Percy Can (*Tf* – 59.09%, *Td* – 15.49%), Skarb Ukrainy/Abel (*Tf* – 40.91%, *Td* – 10.53%), Skarb Ukrainy/w/o No. Ren Nuda (*Tf* – 36.36%, *Td* – 8.95%), OM 11-3007/TR 12-115 (*Tf* – 27.27%, *Td* – 9.85%), OM 2803 / Abel (*Tf* – 31.82%, *Td* – 8.37%), and Marafon/Abel (*Tf* – 45.45%, *Td* – 7.53%).

The heritability coefficient, which exceeded 0.50, was observed in the population of Samuel/Percy Can, with a value of 0.51. In the populations of OM 11-3007/Pushkinskyi, TR 12-115/Vandrounik, and Holz/TR 12-115, no manifestation of transgressive forms was observed.

Table 1. *The heritability coefficient, frequency, and degree of transgression for panicle length in F_2 naked oat populations (2021)*

Crossing combinations	♀	X±Sx	♂	H^2	*Tf*, %	*Td*, %
Skarb Ukrainy/w/o No. Ren Nuda	17.70	18.9±0.5	17.00	0.18	36.36	8.95

Table 1, Continued

Crossing combinations	♀	X±Sx	♂	H^2	*Tf*, %	*Td*, %
Skarb Ukrainy/Abel	17.7	18.6±0.7	17.2	0.42	36.36	10.53
OM 11-3007/TR 12-115	18.90	19.4±0.7	17.7	0.37	27.27	9.85
OM 11-3007/Holz	18.90	19.3±0.6	18.5	0.15	18.18	8.95
OM 11-3007/Pushkinskyi	18.90	18.88±0.5	18.6	0.00	–	–
OM 11-3007/Samuel	18.9	19.8±0.5	19.1	0.15	31.82	1.48
OM 11-3007/Abel	18.9	19.6±0.6	17.2	0.28	40.91	6.90
OM 2803/Marafon	18.10	18.9±0.7	15.6	0.28	22.73	4.93
OM 2803/Abel	18.10	20.0±0.6	17.2	0.24	31.82	8.37
TR 12-115/Vandrounik	17.70	17.6±0.4	17.1	0.00	–	–
Holz/TR 12-115	18.50	18.5±0.6	17.7	0.00	–	–
Marafon/Abel	15.6	18.6±0.4	17.2	0.01	36.36	7.53
Samuel/Percy Can	19.1	21.4±0.9	19.7	0.50	54.55	15.49
Percy Can/Intermis	19.7	20.0±0.5	18.4	0.24	13.64	1.88
Percy Can/Abel	19.70	19.7±0.5	17.2	0.08	4.55	0.00

Note: *Max ♀♂ – maximum value of the trait in parental forms, X±Sx – mean value of the trait in F_2, H^2 – coefficient of heritability in the broad sense, Tf – transgression frequency, Td – transgression degree*
Source: *compiled by the authors of this study*

According to the trait "number of spikes per panicle", positive transgressive forms were observed in all the combinations analysed within the F_2 hybrid populations (Table 2). Among them, the population of Holz/TR 12-115 exhibited a high degree of expression of the heritability coefficient (0.69), eleven populations showed a moderate level (0.34-0.60), and three combinations, OM 11-3007/Pushkinskyi, Skarb Ukrainy/w/o No. Ren Nuda, OM 2803 / Marafon, displayed a low heritability coefficient (0.26, 0.18, and 0.14, respectively).

The frequency of transgressive expression ranged from 4.50% to 54.50%, while the degree of transgression varied from 5.67% to 26.49%. The populations with the highest frequency and degree of transgression were OM 2803 / Abel (*Tf* – 54.50%, *Td* – 24.88%), Marafon/Abel (*Tf* – 50.0%, *Td* – 8.85%), Samuel/Percy Can (*Tf* – 31.80%, *Td* – 26.49%), OM 11-3007/Pushkinskyi (*Tf* – 31.80%, *Td* – 13.33%), OM 11-3007/Samuel (*Tf* – 27.3%, *Td* – 20.75%), and Skarb Ukrainy/Abel (*Tf* – 27.30%, *Td* – 15.84%).

Table 2. *Heritability coefficient, frequency, and degree of transgression for the number of spikes per panicle in F_2 naked oat (2021)*

Crossing combinations	♀	X±Sx	♂	H^2	*Tf*, %	*Td*, %
Skarb Ukrainy/w/o No. Ren Nuda	37.8	41.0±1.8	33.6	0.18	18.20	4.46
Skarb Ukrainy/Abel	37.8	39.2±2.3	36.7	0.48	27.30	15.84
OM 11-3007/TR 12-115	37.8	38.4±1.8	31.3	0.36	22.75	6.09
OM 11-3007/Holz	37.8	38.5±2.5	37.1	0.38	27.30	12.68
OM 11-3007/Pushkinskyi	37.8	42.9±2.3	38.0	0.26	31.80	13.33
OM 11-3007/Samuel	37.8	38.2±4.0	37.8	0.60	27.30	20.75
OM 11-3007/Abel	37.8	39.3±1.8	36.7	0.34	22.30	8.43
OM 2803/Marafon	36.2	39.7±2.1	34.4	0.14	18.20	10.07
OM 2803/Abel	36.2	42.3±2.5	36.7	0.47	54.50	24.88
TR 12-115/Vandrounik	31.3	39.7±1.8	36.4	0.39	13.60	5.67
Holz/TR 12-115	37.1	38.3±4.1	31.3	0.69	22.70	23.17
Marafon/Abel	34.4	38.3±1.8	36.7	0.41	50.0	8.85

Table 2, Continued

Crossing combinations	♀	X±Sx	♂	H^2	*Tf*, %	*Td*, %
Samuel/Percy Can	37.8	40.8±4.6	32.8	0.54	31.80	26.49
Percy Can/Inermis	32.8	39.9±3.5	37.7	0.37	22.70	17.90
Percy Can / Abel	32.8	39.8±2.3	36.7	0.34	4.50	19.66

***Note**: Max ♀♂ – maximum value of the trait in parental forms, X±Sx – mean value of the trait in F_2, H^2 – coefficient of heritability in the broad sense, Tf – transgression frequency, Td – transgression degree*
***Source:** compiled by the authors of this study*

The number of grains in the best parental plants ranged from 37.5 to 52.5 pcs. In F_2, this parameter varied from 49.5 to 64.0 grains (Table 3). Positive transgressions were observed in all F_2 combinations. The heritability coefficient in most investigated populations (67.6%) was moderate, ranging from 0.34 to 0.64, while the other five populations exhibited a low coefficient value. The frequency of transgressions ranged from 18.2% in the population Marafon/Abel to 77.27% in the population OM 2803/Abel. The degree of transgression for this trait ranged from 4.63% to 40.15%. The highest degree of transgression was observed in the populations OM 11-3007/Samuel (40.15%), Holz/TR 12-115 (29.42%), OM 2803/Marafon (27.62%), Skarb Ukrainy/w/o No. Ren Nuda (25.25%), and OM 2803/Abel (22.85%).

The best populations, which exhibited a higher degree and frequency of transgressions for the number of grains per panicle, were OM 2803 / Abel (*Tf* – 77.27%, *Td* – 22.85%), Skarb Ukrainy / w/o No. Ren Nuda (*Tf* – 59.10%, *Td* – 25.25%), OM 11-3007 / Abel (*Tf* – 45.50%, *Td* – 17.15%), OM 2803/Marafon (*Tf* – 50.00%, *Td* – 27.62%), and OM 11-3007/Holz (*Tf* – 50.00%, *Td* – 16.63%), OM 2803 /Abel (*Tf* – 77.27%, *Td* – 22.85%).

***Table 3.** Heritability coefficient, frequency, and degree of transgression for the number of grains per panicle in F_2 of naked oat (2021)*

Crossing combinations	♀	X±Sx	♂	H^2	*Tf*, %	*Td*, %
Skarb Ukrainy/w/o No. Ren Nuda	41.6	54.2±2.8	46.2	0.52	59.10	25.25
Skarb Ukrainy/Abel	41.6	54.9±2.2	52.5	0.39	27.30	5.66
OM 11-3007/TR 12-115	48.4	51.8±1.4	41.2	0.12	40.91	7.65
OM 11-3007/Holz	48.4	54.2±1.8	46.0	0.18	50.00	16.63
OM 11-3007/Pushkinskyi	48.4	53.33±2.4	46.2	0.51	54.60	18.55
OM 11-3007/Samuel	48.4	58.3±3.7	46.7	0.64	50.00	40.15
OM 11-3007/Abel	48.4	62.6±1.7	52.5	0.17	45.50	17.15
OM 2803/Marafon	45.3	58.1±1.5	40.2	0.09	50.00	27.62
OM 2803/Abel	45.3	62.6±1.6	52.5	0.28	77.27	22.85
TR 12-115/Vandrounik	41.2	49.5±2.3	47.8	0.40	40.90	8.07
Holz/TR 12-115	46.0	52.2±3.9	41.2	0.63	22.73	29.42
Marafon/Abel	40.2	48.6±2.7	52.5	0.44	18.20	4.63
Samuel/Percy Can	46.7	51.4±2.8	37.5	0.49	41.00	19.81
Percy Can/Inermis	37.5	54.1±25	50.5	0.50	36.40	17.64
Percy Can/Abel	37.5	56.2±28	52.5	0.46	31.80	14.24

***Note**: Max ♀♂ – maximum value of the trait in parental forms, X±Sx – mean value of the trait in F_2, H^2 – coefficient of heritability in the broad sense, Tf – transgression frequency, Td – transgression degree*
***Source:** compiled by the authors of this study*

The grain weight per panicle in the best parental varieties ranged from 1.11 to 1.33 g. In F_2, this trait ranged from 1.24 to 1.52 g. Analysis of the mean values of parental forms and F_2 populations revealed the presence of positive transgressive variability in all (100%) hybrid combinations of F_2 (Table 4). In 10 populations, the heritability coefficient was high, ranging from 0.66 in the population of OM 11-3007/TR 12-115 to 0.88 in the populations of OM 2803/Abel and Percy Can/Abel. High values of the heritability coefficient may indicate high genotype variability for this trait, which resulted in relatively high values of heritability coefficient, frequency, and degree of transgression.

The frequency of transgression ranged from 18.20% to 81.80%. The degree of transgression ranged from 2.31% to 25.36%. The most valuable populations for selection based on grain weight per panicle are Samuel/Percy Can (*Tf* – 81.80%, *Td* – 20.30%), Percy Can/Inermis (*Tf* – 72.73%, *Td* – 18.12%), Percy Can/Abel (*Tf* – 68.20%, *Td* – 25.36%), Marafon/Abel (*Tf* – 63.64%, *Td* – 19.97%), and others. Variation in plant height in the F_2 populations ranged from 75.4 cm (Holz/TP 12-115) to 99.3 cm (Samuel/Percy Can). Transgressions for this trait were absent in 10 (67.7%) populations. In the populations Skarb Ukrainy/w/o No. Ren Nuda, OM 11-3007/Holz, Marafon/Abel, Skarb Ukrainy/Abel, the frequency of transgressions ranged from 0.19% to 0.61%.

Table 4. *Heritability coefficient, frequency, and degree of transgression for grain weight per panicle in F_2 of naked oat (2021)*

Crossing combinations	♀	X±Sx	♂	H^2	*Tf*, %	*Td*, %
Skarb Ukrainy/w/o No. Ren Nuda	1.20	1.24±0.02	1.11	0.31	22.73	2.31
Skarb Ukrainy/Abel	1.20	1.31±0.01	1.31	0.55	27.30	4.62
OM 11-3007/TR 12-115	1.31	1.33±0.02	1.28	0.66	18.20	4.41
OM 11-3007/Holz	1.31	1.31±0.02	1.25	0.20	40.90	2.94
OM 11-3007/Pushkinskyi	1.31	1.32±0.02	1.25	0.65	31.80	2.94
OM 11-3007/Samuel	1.31	1.40±0.03	1.30	0.72	54.55	11.76
OM 11-3007/Abel	1.31	1.38±0.03	1.31	0.81	59.10	10.29
OM 2803/Marafon	1.29	1.36±0.03	1.25	0.69	45.45	8.89
OM 2803/Abel	1.29	1.39±0.04	1.31	0.88	36.40	11.76
TR 12-115/Vandrounik	1.28	1.30±0.03	1.27	0.69	40.90	5.93
Holz/TR 12-115	1.25	1.28±0.05	1.28	0.55	31.82	9.63
Marafon/Abel	1.25	1.42±0.04	1.31	0.76	63.64	19.97
Samuel/Percy Can	1.30	1.52±0.05	1.33	0.72	81.80	20.30
Percy Can/Inermis	1.33	1.38±0.05	1.25	0.81	72.73	18.12
Percy Can/Abel	1.33	1.49±0.06	1.31	0.88	68.20	25.36

***Note**: Max ♀♂ – maximum value of the trait in parental forms, X±Sx – mean value of the trait in F_2, H^2 – coefficient of heritability in the broad sense, Tf – transgression frequency, Td – transgression degree*
***Source:** compiled by the authors of this study*

Table 5. *Coefficient of inheritance, frequency, and degree of transgression for plant height in F_2 of naked oat (2021)*

Crossing combinations	♀	X±Sx	♂	H^2	*Tf*, %	*Td*, %
Skarb Ukrainy/w/o No. Ren Nuda	86.3	88.5±0.8	77.6	0.19	18.20	5.90
Skarb Ukrainy/Abel	86.3	87.6±1.4	80.6	0.61	36.40	8.40
OM 11-3007/TR 12-115	98.7	90.0±0.7	92.6	–	–	–
OM 11-3007/Holz	98.7	98.9±0.9	89.4	0.33	27.30	5.15
OM 11-3007/Pushkinskyi	98.7	88.4±0.9	94.4	–	–	–
OM 11-3007/Samuel	98.7	95.2±0.7	94.9	0.01	18.20	0.29
OM 11-3007/Abel	98.7	86.8±1.3	80.6	–	–	–
OM 2803/Marafon	92.8	79.0±1.3	78.6	–	–	–
OM 2803/Abel	92.8	93.6±0.6	80.6	–	–	–
TR 12-115/Vandrounik	92.6	88.0±0.8	91.0	–	–	–
Holz/TR 12-115	89.4	75.4±0.9	92.6	–	–	–
Marafon/Abel	78.6	79.0±0.9	80.6	0.35	9.10	0.82
Samuel/Percy Can	104.7	99.3±1.5	104.7	–	–	–

Table 5, Continued

Crossing combinations	♀	X±Sx	♂	H^2	*Tf*, %	*Td*, %
Percy Can/Inermis	104.7	87.1±1.9	99.1	–	–	–
Percy Can/Abel	104.7	91.4±0.7	80.6	–	–	–

Note: *Max ♀♂ – maximum value of the trait in parental forms, X±Sx – mean value of the trait in* F_2*,* H^2 *– coefficient of heritability in the broad sense, Tf – transgression frequency, Td – transgression degree*
Source: *compiled by the authors of this study*

The conducted selection-genetic analysis of studying the nature of inheritance, frequency, and degree of transgressive variability of productivity traits in F_2 of naked oat helped identify transgressive forms in which productivity elements varied widely. The hybrid populations differed in the frequency and degree of transgression. Notably, the nature of heritability H^2 had a considerable influence on the transgression parameters, which is determined, to a greater extent, by the genotype-specific characteristics of the parental components.

In the studies of Ukrainian and foreign scientists, the results of research on transgressive variability in various agricultural crops have been presented (Lozinsky *et al.*, 2021; Cazzola *et al.*, 2020; Al-Bakry, 2021). In most studies, breeding lines and varieties were obtained that were characterized by certain quantitative traits more pronounced compared to the parental forms (Ahamad *et al.*, 2022). For instance, A. Koroluk *et al.* (2022) observed a prominent level of variability in productivity traits in F_2 hybrid populations.

In their research, L.P. Necheporenko and S.D. Orlov (2020) emphasized the importance of focusing on hybrid generations, starting from F_2, in the initial stages of the selection process. The scientists involved genetically diverse domestic and foreign varieties and samples of different ecological and geographical origins in the breeding process to ensure a wide range of formative processes in hybrid generations. As a result of crosses, the oat breeding material significantly differed in key indicators during the research.

N.I. Vasko (2018) notes that the study of ear length is essential for breeding improvement, and selection based on this trait allows the creation of the desired length in combination with a greater number of ears, grains, and larger grain size. Research by several scientists has provided numerous facts about the emergence of new forms in ear length and other characteristics not present in the parental plants, which can be attributed to transgression.

In their research on oat ear productivity in second-generation hybrids (F_2), Petrov *et al.* (2017) determined that the coefficient of heritability (H^2) for this trait exhibited high values in all hybrid populations, along with positive transgressions. However, concerning the trait of the number of grains in the ear, the scientists observed a segregation towards the inferior parental component when parents with different levels of this trait were involved in the crossbreeding. On the other hand, when the parental components had mostly similar values for this trait, the manifestation of negative transgression occurred. During the investigation of the inheritance pattern of this trait, the researchers obtained high heritability coefficients (H^2), which ranged from 53.2 to 68.2, depending on the specific hybrid combination.

A.A. Trushko and S.P. Khaletsky (2019), during their research, identified transgressive forms in all F_2 crossing combinations. In their studies, the scientists paid special attention not only to the inheritance pattern and manifestation of transgressions concerning ear productivity traits but also to the plant height. However, regarding the latter trait, they were interested in both positive and negative transgressions. Meanwhile, N.I. Vasko (2018), studying barley, notes that selecting for plant height is promising, although its impact on productivity is indirect. However, in the breeding process, the level of expression of this trait must be considered, as a reduction in plant height may lead to a loss of yield due to a decrease in vegetative mass and nutrient assimilation. Nevertheless, the aforementioned researchers identified high transgressions both among tall and short forms in their studies. The analysis of yield elements such as "number of grains in the ear" and "grain weight per ear" allowed them to identify transgressions in 60% of hybrid combinations obtained through crossbreeding local ecotypes of oats with geographically distant ones.

Scientific literature has accumulated a wealth of evidence regarding transgressive variability and inheritance patterns of quantitative traits in crops such as wheat, barley, and rye. However, oats, in genetic terms, are still relatively understudied, necessitating a more detailed analysis of trait characteristics and transgressive variability.

CONCLUSIONS

The most valuable hybrid combinations for breeding work aimed at increasing yield are those that exhibit positive transgression in productivity traits. Productivity is the result of the integrated interaction of genes that control all its structural elements, which, in turn, can be inherited independently of each other. Thus, productivity has numerous variations in the interaction of plant traits, resulting in a wide spectrum of manifestations.

The research revealed that the heritability coefficient varied from low to high depending on the genotype, but for most studied oat traits, an intermediate value predominated. Transgressions were observed in all studied traits of F_2 naked oat hybrids. Among the F_2 hybrid populations, the best ones were identified based on the degree and frequency of positive transgression: for ear length – Samuel/Percy Can, Skarb Ukrainy/Abel, Skarb Ukrainy/w/o No. Ren Nuda, OM 11-3007/TR 12-115, OM 2803/Abel, and Marafon/Abel; for the number of ears in the panicle – OM 2803/Abel, Marafon/Abel, Samuel/Percy Can, OM 11-3007/Pushkinskyi, OM 11-3007/Samuel, and Skarb Ukrainy/Abel; for the number of grains per ear – OM 2803/Abel, Skarb Ukrainy/w/o No. Ren Nuda, OM 11-3007/Holz, OM 2803/Marafon, and OM 11-3007/Abel; for grain weight per ear – Samuel/Percy Can, Percy Can/Inermis, Percy Can/Abel, and Marafon/Abel.

The obtained initial material of naked oats will facilitate the continuation of breeding work to create new high-yielding and adapted varieties for the conditions of the eastern Forest-Steppe of Ukraine and to expand the existing genetic diversity.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Прояв трансгресивної мінливості елементів продуктивності у гібридів F_2 вівса голозерного

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Анотація. Одним з найефективніших методів підвищення врожайності, стійкості до абіотичних та біотичних чинників середовища є генетично-селекційне поліпшення сортів. Вирішення цих задач можливе з використанням позитивних трансгресій, які на даному етапі селекції мають важливе практичне значення. Метою досліджень було встановлення коефіцієнту успадковуваності в широкому сенсі (H^2), ступеня і частоти трансгресій за елементами продуктивності у гібридів другого покоління вівса голозерного, створених в результаті схрещування за еколого-географічним принципом та добір господарсько-цінних біотипів для подальшої селекційної роботи. Протягом 2021 року проводили дослідження 15 міжсортових гібридів. Аналізували F_2 та батьківські компоненти за ознаками: висота рослин, довжина волоті, кількість колосків в колосі, кількість зерен з волоті та маса зерна з волоті. Використовували польовий метод дослідження (проведення фенологічних спостережень), лабораторний (структурний аналіз досліджуваного матеріалу) та математично-статистичний (об'єктивна оцінка одержаних експериментальних даних). Високий рівень коефіцієнта спостерігався за ознакою «маса зерна з волоті» в межах 0,66 – 0,88 у гібридних популяцій ОМ 11-3007/Abel, ОМ 2803/Abel, Percy Can/Инермис, Percy Can/Abel. Аналіз другого покоління F_2 міжсортових гібридів вівса голозерного дозволив виділити трансгресії за всіма досліджуваними ознаками. Найбільша кількість позитивних трансгресій встановлено за такими елементами продуктивності: довжина волоті (Тч 31,82 – 59,09 %, Тс 7,53 – 15,49 %); кількість колосків у волоті (Тч 27,30 – 54,50 %, Тс 8,85 – 26,49 %), кількість зерен з волоті (Тч 45,50 – 77,27 %, Тс 16,63 – 27,62 %.) та маса зерна з волоті (Тч 63,64 – 81,80 %, Тс 18,12 – 25,36 %). Селекційно-генетичний аналіз вивчення характеру успадковуваності, частоти і ступеня трансгресивної мінливості ознак продуктивності волоті F_2 вівса голозерного, дозволив виділити значну кількість трансгресивних форм, в яких елементи продуктивності варіюють в широких межах, що свідчить про успішне проведення селекційної роботи в створенні перспективного високопродуктивного селекційного матеріалу

Ключові слова: овес голозерний; елементи продуктивності; гібридні комбінації; батьківські компоненти; успадкування; трансгресія

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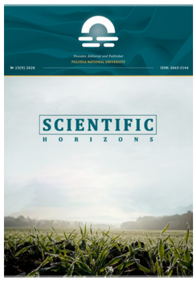

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Amaranth yield depending on the sowing rate

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Abstract. The main value of amaranth lies in its ability to accumulate a large amount of protein in its seeds and leaves. With a seed protein content of 15-18%, amaranth surpasses wheat (12-14%), rice (7-10%), maize (9-10%), and other grain crops. The purpose of this study was to establish the optimal seed sowing rates for amaranth under the conditions of the Western Ukrainian Forest-Steppe zone. The study employed general scientific methods such as analysis, synthesis, experimentation, description, observation, and comparison, as well as field methods like phenological observations and record-keeping, along with statistical and correlation-regression analyses for data

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processing. The sowing rates of the variety Kharkivskyi 1 were investigated under conditions of sufficient moisture on dark-grey forest soil. It was found that the field germination varied with different sowing rates. At a sowing rate of 0.2 million seeds/ha, the field uniformity was 70%, but it decreased to 60% at a sowing rate of 1.2 million seeds/ha, representing a 10% decrease. Higher sowing rates resulted in greater plant density. In the seedling stage, there were 14 plants per 0.2 million seeds/ha sowing rate, while at 1.2 million seeds/ha, the number of plants increased to 72/m². Plant survival during the vegetation period sharply decreased with increased planting density, from 86% at a sowing rate of 0.2 million seeds/ha to 45% at a sowing rate of 1.2 million seeds/ha. Therefore, before harvesting, the plant density was adjusted to 12-32 plants/m². The best combination of the main elements of the structure was found to be 21 plants/m² and 26 plants/m², with a grain weight per plant of 20.4g and 16.1g, respectively. The highest grain yield of amaranth variety Kharkivskyi 1 was obtained at sowing rates of 0.4 million seeds/ha and 0.6 million seeds/ha, resulting in 4.28 t/ha and 4.20 t/ha, respectively. Any increase or decrease in sowing rates led to a decrease in the yield level. The results of this study can be used for further establishment and improvement of the main elements of amaranth cultivation technology by both scientific institutions and agricultural farms

Keywords: amaranth; sowing rate; crop structure; productivity

INTRODUCTION

Amaranth is a fast-growing multipurpose crop that thrives on poor soils and exhibits high resilience to extreme stress conditions. Its grain is considered a potentially valuable supplementary food crop, as it provides significant amounts of micro and macro nutrients as a single crop, unlike many staple food crops in the world. Amaranth is particularly rich in lysine compared to other cereals and pseudo-cereals. Another noteworthy characteristic is its adaptability to various environments, making it a competitive crop suitable for cultivation worldwide (Weerasekara, 2020). In the African continent, amaranth is among the most widely cultivated and consumed local crops (Olaniyi, 2022). The increasing global population, especially in arid and semi-arid regions facing food and land shortages, necessitates the use of lands unsuitable for traditional agriculture due to soil salinity. Soil salinity is a significant issue affecting approximately 24% of Africa. To address this problem, cultivating salt-tolerant, high-yielding amaranth genotypes proves to be a solution (Doza *et al.*, 2019). Currently, amaranth is grown in many countries across the Americas, Southeast Asia, and Africa. However, in Europe, its cultivation potential and utilization remain underestimated (Różewicz, 2021).

Amaranth belongs to the crops characterized by limited cultivation technologies. For the normal growth and development of amaranth plants, they require an adequate area of nutrition, providing sufficient nutrients and water for the formation of necessary vegetative mass and grain. Therefore, the formation of high-yielding amaranth crops largely depends on the optimal sowing rate, which is determined by climatic conditions, soil fertility, fertilization system, biological characteristics of the variety, sowing dates, methods, seed quality, and other factors. Yield decreases both in sparse and dense plant placements on the field. Agrophytocenoses are known for their ability to self-regulate and are sensitive to excessive crop density, which leads to significant reduction of already formed morphological elements: premature drying and wilting of lower layers of leaves, decrease in stem and leaf mass, reproductive organs, and overall plant biomass, resulting in reduced grain yield (Dudka, 2019).

The grain yield level of amaranth largely depends on the number of plants per unit area and their individual productivity. The number of plants is mainly determined by the sowing rate. There are various recommendations for amaranth sowing rates, expressed either in weight (kg/ha) or in quantitative measures (million/ha). Most researchers indicate sowing rates in quantitative terms (Yaniuk & Hriunvald, 2022).

There are no clear recommendations regarding the plant density of amaranth. Some researchers (Shelest *et al.*, 2005; Duda & Kapshtyk, 2021) suggest cultivating amaranth with a sowing rate of 1.0 million/ha, which results in about 10 plants per 1 meter of the row. For optimal yield, it is recommended to have 100-150 thousand plants/ha. Mambetova & Sultanova (2022), in their studies on the growth and development of amaranth plants under different rates of organic and mineral fertilizers, used a sowing rate of 1 kg/ha for grain production and 2 kg/ha for animal feed.

According to Yeshitila *et al.* (2023) from Hawassa University (Ethiopia), in research evaluating the genetic diversity, heritability, and genetic progress for yield and yield-related traits of amaranth genotypes based on agromorphological characteristics, the plant density of amaranth was approximately 44,444 plants/ha, with a row spacing of 0.75 cm and a distance of 0.30 cm between plants within a row. On the other hand, there are research results recommending higher sowing rates for amaranth cultivation. Researchers from the Delta University research farm (Umeri *et al.*, 2022) used a plant density of 83,333 plants/ha in their field studies to assess the effect of urea on the growth and yield of *Amarathus hybridus*.

As noted by Toader *et al.* (2020) in their research on the morphology, biology, productivity, and yield quality of Amaranthus cruentus species, specifically two varieties “Bolivia 153” and “Golden Giant,” in terms of their adaptability to organic farming conditions in Romania, the plant density was 100,000 seeds/ha with a row spacing of 50 cm. Analysing the research data shows that plant density is an important integral indicator for determining the optimal sowing rate of amaranth. Pittelkow *et al*. (2019) observed that the productivity potential of amaranth BRS Alegria was achieved at plant densities of 24.2 and 22.8 plants/m^2 in Lucas do Rio Verde, Montana (Brazil).

In Nigeria, according to Idowu-Agida *et al*. (2020), amaranth seeds are sown in a scheme of 50 cm × 35 cm, and then, after two weeks of sowing, manual thinning is conducted, resulting in a plant density of 57,142 plants/ha. In Dudka's (2020) studies in the northern steppe, slightly higher sowing rates ranging from 0.75 to 1.50 kg/ha were investigated. The highest yield was achieved at a sowing rate of 1.0 kg/ha, with a plant density of 59.3 plants/m^2, resulting in a yield of 1.77 t/ha. Lykhochvor & Petrichenko (2022) report that the amaranth sowing rate varies from 0.3 to 1.0 kg/ha. For grain production, the optimal sowing rate is 300 g/ha (equivalent to 37 seeds/m^2 with a thousand kernel weight of 0.8 g, laboratory germination – 85%) and for green mass, 400 g/ha (equivalent to 50 seeds/m^2). The best plant density during growth and development is 10-25 plants/m^2.

In the conditions of the Western Forest-Steppe, amaranth holds great promise for cultivation, but its potential is still untapped due to the lack of well-adapted agricultural technologies suited to the soil and climatic conditions of the region. Therefore, at present, studying the impact of agronomic practices, particularly sowing rates, on the productivity of amaranth in the Western Forest-Steppe zone, is highly relevant, and this study aims to address this aspect.

MATERIALS AND METHODS

Field research was conducted at the experimental site of Lviv National University of Nature Resources to study the productivity of amaranth based on different sowing rates during the years 2020-2022. The soil of the experimental plot was dark grey podzolized loamy soil with a humus content of 2.3%. The content of readily hydrolysable nitrogen was 80-84 mg, available forms of phosphorus and potassium (according to Chirikov's method) were 108-114 mg and 98-108 mg/kg of soil, respectively. The soil solution had a near-neutral reaction, with a pH of the salt extract being 6.0.

The hydrothermal conditions during the study period deviated from the long-term average data, with slightly warmer temperatures and increased rainfall. In 2020 and 2022, the average temperature during the vegetation period was 15.3°C, which was 0.5°C higher than the long-term data. In 2021, it was 14.8°C, corresponding to the long-term average. The rainfall in 2020 exceeded the norm by 129 mm during the vegetation period, in 2021, it exceeded by 73 mm, and in 2022, by 28 mm.

The study was conducted with a plot area of 30 m^2, and the experiment was repeated four times. The plot arrangement was systematic. Six sowing rates were investigated: 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2 million germinating seeds/ha. The amaranth variety used in the study was "Kharkivsky 1".

The cultivation technology included the following elements. Winter wheat was the preceding crop, and after harvesting it, the stubble was disc ploughed and harrowed. In the autumn, phosphorus, and potassium fertilizers ($P_{60}K_{120}$) were applied during ploughing. In spring, moisture was conserved using heavy harrows. Before sowing, N_{160} was applied as a pre-sowing cultivation. The amaranth seeds were sown in rows with row spacing of 45 cm and at a depth of 1 cm in the last decade of April in all three years of the study. The sowing was done using the Horsh Pronto 4 DS Seeder. To control weeds, inter-row cultivation and the herbicide Fusilade Forte (1.0 l/ha) were used. Spraying was carried out with a backpack sprayer at a rate of 200 l/ha of the working solution. Amaranth was harvested at full seed ripeness in the lower and middle parts of the panicle, and after drying, the amaranth was threshed.

The correlation-regression analysis and statistical processing of the data through the analysis of variance (ANOVA) were performed using the "Statistica 6.0" software. Data were compared using the Tukey's test. Statistically significant differences between samples were considered at $p<0.05$. The data in the tables are presented as the arithmetic mean with the standard deviation (x±SD).

RESULTS AND DISCUSSION

The structure of the agrophytocenosis of the amaranth crop consists of cultivated plants, weeds, microorganisms, and others. The type of agrophytocenosis, which determines the interrelationships both between individual amaranth plants and their dependence on other representatives of flora and fauna, is primarily influenced by field germination. Amaranth is a thermophilic crop with elevated temperature requirements, especially during the sowing and germination period. The specific plant requirements may vary and depend mainly on genetic characteristics. The highest temperatures during the years of the study were observed in May-April 2021, which could explain the highest level of field germination, reaching 65-76% (Table 1).

Table 1. *Field germination of amaranth depending on the sowing rate, %*

Sowing rate, million/ha of germinating seeds	Years			average
	2020	2021	2022	
0.2	66 ± 0.26ab	76 ± 0.26a	68 ± 0.41a	70

Table 1, Continued

Sowing rate, million/ha of germinating seeds	Years			average
	2020	2021	2022	
0.4	66 ± 0.42ba	73 ± 0.53b	65 ± 0.36b	68
0.6	63 ± 0.22c	68 ± 0.64cde	64 ± 0.50c	65
0.8	59 ± 0.50de	68 ± 0.50de	62 ± 0.58d	63
1.0	59 ± 0.52ed	67 ± 0.18edc	60 ± 0.29e	62
1.2	57 ± 0.41f	65 ± 0.39f	58 ± 0.29f	60

Note: *values that contain at least one identical letter in a table column are not different using the Tukey's test ($p<0.05$)*
Source: *the results of the authors' own research*

In 2020 and 2022, the reduced field germination can be attributed to colder temperatures. However, there was sufficient moisture throughout all three years, indicating that it was not a limiting factor. On average, over the three years, the highest field germination was achieved with the minimum sowing rate of 0.2 million seeds/ha, resulting in a 70% field germination. When the sowing rate was increased to 0.4 million seeds/ha, the field germination decreased to 68%, representing a 2% reduction compared to the 0.2 million seeds/ha rate. With the sowing rate of 0.6 million seeds/ha, the field germination dropped by another 3% compared to the previous variant. Furthermore, with sowing rates of 0.8, 1.0, and 1.2 million seeds/ha, the field germination continued to decline (63%, 62%, and 60%, respectively) with an increase in the number of sown seeds. The difference in field germination between the various sowing rate options was relatively small, at 10%.

The number of plants during the seedling stage varied significantly, ranging from 14 to 72 plants/m^2 (Fig. 1). The results of the correlation-regression analysis revealed a moderate inverse relationship between the sowing rate variants and the field germination of amaranth, with a correlation coefficient r=-0.69.

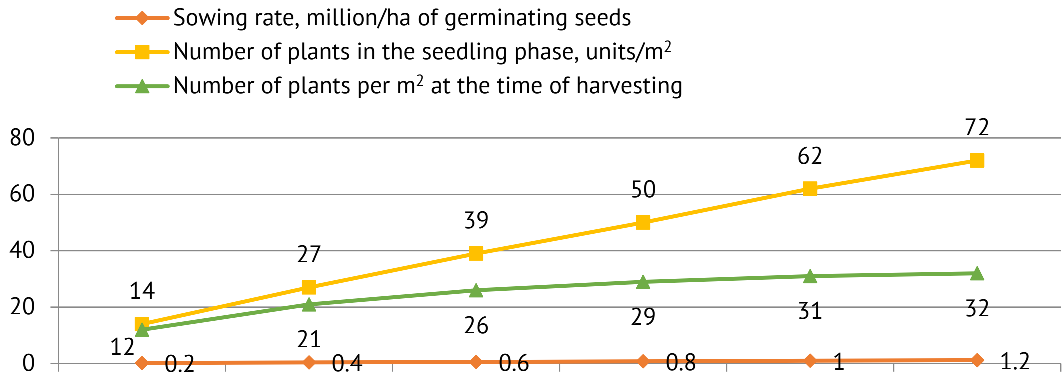

Figure 1. *Influence of sowing rates on the density of plants in the seedling phase and on the time of harvesting, average for 2020-2022*

The survival rate of plants during the vegetation period showed greater variability under the influence of sowing rates compared to field germination. A sizeable portion of plants perished due to intraspecific competition, especially evident in dense plantings and varying seed burial depths. Intense competition occurs during stem growth and vigorous vegetative mass accumulation. Well-developed plants absorb essential moisture and nutrients, outcompeting weaker plants and suppressing their growth by shading them from sunlight, eventually leading to their demise.

A direct correlation was established between sowing rates and the number of plants during the seedling stage, with a correlation coefficient r=1.00. Moreover, a very strong correlation was found between sowing rates and the number of plants/m^2 at the time of harvesting, with a correlation coefficient r=0.94. The survival rate of plants had a greater impact on plant density compared to field germination. Over the three-year period, the highest plant survival rate for amaranth was observed at the lowest sowing rate, reaching 86% (Table 2). Increasing the sowing rate to 0.4 million seeds/ha resulted in a decrease in the survival rate to 79%, and to 0.6 million seeds/ha, it dropped further to 67%. In dense plantings with sowing rates of 0.8, 1.0, and 1.2 million seeds/ha, the survival rate of amaranth plants from the seedling stage to harvesting was the lowest, at 58%, 51%, and 45%, respectively. The difference in survival rate between the variants with the lowest and highest sowing rates amounts to 41%.

Table 2. *Survival of plants during the growing season, %*

Sowing rate, million/ha of germinating seeds	Years				Increment
	2020	2021	2022	average	
0.2	81 ± 0.42a	90 ± 0.47a	87 ± 0.26a	86	41
0.4	76 ± 0.32b	83 ± 0.45b	78 ± 0.22b	79	34
0.6	64 ± 0.37c	72 ± 0.18c	65 ± 0.42c	67	22
0.8	55 ± 0.58d	64 ± 0.39d	55 ± 0.36d	58	13
1.0	47 ± 0.25e	56 ± 0.45e	50 ± 0.26e	51	6
1.2	41 ± 0.41f	51 ± 0.25f	43 ± 0.18f	45	–

Note: *values that contain at least one identical letter in a table column do not differ using Tukey's test (p<0.05)*
Source: *the results of the authors' own research*

As a result of the correlation-regression analysis, a very strong inverse relationship between sowing rates and the survival rate of amaranth plants during the vegetation period was established, with a correlation coefficient r=-0.97. Pelech (2021) noted a higher percentage of amaranth plant survival in the variant with a row spacing of 70 cm and the highest plant density before harvesting when sown with a row spacing of 45 cm, which in the conditions of 2020 and 2019 amounted to 52 and 68 plants/m^2, respectively, at the time of harvest.

The level of amaranth yield is most influenced by two crucial elements of the yield structure: the number of plants per unit area and the grain mass per plant. The sowing rate varied between variants by 20 seeds/m^2 and ranged from 20 to 120 seeds/m^2 (Table 3). The plant density before harvesting fluctuated within a much narrower range, ranging from only 12 to 32 plants/m^2 (Fig. 1). This can be attributed to the fact that in denser plantings, field germination slightly decreased, and the survival rate of plants from the seedling stage to harvesting sharply declined. In the studies by Zubillaga *et al.* (2020), increasing plant density led to a significant decrease in all biometric parameters determined during harvest collection. Intraspecific competition reduced plant height, panicle length, leaf and branch count, stem mass, and diameter, which reflected in smaller individual plant biomass. The reduction in photosynthate sources affected yield components (reduced weight and number of grains per plant) and consequently, the yield per plant. However, the greater number of plants compensated for the grain yield per hectare, although the seed cost and duration of the sowing cycle increased.

The seed mass per plant was highest in the variant with a sowing rate of 0.2 million seeds/ha and amounted to 34.1 g. The individual productivity of amaranth plants was highest in this variant, which can be explained by the fact that there were only 12 plants/m^2, allowing them to have the largest area for nutrient uptake and the best conditions for sunlight exposure and photosynthetic activity. With a sowing rate of 0.4 million seeds/ha, the seed mass per plant decreased to 20.4 g. Increasing the plant density further led to a continued decline in this parameter.

Table 3. *Elements of the structure of the amaranth harvest of the Kharkivskyi 1 variety depending on the sowing rate, the average for 2020-2022*

Sowing rate, million/ha of germinating seeds	Plant height, cm	Panicle length, cm	Weight of seeds per plant, g	Thousand kernel weight
0.2	182 ± 1.09 abcd	68 ± 0.22 a	34.1 ± 0.22 a	0.91 ± 0.010 ab
0.4	182 ± 1.00 bacd	67 ± 0.32 b	20.4 ± 0.36 b	0.91 ± 0.013 ba
0.6	180 ± 1.15 cdeab	64 ± 0.25 c	16.1 ± 0.14 c	0.88 ± 0.004 cd
0.8	180 ± 1.01decba	58 ± 0.34 d	14.1 ± 0.16 d	0.87 ± 0.012 dcef
1.0	178 ± 1.13ecd	53 ± 0.29 e	12.6 ± 0.22 e	0.86 ± 0.003 edf
1.2	170 ± 1.07 f	50 ± 0.18 f	11.7 ± 0.14 f	0.86 ± 0.003 fde

Note: *values that contain at least one identical letter in a table column do not differ using Tukey's test (p<0.05)*
Source: *the results of the authors' own research*

The results of the correlation-regression analysis revealed a strong and very strong inverse relationship between the sowing rates and yield structure indicators. Specifically, the correlation coefficient between the sowing rates and plant height was r=-0.85, between the sowing rates and seed mass per plant was r=-0.87, between the sowing rates and panicle length was r=-0.98, and between the sowing rates and thousand kernel weight was r=-0.95. A strong positive correlation was found between plant height and panicle length (r=0.85) and between plant height and thousand kernel weight (r=0.72), while a moderate positive correlation was observed between plant height and seed mass per plant (r=0.59). A strong positive correlation was also noted between panicle length and seed mass per plant (r=0.78) and between panicle length and thousand kernel weight (r=0.93).

The thousand kernel weight showed minor variation with changes in sowing rates, ranging from 0.86 to 0.91 g. An increase in the area available for nutrient uptake under lower sowing rates led to more vigorous growth and taller plants (by 12 cm). Panicle length also increased under variants with lower sowing rates, with the shortest length of 50 cm observed in the variant with the highest sowing rate of 1.2 million germinating seeds. Comparable findings were reported by Pittelkow *et al.* (2019) in their studies conducted in Brazil, where an increase in plant density from 30 to 62.5/m^2 resulted in reduced panicle weight.

According to Pelech (2021), the wide-row sowing method provided better conditions for the formation of yield components in amaranth. An important indicator, such as the thousand kernel weight, decreased as the inter-row spacing in the crops narrowed. Grain yield of amaranth varied under the influence of sowing rates. Under conditions of sufficient moisture, amaranth negatively responded to higher sowing rates and, consequently, crop densification. The lowest yield was observed with a sowing rate of 1.2 million seeds/ha, where it amounted to 3.76 t/ha (Table 4). Yield remained low also in the variant with a sowing rate of 1.0 million seeds/ha. With a sowing rate of 0.8 million seeds/ha, the yield increased by 0.2 t/ha compared to the sowing rate of 1.0 million seeds/ha. The same level of yield (4.09 t/ha) was recorded for the smallest sowing rate of 0.2 million seeds/ha.

Table 4. *Amaranth grain yield of the Kharkivskyi 1 variety depending on sowing rates, t/ha*

Sowing rate			Years				Increment	
pcs/m^2	million/ha	kg/ha	2020	2021	2022	Average	t/ha	%
20	0.2	0.19	3.70 ± 0.03 ad	4.52 ± 0.03 ad	4.05 ± 0.03 a	4.09	0.33	8.8
40	0.4	0.37	3.88 ± 0.04 bc	4.68 ± 0.03 b	4.28 ± 0.02 b	4.28	0.52	13.8
60	0.6	0.56	3.82 ± 0.04 cb	4.60 ± 0.02 da	4.20 ± 0.02 c	4.20	0.44	11.7
80	0.8	0.75	3.74 ± 0.02 da	4.45 ± 0.04 c	4.11 ± 0.03 d	4.10	0.34	9.0
100	1.0	0.93	3.60 ± 0.03 e	4.20 ± 0.02 e	3.90 ± 0.03 e	3.90	0.14	3.7
120	1.2	1.12	3.45 ± 0.03 f	4.02 ± 0.05 f	3.80 ± 0.02 f	3.76	–	–

Note: *values that contain at least one identical letter in a table column do not differ using Tukey's test (p<0.05)*
Source: *the results of the authors' own research*

According to the results of the correlation-regression analysis, a weak negative correlation was found between the sowing rate and the yield, with a correlation coefficient r=-0.46.

With an increase in the sowing rate, the survival rate of amaranth plants decreased, which is supported by the findings of Pelech (2021). During the full emergence period, the plant density per unit area was higher, by 16-33 plants/m^2, in the row sowing variant compared to the wide-row sowing, due to the higher sowing rate (100-110 thousand seeds/ha). During the harvesting period, the number of amaranth plants in the row sowing variant was 14 plants/m^2 lower (on average for years and varieties) compared to the wide-row sowing, resulting in 30-34% fewer plants being preserved.

The lowest yield in the study was obtained in 2020, which can be explained by specific hydrothermal conditions, namely excessive rainfall during two months – May and June. The excessive rainfall led to soil waterlogging, displacing air, and causing oxygen deficiency in the soil for the normal development of the root system, as well as increased weed infestation, ultimately resulting in a yield reduction. This is consistent with the findings of other researchers. Voropay *et al.* (2020) noted that during the vegetative period, the water requirements of amaranth and other crops change depending on their biological needs and current weather conditions. Critical periods for waterlogging include spring floods and summer-autumn floods, which reduced the yield of the studied crops in 2019.

The highest yields were achieved with sowing rates of 0.4 million seeds/ha and 0.6 million seeds/ha, amounting to 4.28 t/ha and 4.20 t/ha, respectively. This was 0.52 t/ha and 0.44 t/ha higher compared to the least productive variant. It should be noted that the highest yield was obtained with plant densities of 21 plants/m^2 and 26 plants/m^2, along with grain weights per plant of 0.91 g and 0.88 g. According to the findings of Niveyro

& Salvo (2017), the highest grain yield was obtained when sowing amaranth in wide rows with a spacing of 70 cm, resulting in an average yield of 23.2 kg/ha (across different varieties).

The results of Zubillaga *et al*. (2020) demonstrated the yield potential of *A. cruentus* in the lower valley of the Negra River, representing the southernmost density study conducted for this pseudo-cereal worldwide. The best plant density of 116,000 plants/ha with a row spacing of 0.70 m was established. This density allows for a crop from which optimal biological and economic yields can be obtained.

CONCLUSIONS

Increasing the sowing rate resulted in a systematic reduction in amaranth field germination. The highest field germination (70%) was observed for the lowest sowing rate of 0.2 million seeds/ha. For the sowing rate of 1.2 million seeds/ha, the stand density decreased to 60%, representing a 10% decrease.

The number of plants during the seedling stage increased with higher sowing rates, ranging from 14 plants/m^2 for the sowing rate of 0.2 million seeds/ha to 72 plants/m^2 for the sowing rate of 1.2 million seeds/ha, an increase of 58 plants. However, plant survival during the vegetative period significantly decreased with increased crop density, dropping from 86% for the sowing rate of 0.2 million seeds/ha to 45% for the sowing rate of 1.2 million seeds/ha. Consequently, the number of plants before harvest levelled out compared to the seedling stage, ranging from 12 to 32 plants/m^2, resulting in a reduced difference of 20 plants/m^2.

The highest grain yield was achieved with specific combinations of key crop structure elements: plant density per unit area of 21 plants/m^2 and 26 plants/m^2, and grain weight per individual plant of 20.4 g and 16.1 g, respectively. The highest grain yield for Amaranthus variety "Kharkivsky 1" was obtained with sowing rates of 0.4 million seeds/ha and 0.6 million seeds/ha, resulting in yields of 4.28 t/ha and 4.20 t/ha, respectively. Both increasing and decreasing the sowing rate led to a decline in grain yield.

The correlation-regression analysis revealed a strong and very strong inverse relationship between the sowing rates and crop structure indicators, and a weak inverse relationship between the sowing rate and grain yield. The established sowing rates for amaranth will be employed in further scientific research for the development and improvement of grain amaranth cultivation techniques in the conditions of the Western Forest-Steppe region.

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None.

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Урожайність амаранту залежно від норми висіву

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Анотація. Головною цінністю амаранту є здатність нагромаджувати у зерні і листках велику кількість білка. За вмістом у насінні білка (15-18 %) амарант перевищує пшеницю (12-14 %), рис (7-10 %), кукурудзу (9-10 %) та інші зернові культури. Метою роботи було встановлення оптимальних норм висіву насіння амаранту в умовах зони Лісостепу західного України. У дослідженні використано загальнонаукові методи (аналіз, синтез, експеримент, опис, спостереження та порівняння), польові (фенологічні спостереження та облік), а також статистичні і кореляційно-регресійні аналізи обробки даних. Було досліджено норми висіву амаранту сорту Харківський 1 в умовах достатнього зволоження на темно-сірому опідзоленому ґрунті. Встановлено, що під впливом норм висіву змінювалась польова схожість. За норми висіву 0,2 млн/га вона становила 70 %, а за висівання 1,2 млн/га знизилась до 60 %, або на 10 %. На варіантах з вищими нормами висіву густота рослин була більшою. У фазі сходів за висіву 0,2 млн/га було 14 рослин, а за висіву 1,2 млн/га кількість рослин зросла до 72 шт/м^2. Виживання рослин за вегетаційний період різко зменшувалось при загущенні посівів: з 86% за норми висіву 0,2 млн/га до 45% за висіву 1,2 млн/га. Тому перед збиранням густота рослин вирівнялась, на м^2 12-32 було рослини. Оптимальним поєднанням основних елементів структури виявилось: 21 рослин/м^2 та 26 рослин/м^2 і маса зерна з однієї рослини 20,4 г та 16,1 г. Найвищу врожайність зерна амаранту сорту Харківський 1 одержано за норм висіву 0,4 млн/га та 0,6 млн/га – відповідно 4,28 т/га та 4,20 т/га. Збільшення чи зменшення норми висіву призводить до падіння рівня врожайності. Результати даного дослідження можуть використовуватися для подальшого встановлення та удосконалення основних елементів технології вирощування амаранту як науковими установами, так аграрними господарствами

Ключові слова: амарант; норма висіву; структура посівів; продуктивність

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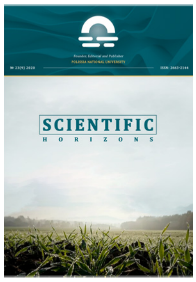

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Selection of highly adaptive source material of watermelon for selection for early ripening

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Abstract. In terms of watermelon selection, the issue of stability of obtaining high yields in the conditions of manifestation of abiotic stressors of the external environment is relevant. The purpose of this study was to select a highly adaptive source material of watermelon according to the duration of the growing season and its components for use in breeding for early ripening. 101 collection samples of watermelon from 9 countries of the world were analysed. The study was based on the following methods: general scientific, measurement and weight, calculation, statistical. The watermelon collection was divided into ripeness groups and the sample was ranked according to the "duration of the seedling-ripening period". The study established the amplitude

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(A_m) and range of variation (*Lim*) of the signs of the duration of the components of the growing season. Samples with the smallest individual interphase periods were selected for use in selection for early ripening. The study found V_i – general adaptive capacity (GAC), σ^2SAC_i – specific adaptive capacity (SAC), Sg_i – genotype stability, b_i – regression coefficient of genotype response to changing conditions (plasticity), SVG_i – selection value of the watermelon collection genotype based on the "duration of the growing season period". According to the general adaptive capacity, the samples with the shortest duration of the "seedling – ripening" period were selected – 19 samples (V_i=-11.72...-6.05). As the most stable genotypes according to the "duration of the growing season" characteristic, 32 collection samples with a low value of the specific adaptive capacity indicator were selected, 23 of which are early ripening. The high stability of the genotype (*Sgi*) according to the characteristic "duration of the seedling-ripening period" was determined in 31 collection samples, of which 24 were early ripening. Based on the results of determining the regression coefficient (ecological plasticity coefficient), according to the characteristic "duration of the growing season", the collection samples of watermelon were divided into three groups – with low (b_i=0.01-2.20), medium (b_i=2.21-4.22), and high (b_i=4.23-6.24) ecological plasticity. According to the selection value of the genotype according to the trait "duration of the seedling-ripening period", 18 collection samples had high indicators (SVG_i=110.22-119.92), which are valuable for use in selection work with watermelon as sources of the characteristic "early ripeness"

Keywords: watermelon; selection; early ripening; adaptive capacity; stability; plasticity; selection value

INTRODUCTION

It is important to have a year-round pipeline supply of products for adequate nutrition of the population. For vegetable and melon products, it is important to receive products in an earlier period, which will provide the population with wholesome vitamin products and contribute to strengthening food security. A biological feature of melon crops, including watermelon, is that they change their growing season depending on the weather conditions of the year: in hot, dry years, the number of days from germination to the beginning of ripening is sharply reduced, and therefore some genotypes can shift from later-ripening to early-ripening groups and middle-early and vice versa. The greater the sum of active temperatures, the earlier the appearance of female flowers and early ripening, and vice versa, which changes the duration of the growing season. For agricultural production, the stability of receiving high-quality products in the planned terms is important, which can be ensured to a greater extent only by a highly adaptive genotype. The ability of ecological adaptation of newly created genotypes to changes in environmental factors is a separate problem in modern agricultural production, and therefore the creation of highly adaptive heterosis hybrids is still relevant.

According to O. Sergienko & Z. Linnik (2022), it is precisely the lack of high-yielding varieties in the production that are adapted to soil and climatic conditions, namely extreme ones, that is the main limiting factor without which a significant increase in the productivity of melon crops, including watermelon, is impossible. Therefore, at the current stage of the development of agricultural science, researchers (Vozhehova, 2018; Naumov & Lymar, 2019) pay attention to the urgent issue of creating and introducing environmentally sustainable genotypes into production, which allow for stable high yields. The theoretical basis of adaptive crop production is ecological plant genetics. The ecological-genetic approach to breeding allows developing ways and methods of rational use of genotypes and obtaining new varieties and hybrids that are resistant to adverse environmental factors, obtaining information about the norm of the reaction of the genotype, etc. (Vasko *et al.*, 2019). Thus, for production, genotypes with high adaptive capacity are valuable, which can provide the maximum level of manifestation of valuable economic traits, including early ripening in changing environmental conditions. Highly adapted starting material allows creating new varieties and hybrids in different areas of selection, specifically, selection for early ripening is impossible without stable sources and donors.

The highly adaptive source material is selected by breeders for most vegetable and melon crops. Thus, at the Dnipropetrovsk research station of the Institute of Vegetable and Melon of the National Academy of Agrarian Sciences, due to the results of breeding research by I. Sydorka & V. Zavertaluk with watermelon culture under artificial agro-climatic conditions (variable sowing dates and plant feeding area), the "Method of selection of plastic lines and hybrids of ordinary watermelon" was developed in 2015 and adaptive source material was selected based on valuable economic characteristics. For carrot culture (*Daucus carota* L.), the analysis of the adaptive potential of the original selection material performed by I. Pidlubenko *et al.* (2022) helped identify ecologically stable sources with high general and specific adaptive capacity for selection for the yield of root crops and β-carotene content. The analysis of correlations of quantitative traits and their interaction with biotic and abiotic factors of the environment helped S. Kondratenko & Yu. Lancaster (2022) significantly increase the efficiency of selection work on the creation of highly adaptive forms of zucchini with a stable phenotypic response of the genotype to changing growing conditions. According to N. Vorobiova (2021), it was proved that environmental factors have the greatest influence on the tomato yield, and therefore, for successful selection, it is necessary to create highly adaptive source material for each direction of selection.

In the matter of watermelon breeding, according to Z. Sych (2021), the issue of insufficient stability and the level of fulfilment of the potential of early ripening and yield to provide valuable vitamin products is still relevant, and can be solved only by creating new early-ripening genotypes with a complex of valuable economic traits and high adaptive capacity.

The world's gene pool of watermelon collections is the most valuable source of creating new competitive genotypes of the early ripeness group, which combine resistance to biotic and abiotic factors of the environment with other economically valuable traits. Ukrainian researchers V. Kirian *et al.* (2021), Z. Linnik *et al.* (2021) believe that the investigation of the global genetic potential of watermelon culture using an integrated approach in determining stable sources of selection traits, their involvement in hybridization with the subsequent use of analytical selection methods allows creating a diverse source material and fruitfully using it in varietal and heterosis selection of this culture.

That is why the purpose of this study was to determine the adaptive potential of the watermelon collection for their further use in various areas of selection, specifically for early ripening.

MATERIALS AND METHODS

Experimental studies were conducted in 2018-2020, in the northern part of the Left Bank Forest-Steppe of Ukraine, in the central moderately humid area of the Kharkiv region. The experiments were conducted on soils inherent in the Forest-Steppe zone – typical low-humus medium loamy chernozem on loess rocks (pH of salt extract – 5.7; sum of absorbed bases – 26.0 mg-eq per 100 g of soil; hydrolytic acidity – 2.8 mg-eq per 100 g of soil; humus content – 4.3%; hydrolyzable nitrogen – 139.0 mg/kg; mobile phosphorus – 106-119 mg/kg and exchangeable potassium – 93 mg/kg of soil). The climate of the experimental area is temperate-continental. Experiments were located on a natural infectious background.

The object of the study was collection samples of watermelon – 101 variety samples from 9 countries of the world (from Ukraine, China, the USA, Moldova, Kazakhstan, Thailand, the Czech Republic, Italy). The Max Plus variety (Ukraine) served as the standard. A study of the adaptive potential of the watermelon collection by the length of the growing season was conducted. Phenological observations were made noting the beginning and end of each of the phases: emergence, formation of the third true leaf, flowering, fruiting, biological maturity. The beginning of the phase was considered when 10%, and the end – 75% of the total number of plants on the plot entered the corresponding phase. According to the results of the phenological study, the samples were divided into four groups of ripeness according to the length of the "seedlings – ripening" period: early ripening (65-80 days), medium-early (81-85 days), medium-ripening (86-95 days) and medium-late (96-105 days). Biometric measurements of plants and fruits (stem length, fruit diameter, ovary diameter, 10 internode length, leaf length, leaf base width) were performed on 10 plants of each genotype. Harvesting and accounting of the harvest in nurseries was performed manually, using the weighing method with the division of fruits into fractions: large, medium, small, non-marketable.

The following indicators were determined: V_i – general adaptive capacity (GAC), $\sigma^2 SAC_i$ – specific adaptive capacity (SAC), Sg_i – genotype stability, b_i – regression coefficient of the genotype's response to changing conditions (plasticity), SVG_i – selection value of the genotype. Plant growing technology is generally accepted for the Forest-Steppe zone of Ukraine (DSTU 3805-98, 1998; DSTU 5045:2008, 2008). Seeds were sown in the first or second decade of May, depending on weather conditions. The sowing scheme in the experiments was 1.4×0.7 m. The registered area of the plot was 19.6 m^2. Sowing was performed manually as needed, with water added to the hole. During the vegetation period, two manual weedings and three inter-row soil treatments were performed to care for the plants.

The system of nutrition and protection of watermelon plants was performed according to scientific and practical recommendations (Kuts *et al.*, 2021). The study was conducted pursuant to the generally accepted methods of selection work (Horova & Yakovenko, 2001; Lymar *et al.*, 2001; Korniienko *et al.*, 2016). The collection samples were chosen and evaluated according to different selection areas per the recommendations (Serhiienko *et al.*, 2020; Ivchenko *et al.*, 2022; Vitanov *et al.*, 2022). The methodology (Kilchevskiy & Khotyleva, 1997) was used to estimate the parameters of adaptive capacity and stability of genotypes. The coefficient of ecological plasticity (b_i) was calculated according to the method described in (Eberhart & Russel, 1966). Statistical and mathematical processing of the obtained research results was performed using the Statistica program.

RESULTS AND DISCUSSION

According to the results of phenological observations, it was established (Table 1) that the group of early ripening samples was the most numerous both in average data and in individual years – 57% in 2018, 76% in 2019, and 68% in 2020. According to average data (X_{med}), 73 samples of the collection are classified as early-ripening. The middle-early group – 33% of samples (2018), 4% (2019), and 25% (2020), and 12 samples of the collection on average in 3 years. 7% of samples (2018), 9% (2019), and 7% (2020) were classified as medium-ripening. During 3 years of research, 15 collection samples were assigned to the medium-ripening group. The group of middle-late samples was the least numerous – according to three years of data, only 1 sample of the collection is attributed to it, but the study observed the following manifestation of the characteristic over the years – 4% of samples in 2018, 12% in 2019, and 1% in 2020.

***Table 1.** Distribution of collection samples of watermelon according to the duration of the period "seedlings-ripening" (2018-2020)*

Ripening group		Accession percentage and number			
		%			N
		2018	2019	2020	$\bar{X}$
1	Early-ripening (65-80 days)	57	76	68	73
2	Middle-early (81-85 days)	33	4	25	12
3	Medium-ripening (86-95 days)	7	9	6	15
4	Middle-late (96-105 days)	3	11	1	1
Total (101 accessions)					
"seedling-ripening" period length, days					
$\bar{X}$		80.05	77.32	76.79	78.05
Ij		2.00	-0.74	-1.26	-
X_{min}		63	66	62	64
X_{max}		103	103	97	101
A_m - X_{max} - X_{min}		40	37	35	37

***Source:** compiled by the authors*

The limit and amplitude of variation of signs of the duration of the growing season in collection samples were established. 44 samples were picked for selection for early ripening, which during the three-year study consistently had a period "seedlings–ripening" of less than 80 days.

To confirm the statistical dependence of the characteristic "duration of the growing season" on external environmental factors, the sample was ranked according to the characteristic "duration of the seedling-ripening period". The calculated Spearman rank correlation coefficient was ρ=0.69, which, according to the Chaddock scale, indicates a significant correlation dependence. According to the entire sample, 50% of the samples of each year were consistently in a certain ripening group, these are 44 early-ripening samples, 3 – middle-early, 2 – medium-ripening, and 1 middle-late sample. It was found that 24% of the variety samples of the collection slightly changed the length of the growing season in certain years, and therefore 17 early-ripening samples increased the growing season and were classified as middle-early, 3 middle-early samples were classified as early-ripening, and 4 medium-ripening samples in certain years were classified as middle-late. On 26% of the samples of the collection, the conditions of the year had a considerable influence.

The limit and amplitude of variation of the signs of the components of the growing season in the collection samples of watermelon were established (Table 2).

***Table 2.** Variability of the characteristics of the components of the growing season in collection samples of watermelon, 2018-2020*

Limits and amplitude of variation		Interphase length, days				
		Emergence–stem formation	Emergence – anthesis of female flowers	Emergence – fruit setting	Anthesis of female flowers – fruit setting	Emergence – ripening
2018	*Lim*	22-34	32-49	40-58	3-18	63-103
	Am	12	17	18	15	40

Table 2, Continued

Limits and amplitude of variation		Interphase length, days				
		Emergence–stem formation	Emergence – anthesis of female flowers	Emergence – fruit setting	Anthesis of female flowers – fruit setting	Emergence – ripening
2019	*Lim*	19-31	28-49	35-51	1-10	66-103
	Am	12	21	16	9	37
2020	*Lim*	13-26	28-43	32-52	1-10	62-97
	Am	13	15	20	9	35
$\bar{X}$	*Lim*	18-30	28-42	36-54	2-12	64-101
	Am	12	18	18	10	37

Source: *compiled by the authors*

The analysis of the duration of the growing season and its components showed that the limit of variation (*Lim*) of the duration of the "seedling–ripening" period of samples in 2018 was 63...103 days, in 2019 – 66....103 days, in 2020 – 62...97 days. The amplitude of variation (A_m) of the duration of the "seedling–ripening" period in 2018 was equal to 40 days, in 2019 – 37 days, in 2020 – 35 days, which indicates that the weather conditions of the growing season in 2020 were more favourable for most watermelon samples and they show characteristics of early ripeness. That is why the early-ripening forms were selected based on the results of provocative research under the conditions of 2018 and 2019, which will further increase the efficiency of the selection process.

On average, over the years of study, the limit of character variation was equal to the duration of the periods: "seedling-stem formation" *Lim*=18...30 days; "seedling-anthesis of female flowers" *Lim*=28...42 days; "seedlings-fruit setting" *Lim*=36...54 days; "anthesis of female flowers-fruit setting" *Lim* = 2...12 days; "seedling-ripening" *Lim*=64...101 days. The amplitude of variation (A_m) of the duration of the components of the growing season ranged from 10 to 37 days.

For use in selection for early ripening, samples with the smallest individual interphase periods are valuable. According to the study results, groups of the following samples were identified, namely: "seedling–stem formation" – 10 samples: Yanusyk, Skarb, Snezhok, Alyy Sladkiy, Medovyk, Sakharnyy Malysh, Kytay No. 3, Wm 19, Ganosik, and Minimeloni – "seedling-anthesis of female flowers" – 3 samples: Zhyoltyy Ranniy, Monomakh, Yanusyk;

– "seedlings-fruit setting" – 8 samples: Shapka Imperatora, Yanusyk, Medovyk, Syurpryz, Pivnichne Siaivo, Borysfen, Karapuz, Zhyoltyy Ranniy;

– "anthesis of female flowers-fruit setting" – 3 samples: Snezhok, Medovyk, Lyshchyna Kust;

– "seedling-ripening" - Syurpryz, Tailand 1, Karapuz, Lezheboka Medovyi, Podarok Solntsa, Zhyoltyy Ranniy ($\bar{X}$<70 days).

Parameters of ecological variability of collection samples of watermelon based on the characteristic "duration of the growing season" were established for three years of the study. Collection samples that were highlighted in terms of adaptability for selection for early ripening are presented in Table 3 ($\bar{X}$<70 days).

Table 3. *Parameters of environmental variability of watermelon collection samples, highlighted in terms of adaptability according to the characteristic "duration of the seedling-ripening period" (average for 2018-2020)*

seq. no.	Collection sample	The duration of the "seedling-ripening" period, days					
		X_{med}	V_i	σ^2SAC_i	Sg_i	b_i	SVG_i
1	Maks Plius	81.00	2.95	7.00	3.27	-1.15	97.44
2	Bolshaya Pekinskaya Radost	78.67	0.61	4.33	2.65	-0.50	104.37
3	Syurpyz	67.00	-11.05	3.00	2.59	0.98	118.88
4	Sladkiy Briliant	70.00	-8.05	28.00	7.56	2.85	86.88
5	Atamanskyi	79.00	0.95	4.00	2.53	0.89	104.70
6	Tailand No. 1	69.00	-9.05	13.00	5.23	1.87	101.62
7	Yarylo (Fliura Market)	78.00	-0.05	1.00	1.28	0.45	113.85
8	Pivnichne Siaivo	70.33	-7.72	2.33	2.17	0.86	117.22
9	Borysfen	77.00	-1.05	1.00	1.30	0.53	114.85

Table 3, Continued

seq. no.	Collection sample	The duration of the "seedling-ripening" period, days					
		X_{med}	V_i	$\sigma^2 SAC_i$	Sg_i	b_i	SVG_i
10	Foton 1	77.33	-0.72	2.33	1.98	0.86	110.22
11	Foton 2	72.33	-5.72	2.33	2.11	0.86	115.22
12	Favoryt	71.33	-6.72	2.33	2.14	0.86	116.22
13	Karapuz	67.33	-10.72	5.33	3.43	1.31	113.85
14	Lezheboka Medovyi	69.00	-9.05	13.00	5.23	1.87	101.62
15	Costa Rica	71.33	-6.72	6.33	3.53	1.39	108.16
16	Lyshchyna Kust	75.67	-2.39	0.33	0.76	-0.33	119.63
17	Arb. Kust Lyshchyna	76.67	-1.39	1.33	1.51	0.65	113.92
18	Wm 16	75.67	-2.39	1.33	1.53	0.65	114.92
19	Wm 18	75.67	-2.39	1.33	1.53	0.65	114.92
20	Wm 19	70.67	-7.39	1.33	1.63	0.65	119.92
21	Wm 20	75.67	-2.39	1.33	1.53	0.65	114.92
22	Wm 23	71.33	-6.72	1.33	1.62	0.41	119.26
23	Sladkiy Briliant No.1	76.67	-1.39	1.33	1.51	0.65	113.92
24	Zhyoltoye Chudo	71.00	-7.05	4.00	2.82	1.06	112.70
25	Solnyshko	71.33	-6.72	2.33	2.14	0.86	116.22
27	Lunnyy	71.33	-6.72	6.33	3.53	1.39	108.16
28	Zhyoltyy Ranniy	66.33	-11.72	6.33	3.79	1.39	113.16
29	Ganosik	71.67	-6.39	14.33	5.28	2.16	97.48
30	No. 7Zx	79.67	1.61	4.33	2.61	1.19	103.37
31	No. 6	79.67	1.61	4.33	2.61	1.19	103.37
32	No. 5	79.67	1.61	4.33	2.61	1.19	103.37
33	No. 4	79.67	1.61	4.33	2.61	1.19	103.37
34	No. 9	79.67	1.61	4.33	2.61	1.19	103.37
According to the entire sample of 101 samples:							
	X_{med}	78.05	-	-	-	-	-
	X_{min}	64	-11.72	0.33	0.76	-4.12	-6.05
	X_{max}	101	21.95	161.33	17.13	6.24	119.92
	$A_m - X_{max} - X_{min}$	37	33.67	161.00	16.37	10.36	125.97

Source: *compiled by the authors*

High general adaptive capacity (*GAC*) characterizes genotypes by their ability to provide the maximum level of manifestation of the characteristic. For selection work on early ripening, samples with the shortest vegetation period, i.e., with minimal manifestation of the trait, are of practical value. According to the general adaptive capacity, the samples with the shortest duration of the "seedling–ripening" period were selected – 19 samples (V_i=-11.72...-6.05).

As the most stable genotypes according to the characteristic "duration of the growing season", 32 collection samples with a low value of the specific adaptive capacity (*SAC*) indicator were selected, 23 of which belong to early-ripening. The most stable in terms of specific adaptive capacity (SAC) are the early ripening collection samples – Lyshchyna Kust ($\sigma^2 SAC_i$ – 0.33); Yarylo, Borysfen ($\sigma^2 SAC_i$=1.00); Arb. Kust Lyshchyna, Wm 16, Wm 18, Wm 19, Wm 20, Wm 23, Sladkiy Brilliant ($\sigma^2 SAC_i$=1.33) are consistently early-ripening. 38 samples of different maturity groups had low stability of the characteristic "duration of the vegetation period"; other samples of the collection had average stability.

The main indicator of the stability of the variety is Sg_i – the stability of the genotype. According to many authors, the stability of the variety can be related to the high adaptability of each genotype to various growing conditions (individual buffering). Individual buffering prevails in a genetically homogeneous population. The high stability of the genotype according to the characteristic "duration of the seedling-ripening period" over three years of the study was determined in 31 collection samples, of which 24 samples were early ripening. The most stable were Lyshchyna Kust (Sg_i=0.76); Yarylo (Sg_i=1.28); Borysfen (Sg_i=1.30); Arb. Kust Lyshchyna, Sladkiy Brilliant (Sg_i=1.51); Wm 16, Wm 18, Wm 20 (Sg_i=1.53); Wm 19 (Sg_i=1.63).

According to the results of determining the numerical value of b_i – the coefficient of regression (coefficient of ecological plasticity), according to the length of the growing season, the collection samples of watermelon were divided into three groups – with low, medium, and high ecological plasticity. According to the results of the present study, the early-ripening collection samples Samurai, Snezhok, Rubinovoye Serdtse, Sladkaya Dakota, and the mid-early sample Lypa can be attributed to hybrids of the intensive type with an increased response to growing conditions (b_i=4.23-6.24). According to the study results, 20 collection samples, of which 15 are early ripening, are characterized by an average level of ecological plasticity (b_i=2.21-4.22). The third group, according to the characteristic "duration of the growing season", includes most collection varieties (76%) with an ecological plasticity coefficient from 0.01 to 2.20, which respond to a slight change in growing conditions.

In terms of the selection value of the genotype (SVG_i) according to the characteristic "duration of the seedling-ripening period", 18 collection varieties had high values of the indicator (SVG_i=110.22-119.92), which are valuable for the selection work for early maturity.

Most breeders consider the identification of new sources of valuable stable, plastic traits with a defined rate of reaction to changing growing conditions to be a major area of melon crop research, which allows solving the problem of competitive varieties and hybrids with given parameters. Breeding work on the creation and selection of early-ripening genotypes (lines and hybrids) of watermelon with high adaptive capacity was conducted at the Dnipropetrovsk research station of the Institute of Vegetable and Melon of the National Academy of Agrarian Sciences. The best known method of assessing ecological plasticity and stability of hybrid watermelon populations was used by breeder Z. Sych when creating the Voskhod variety, when hybrid combinations and varieties were evaluated for three years based on the characteristics "fruit mass" and "dry soluble matter content". Then, according to the method of V. Pacudin & L. Lopatyna, calculations were made to determine the parameters of stability and plasticity of this breeding material and the best genotypes were selected. In this study, when selecting valuable forms based on the characteristic "early maturity", the authors also applied the principle of evaluating selection material in changing environmental conditions over the years of study and selected highly adaptive genotypes.

In 2011-2015, station scientists I. Sydorka & V. Zavertaluk investigated nine artificial agrophones and selected lines with a regression coefficient close to one, which were used to create early-ripening highly plastic watermelon hybrids. Analogous studies on the creation of highly adaptive source material were conducted by breeders in the south of Ukraine. Thus, since 2010, adaptive breeding has been introduced at the Southern State Agricultural Station. Breeders of the station created early-ripening varieties: Sotnyk, Spaskyi, Knyazhych, Charivnyk, Portiyniy, and Mandrivnyk F_1 and Ranok F_1 hybrids, which were involved in the present study, but in the conditions of the Ukrainian Forest-Steppe they did not stand out in terms of the level of adaptability.

V. Lymar & O. Kholodnyak (2020) approached the solution of the issue by selecting forms that, due to internal mechanisms, can resist stress and adapt to such conditions without substantial changes in physiological parameters, as well as quickly restore the physiological state by investigating their physiological signs of resistance, which is the main way to improve adaptation in laboratory conditions. The above authors investigated the physiological indicators of stability, namely: the ability of the embryo to start growing under control of the environmental conditions using osmotic solutions. Samples were selected according to precociousness, combining varieties with a close growing season. This was due to differences in the physiological parameters of their seeds. The authors concluded that since the signs of abiotic resistance are formed during the entire ontogenesis, the lines should be assessed and selected for resistance to stress effects not only at the stages of seed germination, but during the vegetation process, which fully corresponds to the present study.

According to O. Shablya & O. Kholodnyak (2021), the parameters of ecological variability of each genotype are vital, since with the growth of the potential productivity of varieties and hybrids, their demand for cultivation technology increases considerably, the dependence of the size and quality of the harvest not only on biotic, but on abiotic factors, increases.

In the conditions of climate change, the cultivation of new highly adaptive varieties and hybrids of the culture is necessary to ensure a sufficient harvest of watermelon. It was the assessment of ecological plasticity and stability of watermelon varieties that allowed Z. Sych (2021) to identify the top watermelon varieties for each region of Ukraine. According to the results of many years of research by R. Vozhehova (2018), methods of selection and creation of new heat-resistant agrochemically effective genotypes of watermelon adapted to cultivation in the conditions of the Steppe zone of Ukraine were established; new varieties of watermelon were created: Tavriiskyi, Snizhok, Krasen, Orfei, Tsilnolystnyi, Spaskyi, Khersonskyi, Kniazhych, Alians, Charivnyk, Mriia, Favoryt, Paralaks, Vohnedar.

Scientists are conducting analogous studies on other melon crops. According to V. Khareba *et al.* (2019), assessment of the ecological plasticity and stability of large-fruited pumpkin varieties according to the main valuable economic indicators in the conditions of the Forest-Steppe of Ukraine with the application of the methodology used in this study allowed selecting a set of varieties for a certain growing zone.

In the conditions of climate change, to ensure a sufficient harvest of watermelon, it is necessary to grow new highly adapted varieties and hybrids of the culture, and therefore analogous studies are conducted by breeders – O. Shablya & O. Kholodnyak (2021), Z. Sych (2021) – to create new varieties and hybrids watermelon in different climatic zones of Ukraine. These authors established that the environmental variability parameters of each watermelon genotype differ depending on the soil and climatic conditions of cultivation. Thus, according to the research of O. Shablya and O. Kholodnyak (2021), the importance of the relevant parameters of the environmental variability of each genotype was proved, since with the growth of the potential productivity of varieties and hybrids, their demand for cultivation technology increases considerably, the dependence of the size and quality of the harvest not only on biotic, but on abiotic factors, increases.

CONCLUSIONS

Based on the results of the assessment, it was found that the group of early-ripening samples was the most numerous, both according to average data and experimental data for individual years. According to average data (X_{med}), 73% of collection samples are classified as early-ripening. 44 samples were picked for selection for early ripening, which during all the years of the study consistently had a period "seedling-maturation" of less than 80 days. The sample was ranked according to the characteristic "duration of the seedling-ripening period", the calculated correlation coefficient of the ranks was ρ=0.69, which, according to the Chaddock scale, indicates a significant correlation. Research has established the limit and amplitude of variation of the signs of the components of the growing season of collection samples. 30 samples with the smallest individual interphase periods were selected for use in selection for early-ripening. According to the general adaptive capacity, the samples with the shortest period "seedling-ripening" were selected – 19 samples (V_i=11.72-6.05). 32 collection samples with a low value of the indicator of specific adaptive capacity were selected, 23 of which belong to early ripening. The high stability of the genotype according to the characteristic "duration of the seedling-ripening period" was determined in 31 collection samples, of which 24 are early-ripening. According to the results of determining the regression coefficient (ecological plasticity coefficient), in terms of the characteristic "duration of the growing season", the collection samples of watermelon were divided into three groups – with low (b_i=0.01-2.20), medium (b_i=2.21-4.22), and high (b_i=4.23-6.24) ecological plasticity. According to the selection value of the genotype according to the characteristic "duration of the seedling-ripening period", 18 collection samples had high indicators (SVG_i=110.22-119.92), which are valuable for use in selection work with watermelon as sources of the characteristic "early ripeness".

The study on the selection of highly adaptive raw material of watermelon based on the trait "early ripeness" helped identify genotypes that correspond to the modelled traits, and their involvement in the selection process to create early-ripening varieties and hybrids with high adaptability will increase the efficiency of selection work in this area; the introduction of new genotypes will extend the period of availability of valuable vitamin products earlier (from 10 days to 20 days earlier), which will contribute to providing the population with healthy nutrients; will increase the amount of cultivation and the yield level of watermelon, which in turn will increase the profitability of production (at least by 20%) and contribute to ensuring food security of Ukraine. This is what determined the relevance of this study and proved the perspective of conducting it on other valuable selection traits that have great economic importance.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Відбір високоадаптивного вихідного матеріалу кавуна для селекції на ранньостиглість

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Анотація. У питанні селекції кавуна залишається актуальною проблема стабільності отримання високої урожайності в умовах прояву абіотичних стресорів зовнішнього середовища. Метою завдання було виділення високоадаптивного вихідного матеріалу кавуна за тривалістю вегетаційного періоду та його складових для використання у селекції на ранньостиглість. Було проаналізовано 101 колекційний зразок кавуна з 9 країн світу. В основу дослідження покладено такі методи: загальнонаукові, вимірювально-вагові, розрахункові, статистичні. Проведено розподіл колекції кавуна на групи стиглості та ранжування вибірки за ознакою «тривалість періоду сходи – достигання». Дослідженнями встановлено амплітуду (A_m) та розмах варіювання *(Lim)* ознак тривалості складових вегетаційного періоду. Для використання в селекції на ранньостиглість виділено зразки з найменшими окремими міжфазними періодами. Визначено: V_i – загальна адаптивна здатність (ЗАЗ), $\sigma 2САЗ_i$ – специфічна адаптивна здатність (САЗ), *Sgi* – стабільність генотипу, b^i – коефіцієнт регресії реакції генотипу на зміну умов (пластичність), $СЦГ_i$ – селекційна цінність генотипу колекції кавуна за ознакою «тривалість вегетаційного періоду». За загальною адаптивною здатністю виділено зразки з найменшою тривалістю періоду «сходи – достигання» – 19 зразків (V_i=-11,72…-6,05). Як найбільш стабільні генотипи за ознакою «тривалість вегетаційного періоду» виділено 32 колекційних сортозразка з низьким значенням показника специфічної адаптивної здатності, 23 з яких відносяться до ранньостиглих. Високу стабільність генотипу (*Sgi*) за ознакою «тривалість періоду сходи – достигання» визначено у 31 колекційного зразка, з яких 24 відносяться до ранньостиглих. За результатами визначення коефіцієнта регресії (коефіцієнта екологічної пластичності), за ознакою тривалість вегетаційного періоду колекційні зразки кавуна було розподіллено на три групи – з низькою (b_i=0,01-2,20), середньою (b_i=2,21-4,22), та високою (b_i=4,23-6,24) екологічною пластичністю. За селекційною цінністю генотипу за ознакою «тривалість періоду сходи – достигання» високі показники мали 18 колекційних зразків ($СЦГ_i$=110,22-119,92), які мають цінність для використання у селекційної роботі з кавуном в якості джерел ознаки «ранньостиглість»

Ключові слова: кавун; селекція; ранньостиглість; адаптивна здатність; стабільність; пластичність; селекційна цінність

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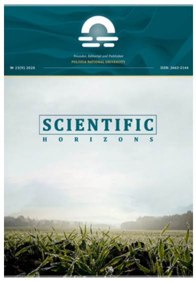

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The influence of agrotechnical measures on the number of melanin-synthesizing microorganisms

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Abstract. In connection with the growing scale of soil dehumification, studies of the patterns of synthesis of the precursors of humus molecules – melanins of bacterial origin – are becoming increasingly relevant. The purpose of this study was to establish the influence of the main factors of agricultural production on the spread of melanin-synthesizing microorganisms: the method of basic soil cultivation, mineral fertilizers,

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and the type of agricultural crop. Research methods: microbiological, laboratory-analytical, statistical, correlational. As a result, the study found for the first time that the main cultivation of the soil affects the number of melanin-synthesizing microorganisms: micromycetes, bacteria, *a*zotobacter. In the variant without the application of mineral fertilizers (control), the soil was characterized by the minimum amount of melanin-synthesizing bacteria using the No-till technology, 28.8% more – using disking, and 2.4 times more – using ploughing. The number of melanin-synthesizing micromycetes in the variant without fertilizers was also maximum upon ploughing, the average number was observed with No-till technologies, and the minimum number – using shallow disk tillage. Application of mineral fertilizers in a dose of $N_{30}P_{30}K_{65}$ leads to an increase in the number of melanin-synthesizing bacteria in the ploughing option by 3.58 times, disking by 3.53 times, No-till technology by 2.28 times. An increase in the dose of mineral fertilizers to $N_{150}P_{100}K_{120}$ contributes to an increase in the number of melanin-synthesizing bacteria by 5.04 times upon ploughing, 5.78 times upon disking, and 2.24 times upon no-till technologies. The medium-significant nature of the relationship between the content of humus and the number of melanin-synthesizing bacteria (r=0.528) and their share in the total number of microorganisms (r=0.470) suggested that in chernozem inherent in growing sunflowers, humus is formed mainly with the participation melanins of bacterial origin. Metabolites of polysaccharide-synthesizing bacteria take part in the formation of the resistance of humus molecules to microbial mineralization, the probability of the formation of colonies of which has a moderately significant relationship with the content of humus (r=0.532). The results of these studies can be used in the development of recommendations for regulating the content of humus in agricultural soils, preventing its excessive mineralization, which will allow preserving and increasing soil fertility

Keywords: melanins; bacteria; micromycetes; azotobacter; humus; proportion; correlation

INTRODUCTION

Soil organic matter, and humus in particular, is the final product of microbial transformation of molecules released from dead plant and animal cells (Lorenz *et al.*, 2021, Savarese *et al.*, 2021, Soil Humus Formation, 2018). Humus is of fundamental importance in ecosystems, regulating global carbon and nitrogen cycles, plant and microorganism growth, and soil functions. Pan *et al.* (2009) and Ping *et al.* (2009) noted that the accumulation of humus in agricultural ecosystems is necessary not only for preserving soil fertility and forming the productivity of agricultural crops, but for stabilizing soil organic carbon and reducing greenhouse gas emissions into the atmosphere. Nevertheless, the growth of food production increases the risk of depletion of arable land, which leads to dehumification, erosion, and desertification. In this regard, the study of the patterns of the synthesis of humic compounds and their precursors – melanins of bacterial origin – is relevant and timely.

Melanins are produced by heterotrophic bacteria, micromycetes, and are dark-coloured pigments. For many producers, these pigments are secondary metabolites that contribute to photoprotection (a photoprotector that effectively absorbs and dissipates solar radiation as heat), predation, predation protection, metal resistance (metal chelating sorbents) (Fisher *et al.*, 2019, Dornelas *et al.*, 2022). Tran Ly *et al.* (2020) believe that melanins bind organic compounds for detoxification, and act as an organic semiconductor.

The study (Reddy *et al.*, 2007) investigated the patterns of melanin synthesis by the actinobacterium *Modestobacter versicolor sp. nov.* isolated from biological crusts of the surface layer of the soil of the Colorado Plateau (USA), the cells of which produce melanin-like pigments under conditions of oligotrophy, i.e., when grown on an oligotrophic medium, but not when grown on a copyotrophic medium. Induction of melanogenesis by *Modestobacter versicolor sp. nov.* does not depend on the growth phase of the crop or lighting conditions, including UVB and UVA-irradiation, but UVB exposure can increase total pigment synthesis, while growth under low nitrogen conditions inhibits its synthesis.

Fungi, especially ascomycetes, synthesize melanin molecules in their cell walls to protect against fungivores and harsh abiotic conditions (Ekblad *et al.*, 2013, Baskaran *et al.*, 2019). The authors (Edwards *et al.*, 2021) believe that the synthesis of melanins also protects producers from the damaging effects of ultraviolet radiation.

Thus, to date, the regularities of melanin synthesis as a biotechnological product in producer monocultures and the possibilities of their application in practice have been investigated. However, the ecological aspects of the distribution of melanin-synthesizing microorganisms in nature, and especially in the soils of agrocenoses, are still understudied. The issue of influence on the spread of melanin-synthesizing microorganisms of the main factors of agricultural production: the method of basic soil cultivation and mineral fertilization are still unexplored. The present study aims to solve these problems, the results of which are presented below.

MATERIALS AND METHODS

The investigation was conducted in a stationary experiment on the study of short-rotational crop rotations at the Panfilsk research station of the National Research Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine", established in 2009.

The soil of the experimental plots is a typical shallow coarse-grained and light-loam chernozem, which lies on a carbonate light loamy forest. Before starting the experiment, the soil was characterized by the following agrochemical parameters: humus content – 3.17%; soil pH 6.15; hydrolytic acidity – 3.15 mg-eq/100 g of soil; the amount of absorbed bases – 14.1 mg-eq/100 g; exchange bases: calcium – 7.43; magnesium – 1.14 mg-eq/100 g of soil; degree of saturation with bases – 56%, easily hydrolysable nitrogen content – 72.8 mg/kg; mobile phosphates – 300.0 mg/kg, exchangeable potassium – 95.5 mg/kg of soil.

The study was conducted in crop rotation: sunflower – soybean – winter wheat – spring barley – sunflower. The object of the study was the variants of the stationary experiment: 1 – No-till technology, without fertilizers (control); 2 – No-till technology, $N_{30}P_{30}K_{65}$, 3 – No-till technology, $N_{150}P_{100}K_{120}$; 4 – Disking (shallow disk cultivation 10-12 cm deep), without fertilizers; 5 – Disking, $N_{30}P_{30}K_{65}$; 6 – Disking, $N_{150}P_{100}K_{120}$, 7 – Ploughing 25-27 cm deep, without fertilizers; 8 – Ploughing 25-27 cm deep, $N_{30}P_{30}K_{65}$, 9 – Ploughing 25-27 cm deep, $N_{150}P_{100}K_{120}$. In 2021, the variants under study were used to cultivate the sunflower hybrid "Tor", the predecessor of which was spring barley. The size of the sowing area was 25*6=150 m^2, the accounting area was 100 m^2. The experiment was repeated three times, the placement of variants and repetitions was systematic.

The number of microorganisms of the main ecological-trophic, functional, and systematic groups was estimated according to the method of sowing soil suspension on the corresponding general, elective, and special nutrient media in three repetitions (Dubey *et al.*, 2020, Lee *et al.*, 2021). The number of colonies was counted for 21 days depending on the growth rate and physiological characteristics of microorganisms of a certain ecological-trophic group. Indicators of the intensity of processes of mineralization of nitrogen compounds, soil organic matter, humus, probability of bacterial colony formation (PCF) were calculated as described earlier (Malynovska *et al.*, 2023). For a general assessment of the biological state of the soil, the indicator of total biological activity (TBA) was calculated using the method of relative values (Rusakova, 2013). The content of humus in the soil was determined according to (DSTU 4289:2004).

Statistical processing of experimental data was performed according to methods generally accepted in soil science and soil microbiology using Microsoft Excel and Statistica 10 computer programs. Determination of correlations between the indicators under study and their closeness was assessed based on the results of correlation analysis obtained using Microsoft Excel 2010.

RESULTS

The results of the study are presented in Table 1, Figure 1. The analysis of the results of these studies suggested that the main tillage affects the number of melanin-synthesizing microorganisms: micromycetes, bacteria, *a*zotobacter. In the variant without fertilizers, the soil was characterized by the maximum number of melanin-synthesizing bacteria when ploughing was used, by 28.8% less – when disking, and 2.4 times less – when using No-till technology. With the minimum dose of fertilizers ($N_{30}P_{30}K_{65}$), this regularity was preserved: the number of melanin-synthesizing bacteria in the ploughing variant exceeded the number of such bacteria by disking by 30.7%, upon No-till technology – 3.76 times. At the maximum dose of fertilizers ($N_{150}P_{100}K_{120}$), the corresponding indicators were 12.4% and 5.4 times.

Table 1. *The number of microorganisms in chernozem typical for growing sunflowers, million CFU*/g of dehydrated soil*

Variant	*Azotobacter*, % fouling of soil clods	Pedotrophs	Cellulose-destroying bacteria	Polysaccharide synthesizing	Actinomycetes	Micromycetes	Melanin-synthesizing micromycetes	Share of melanin-synthesizing micromycetes in the total amount, %	Melanin-synthesizing bacteria	Share of melanin-synthesizing bacteria in the total number, %	Autochthonous	Total number
No-till technology, without fertilizers	41.3	86.3	65.5	12.0	10.3	0.308	0.0220	7.14	2.48	0.26	20.1	950.3
No-till technology, $N_{30}P_{30}K_{65}$	18.7	116.8	54.8	14.2	16.5	0.423	0.0350	8.27	5.66	0.56	9.83	1,010.7
No-till technology, $N_{150}P_{100}K_{120}$	18.7	79.0	94.4	16.7	13.0	0.525	0.0560	10.7	5.56	0.52	10.5	1,079.0
Disking, without fertilizers	26.7	150.8	69.3	14.4	18.1	0.430	0.0142	3.30	4.62	0.37	15.2	1,250.7
Disking, $N_{30}P_{30}K_{65}$	36.0	152.5	81.6	25.7	20.8	0.824	0.0645	7.82	16.3	1.15	17.5	1,421.6
Disking, $N_{150}P_{100}K_{120}$	40.7	192.4	86.5	6.60	19.8	0.535	0.0452	8.45	26.7	2.03	18.0	1,315.5
Ploughing, without fertilizers	96.0	88.9	90.2	12.3	12.1	0.250	0.0317	12.7	5.95	0.62	15.8	959.1

Table 1, Continued

Variant	*Azotobacter*, % fouling of soil clods	Pedotrophs	Cellulose-destroying bacteria	Polysaccharide synthesizing	Actinomycetes	Micromycetes	Melanin-synthesizing micromycetes	Share of melanin-synthesizing micromycetes in the total amount, %	Melanin-synthesizing bacteria	Share of melanin-synthesizing bacteria in the total number, %	Autochthonous	Total number
Ploughing, $N_{30}P_{30}K_{65}$	22.0	98.0	51.2	10.4	13.1	0.356	0.0346	9.72	21.3	2.72	13.1	783.4
Ploughing, $N_{150}P_{100}K_{120}$	25.3	46.4	63.2	4.21	8.77	0. 239	0.0175	7.32	30.0	4.63	10.5	648.6
LSD_{05}	3.55	8.74	2.12	3.15	1.88	0.05	0.002		0.08		0.98	

Note: *CFU * – colony-forming unit*
Source: *developed by the authors of this study*

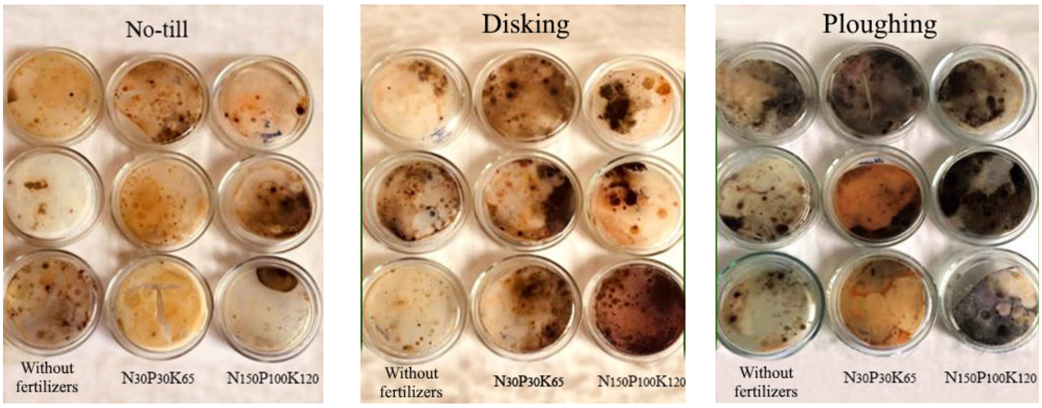

Figure 1. *Synthesis of melanins by microorganisms of chernozem typical for the use of no-till technology as the main tillage, disking 10-12 cm deep and ploughing 25-27 cm deep*

The share of melanin-synthesizing bacteria in the total number of microorganisms also depends on the method of the main soil cultivation: in the variant without fertilizers, the maximum value of this indicator is characterized by the soil with the use of ploughing, by 67.6% less – the soil with the use of disking, by 2.38 times smaller value – the soil upon No-till. As a result of the incertion of mineral fertilizers, the share of melanin-synthesizing bacteria in the total number of microorganisms increases under all methods of soil cultivation, especially significantly – under ploughing.

Somewhat different patterns are observed for melanin-synthesizing micromycetes, specifically, in the version without fertilizers, the maximum number of these microorganisms is observed when ploughing is used, but the average number is not observed when disking is used (as for melanin-synthesizing bacteria), but with No-till technologies. The insertion of mineral fertilizers in the minimum dose changes the pattern even more: the maximum number of melanin-synthesizing micromycetes is found when using disking, the same – when using ploughing and No-till technology. At the maximum dose of fertilizers, the highest number of melanin-synthesizing micromycetes is sown from the soil in the No-till technology variant, the average – from the soil of the disking variant, the minimum – after ploughing. The number of melanin-synthesizing micromycetes under No-till technology significantly increases compared to the option without fertilizers when applying the maximum dose of fertilizers, which correlates with an increase in phytotoxicity of the soil by 9.52% (Tables 1, 2). Perhaps this is explained by the fact that micromycetes are the main toxin producers in the soil.

Table 2. *Indicators of the intensity of mineralization processes and phytotoxic properties of typical chernozem under various agrotechnical and agrochemical measures*

No.	Variant	Pedotrophicity index	Oligotrophy coefficient	Nitrogen mineralization coefficient	Humus mineralization activity, %	Total biological activity	Weight of 100 plants of the test culture – winter wheat, g
1	No-till technology, without fertilizers	0.175	0.117	0.282	23.3	727.2	11.5
2	No-till technology, $N_{30}P_{30}K_{65}$	0.226	0.183	0.268	8.42	765.6	10.3

Table 2, Continued

No.	Variant	Pedotrophicity index	Oligotrophy coefficient	Nitrogen mineralization coefficient	Humus mineralization activity, %	Total biological activity	Weight of 100 plants of the test culture – winter wheat, g
3	No-till technology, $N_{150}P_{100}K_{120}$	0.146	0.196	0.297	13.3	904.9	10.5
4	Disking, without fertilizers	0.248	0.112	0.373	10.1	910.8	12.8
5	Disking, $N_{30}P_{30}K_{65}$	0.229	0.209	0.350	9.11	1221.4	10.3
6	Disking, $N_{150}P_{100}K_{120}$	0.303	0.113	0.285	9.36	1094.8	9.32
7	Ploughing, without fertilizers	0.228	0.238	0.339	17.8	784.5	10.9
8	Ploughing, $N_{30}P_{30}K_{65}$	0.304	0.190	0.440	13.4	839.8	11.0
9	Ploughing, $N_{150}P_{100}K_{120}$	0.155	0.180	0.308	22.6	586.9	10.2
	LSD_{05}						0.11

Source: *developed by the authors of this study*

Upon disking, the highest number of melanin-synthesizing micromycetes is observed at the lowest of the investigated doses of fertilizers, which exceeds the indicator of the option without fertilizers by 4.54 times, the indicator of the option with the maximum dose of fertilizers – by 1.43 times. Upon ploughing, the maximum number of melanin-synthesizing micromycetes is also observed in the variant with the lowest of the investigated doses of fertilizers and significantly exceeds the number of these microorganisms only in the variant with the dose of fertilizers $N_{150}P_{100}K_{120}$ – by 1.98 times. This is explained, perhaps, by the fact that the dose of $N_{150}P_{100}K_{120}$ fertilizers turned out to be inhibitory for such tillage as disking and ploughing.

An important indicator is not only the number of melanin-synthesizing micromycetes, but their share in the total number of fungi. In the variant without fertilizers, the share of melanin-synthesizing micromycetes is maximum when ploughing is carried out, average – when using No-till technology, minimum – upon disking. Application of fertilizers leads to an increase in the share of melanin-synthesizing micromycetes in their total number under No-till technologies and disking. Conversely, upon ploughing, the share of melanin-synthesizing micromycetes decreases by 30.7% when $N_{30}P_{30}K_{45}$ is applied, and by 73.5% when $N_{150}P_{100}K_{120}$ fertilizer doses are applied. When disking is used as the main tillage, the share of melanin-synthesizing micromycetes gradually increases: from 3.30% (without fertilizers) to 7.83% ($N_{30}P_{30}K_{45}$) and up to 8.45% ($N_{150}P_{100}K_{120}$), which corresponds to the classic ideas about the increase in the toxic load with an increase in the dose of mineral fertilizers containing heavy metal impurities.

The spread of *a*zotobacter as a melanin-synthesizing microorganism is influenced, on the one hand, by doses of nitrogen fertilizers, and on the other hand by soil pollution with pollutants. A manifestation of the inhibitory effect of nitrogen fertilizers is a decrease in the number of *a*zotobacter with an increase in their dose: when using No-till technology by 2.21 times, when ploughing – by 4.36 and 3.79 times, respectively, with an increase in the dose of fertilizers. When disking, the number of *a*zotobacter ranges from 26.7 to 40.7% of soil clod growth. In addition, the number of *a*zotobacter is affected by the method of main soil cultivation, in the variant without fertilizers, its maximum number is observed when ploughing is used, possibly because ploughing provides better soil aeration, and representatives of the genus *a*zotobacter are obligate aerobes and require the presence of oxygen for their existence. With the incertion of mineral fertilizers, the development of *a*zotobacter in ploughed soil is suppressed to a greater extent than with disk shallow tillage, but to a lesser extent than with No-till technology, which is due, perhaps, to the difficulty of nitrogen diffusion of fertilizers into the soil.

One of the important characteristics of the microbial cenosis is the specific content of autochthonous microorganisms. According to the obtained data, the highest level of humus mineralization is observed in the version without fertilizers when using No-till technology (23.3%), the average level – when ploughing (17.8%), the minimum – when disking (10.1%) (Table 2). When using No-till technology, the application of mineral fertilizers in the dose of $N_{30}P_{30}K_{45}$ leads to a decrease in the activity of mineralization of humus by 2.77 times, as a result of the application of fertilizers in the dose of $N_{150}P_{100}K_{120}$ – by 75.0%, which is associated with better vegetative growth of plants, greater allocation root exudates, which, in turn, slows down the destruction of humus as a less available substrate. When disking, the application of mineral fertilizers slows down the mineralization of humus by 10.9% and 7.91%, respectively. The tendency to activate the decomposition of humus compounds at the maximum of the investigated doses of fertilizers is observed both upon disking and upon ploughing. In the variant using ploughing, the activity of humus destruction exceeds the indicators of the control (without fertilizers) and the variant with the minimum dose of fertilizers, which indicates the suboptimal dose of fertilizers $N_{150}P_{100}K_{120}$. The regularities regarding the activation of humus decomposition under the influence of various agricultural practices coincide with those previously established.

The index of pedotrophicity, which reflects the level of consumption of organic matter, in the variant using No-till technology, with the application of the minimum dose of fertilizers, increases by 29.1%, and with the application of the maximum dose of fertilizers, it decreases by 19.9% compared to the control. In the variant using disking, the pedotrophicity index slightly decreases with the minimum dose of fertilizers, while with the maximum dose it increases by 22.2%. When ploughing, the patterns of changes in the activity of consumption of soil organic matter are comparable to those observed when using No-till technology. The pedotrophicity index in the version without fertilizers has the maximum value upon disking, the average value upon ploughing, the minimum value upon using no-till technology. As a result of applying fertilizers in the dose of $N_{30}P_{30}K_{45}$, ploughing begins to be characterized by the maximum level of consumption of soil organic matter, when applying fertilizers in the dose of $N_{150}P_{100}K_{120}$ – soil cultivation with disc tools.

To establish the relationship between the indicators under study, a correlation analysis was conducted, which showed that the content of humus in typical chernozem correlates with the number of autochthonous microorganisms, melanin-synthesizing bacteria, their share in the total number of microorganisms, the PCF of polysaccharide-synthesizing bacteria and the activity of humus mineralization (Table 3).

Table 3. *Correlation coefficients between indicators of the state of the microbial cenosis and the content of humus in chernozem typical for growing sunflowers*

Indicator	Azotobacter, % fouling of soil clods	Polysaccharide synthesizing	Autochthonous	Micromycetes	Melanin-synthesizing micromycetes	Share of melanin-synthesizing micromycetes in the total amount, %	Melanin-synthesizing bacteria	Share of melanin-synthesizing bacteria in the total number, %	Total number of microorganisms	PCF of azotobacter	PCF of micromycetes	PCF of polysaccharide-synthesizing bacteria	Humus mineralization activity, %	Total biological activity	Humus content, %
Azotobacter, %	1.000														
Polysaccharide synthesizing	-0.038	1.000													
Autochthonous	0.460	0.156	1.000												
Micromycetes	-0.268	0.757	0.213	1.000											
Melanin-synthesizing micromycetes	-0.060	0.627	0.038	0.815	1.000										
Share of melanin-synthesizing micromycetes in the total amount, %	0.505	-0.017	-0.164	-0.135	0.444	1.000									
Melanin-synthesizing bacteria	-0.186	-0.477	-0.101	0.050	0.078	0.004	1.000								
Share of melanin-synthesizing bacteria in the total number, %	-0.226	-0.597	-0.322	-0.257	-0.190	-0.005	0.909	1.000							
Total number of microorganisms	0.033	0.626	0.477	0.830	0.551	-0.256	-0.193	-0.543	1.000						
PCF of azotobacter	0.543	-0.088	0.050	-0.439	-0.450	0.079	-0.228	-0.089	-0.179	1.000					
PCF of micromycetes	-0.645	0.498	1.000	0.480	0.553	0.064	-0.075	-0.048	0.070	-0.330	1.000				
PCF of polysaccharide-synthesizing bacteria	-0.059	0.375	-0.399	0.079	0.415	0.515	-0.621	-0.589	-0.027	-0.259	0.499	1.000			

Table 3, Continued

Indicator	Azotobacter, % fouling of soil clods	Polysaccharide synthesizing	Autochthonous	Micromycetes	Melanin-synthesizing micromycetes	Share of melanin-synthesizing micromycetes in the total amount, %	Melanin-synthesizing bacteria	Share of melanin-synthesizing bacteria in the total number, %	Total number of microorganisms	PCF of azotobacter	PCF of micromycetes	PCF of polysaccharide-synthesizing bacteria	Humus mineralization activity, %	Total biological activity	Humus content, %
Humus mineralization activity, %	0.294	-0.373	-0.152	-0.608	-0.448	0.127	0.049	0.312	-0.654	0.141	-0.191	-0.059	1.000		
Total biological activity	-0.039	0.773	0.156	0.944	0.788	-0.046	0.101	-0.183	0.775	-0.245	0.391	-0.035	-0.415	1.000	
Humus content, %	-0.099	-0.014	-0.338	-0.114	-0.052	-0.053	0.528	0.470	0.029	0.382	0.134	0.532	-0.335	-0.231	1.000
Yield, t/ha	-0.160	-0.587	0.135	-0.105	0.045	0.148	0.913	0.899	-0.329	-0.244	-0.052	-0.499	0.138	-0.079	0.320

Source: *developed by the authors of this study*

The content of humus is inversely correlated with the physiological and biochemical activity of azotobacter cells. Since both azotobacter, which can synthesize melanins (Noar *et al.*, 2018), and polysaccharide-synthesizing bacteria are related to the synthesis of humus molecules and take part in the formation of its resistance to bacterial mineralization (Iutinskaya, 1989), the emergence of these connections is understandable. The number of melanin-synthesizing bacteria in typical chernozem has an inverse highly significant relationship with the PCF of polysaccharide-synthesizing bacteria (r=-0.625). The share of melanin-synthesizing bacteria in the total number of microorganisms is inversely correlated with the number of polysaccharide-synthesizing bacteria (r=-0.597), the total number of microorganisms (r=-0.543), and the PCF of polysaccharide-synthesizing bacteria (r=-0.589).

The effect of mineral fertilizers, especially nitrogen fertilizers, on the number of melanin-synthesizing bacteria and micromycetes indicates that the main macroelements are necessary to reproduce representatives of this valuable agronomic group of microorganisms and their synthesis of melanins in natural soil conditions. This is confirmed by observations of the growth of microorganisms in monocultures. Thus, Reddy *et al.* (2007) showed that the growth of *Modestobacter versicolor sp. nov.* in conditions of low content of nitrogen compounds is accompanied by inhibition of melanin synthesis. Therefore, the incertion of mineral fertilizers into the soils of agrocenoses is necessary not only to optimize the mineral nutrition of agricultural plants, but to preserve and reproduce such an important factor of potential soil fertility as the humus content.

Soil microorganisms take part in the synthesis of humus in three ways: 1) through the synthesis of melanins, 2) the synthesis of exopolysaccharides and other secondary metabolites, 3) the synthesis of enzymes (Soil Humus Formation, 2018). The highly significant nature of the relationship between the content of humus and the number of melanin-synthesizing bacteria (r=0.528) and their share in the total number of microorganisms (r=0.470) suggests that humus is formed mainly with the participation of melanins of bacterial and not fungal origin, which is also confirmed by the low inverse correlation coefficients between the humus content and the number of melanin-synthesizing micromycetes (r=-0.052) and their share in the total number of fungi (r=-0.053). Since a low inverse correlation coefficient was found between humus content and the number of azotobacter (r=-0.099), it can be assumed that melanins of bacteria of the genus *Azotobacter* take a minor part in the synthesis of humus molecules when growing sunflowers on typical chernozem, but this is contradicted by a sufficiently high correlation coefficient between humus content and physiological and biochemical activity of azotobacter cells (r=0.372). It is known that with a small number of bacteria of a certain group, they can quickly activate the synthesis of metabolites due to an increase in the physiological and biochemical activity of cells without increasing the number of cells, i.e., reproduction.

Earlier, Iutinskaya (1989) showed that decomposition products of microbial exopolysaccharides react with humus molecules, resulting in the formation of complexes more resistant to microbial degradation. The obtained data confirmed the existence of a direct, moderately significant relationship between the physiological and biochemical activity of cells of polysaccharide-synthesizing bacteria and the content of humus (r=0.532), which reflects the increase in the resistance of humus molecules to mineralization by autochthonous microorganisms. This phenomenon contributes to the accumulation of humus since the mineralization activity of such polysaccharide-humate complexes decreases.

Between the content of humus and the number of autochthonous (humus-degrading) microorganisms, a moderately significant inverse correlation was found (r=-0.338), which emphasizes the negative influence of autochthonous bacteria on the accumulation of humus. In addition, a moderately significant inverse correlation (r=-0.335) was found between the humus content and the activity of humus mineralization by soil microorganisms, which is quite natural and is confirmed by the results of previous studies (Malynovs`ka *et al.*, 2021)

The analysis of the obtained data shows that the number of polysaccharide-synthesizing microorganisms has a direct correlation with the number of micromycetes (r=0.757), melanin-synthesizing micromycetes (r=0.627), and an inverse correlation with the number of melanin-synthesizing bacteria (r=-0.477), their share in the total number of microorganisms (r=-0.597), insignificant connection – with the number of azotobacter. This suggests that when there are such conditions in the soil that melanins of micromycetes take a greater part in the synthesis of humus molecules, the role of polysaccharide-synthesizing bacteria becomes more significant.

The highly significant correlation coefficient between the number of melanin-synthesizing bacteria (r=0.913), their share in the total number of microorganisms (r=0.899) and the crop yield are noteworthy. Perhaps this is a reflection of the constantly operating mechanism of the influence of melanin synthesis on the content of humus in typical chernozem, since the connection between the synthesis of humus and the productivity of agricultural crops is not so direct, it can become direct only under conditions of long-term action.

It was previously shown that in grey forest soil, closer relationships are formed between the humus content and the number of melanin-synthesizing micromycetes (r=0.811) and their share in the total number of fungi (r=0.915), with the number of melanin-synthesizing bacteria forming medium-level relationships significance (r=0.417), as with their share in the total number of microorganisms (r=0.450). In typical chernozem, the synthesis of humus is more influenced by melanin-synthesizing bacteria, the physiological and biochemical activity of azotobacter cells and polysaccharide-synthesizing bacteria. Thus, the processes of humus synthesis with the participation of melanins take place in diverse types of soils according to various patterns, depending on the agricultural methods used.

CONCLUSIONS

It was found that the main tillage and doses of mineral fertilizers affect the number of melanin-synthesizing microorganisms in typical chernozem. The soil upon ploughing at 25-27 cm is characterized by the largest number of melanin-synthesizing bacteria, the average – upon shallow disc tillage at 10-12 cm, the smallest number – when using No-till technology.

Application of mineral fertilizers in a dose of $N_{30}P_{30}K_{65}$ increases the number of melanin-synthesizing bacteria by 3.6 times (ploughing), 3.5 times (disking), and by 2.3 times – when using No-till technology. The use of mineral fertilizers in a dose of $N_{150}P_{100}K_{120}$ contributes to the growth of the number of melanin-synthesizing bacteria by 5.0 times when ploughing, 5.8 times when disking, and 2.2 times when using no-till technologies.

The maximum number of melanin-synthesizing micromycetes is observed in the soil of the variant without fertilizers when ploughing is used, the average number is observed when using the No-till technology, and the minimum number is observed using disking. Application of mineral fertilizers in a dose of $N_{30}P_{30}K_{65}$ changes the pattern: the largest number of melanin-synthesizing micromycetes is found in the soil when using disking, while ploughing and no-till technology reveal the same number of melanin-synthesizing micromycetes.

The number of melanin-synthesizing bacteria (r=0.528) and their share in the total number of microorganisms (r=0.470) has the greatest influence on humus synthesis in chernozem typical of sunflower cultivation. Melanins produced by azotobacter cells take part in the synthesis of typical chernozem humus, which is confirmed by the direct average correlation coefficient between the humus content and the physiological and biochemical activity of azotobacter cells (r=0.372).

Polysaccharide-synthesizing bacteria take part in the formation of the resistance of humus molecules to microbial mineralization, the probability of the formation of colonies of which has a moderately significant relationship with the content of humus (r=0.532). In the synthesis of humus molecules of chernozem typical for growing sunflowers, melanins of fungal origin take a minor part, which is confirmed by the low inverse values of the correlation coefficients between the humus content and the number of melanin-synthesizing micromycetes (r=-0.052) and their share in the total number of fungi (r=-0.053).

The study of the impact of agrotechnical and agrochemical factors on the processes of synthesis of melanins, which are the precursors of humus molecules, has the prospect of continuing, involving other agricultural crops grown on typical chernozem, since the type of agricultural crop substantially affects the course of mineralization and synthesis processes in the microbial community of the rhizosphere soil.

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None.

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Вплив агротехнічних заходів на чисельність меланінсинтезувальних мікроорганізмів

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Анотація. В зв'язку із зростанням масштабів дегуміфікації ґрунтів все більш актуальними стають дослідження закономірностей синтезу попередників гумусових молекул – меланінів бактеріального походження. Мета досліджень полягає в установленні впливу на розповсюдження меланінсинтезувальних мікроорганізмів основних чинників агровиробництва: способу основного обробітку ґрунту, мінерального удобрення, виду сільськогосподарської культури. Методи дослідження: мікробіологічний, лабораторно-аналітичний, статистичний, кореляційний. В результаті проведених досліджень вперше встановлено, що основний обробіток ґрунту впливає на чисельність меланінсинтезувальних мікроорганізмів: мікроміцетів, бактерій, азотобактера. У варіанті без внесення мінеральних добрив (контроль) мінімальною кількістю меланінсинтезувальних бактерій характеризується ґрунт за застосування No-till-технології, на 28,8 % більшою – із застосуванням дискування і у 2,4 раза більшою – за проведення оранки. Кількість меланінсинтезувальних мікроміцетів у варіанті без добрив також максимальна за застосування оранки, середня кількість спостерігається за No-till-технології, мінімальна кількість – за використання мілкого дискового обробітку. Внесення мінеральних добрив у дозі $N_{30}P_{30}K_{65}$ призводить до збільшення чисельності меланінсинтезувальних бактерій у варіанті оранки в 3,58 рази, дискування – 3,53, No-till –технології – в 2,28 рази. Зростання дози мінеральних добрив до $N_{150}P_{100}K_{120}$ сприяє збільшенню чисельності меланінсинтезувальних бактерій за оранки в 5,04 раза, за дискування – 5,78, за No-till-технології – в 2,24 раза. Середньозначимий характер зв'язку між вмістом гумусу і чисельністю меланінсинтезувальних бактерій (r=0,528) та їхньою часткою у загальній кількості мікроорганізмів (r=0,470) дозволяє зробити висновок про те, що у чорноземі типовому за вирощування соняшнику гумус утворюється, в основному, за участі меланінів бактеріального походження. У формуванні стійкості молекул гумусу до мікробної мінералізації приймають участь метаболіти полісахаридсинтезувальних бактерій, вірогідність формування колоній яких має середньозначимий зв›язок із вмістом гумусу (r=0,532). Результати цих досліджень можуть бути використані при розробленні рекомендацій щодо регулювання вмісту гумусу в агроземах, запобігання його надмірної мінералізації, що дозволить зберегти та підвищити родючість ґрунтів

Ключові слова: меланіни; бактерії; мікроміцети; азотобактер; гумус; частка; кореляція

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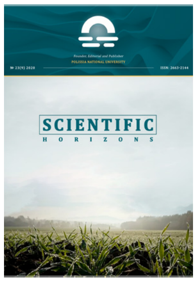

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Analysis of modern technologies for growing cherry varieties in temperate climates

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Abstract. The research relevance is predefined by the need to optimise fruit crop cultivation systems considering weather conditions. The research aims to test the grafting technology of intensive sweet cherry plantations on small and medium-sized rootstocks. The leading method in achieving the research goal was a field experiment. The main results of this study are as follows: the leading technologies for increasing the yield of sweet cherry varieties depending on the impact of environmental stress factors are presented; the use of clone rootstock

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technology in sweet cherry plantations in temperate climates is substantiated. According to a set of indicators of productivity formation, the yield of plantations of different designs was predicted. Namely, the scheme of variety-rootstock combinations of intercalary placement, its length, and parameters of the growth complex for plants were revealed; indicators of physiological activity, growth, productivity, fruit quality, and economic efficiency in intensive sweet cherry plantations were determined. It has been established that the application of this technology will increase yields and improve the quality parameters of sweet cherry fruits by developing varieties with compact crowns, which will allow to compact the plantations. It has been analysed that climatic conditions are the main factor in the process of harvest formation. A list of stress factors of temperate climate that affect the yield of sweet cherries has been identified. It is proved that the introduction of clonal rootstock technology is the most effective for growing intensive plantations of sweet cherries in a temperate climate. Practically, the research aims to determine and test a set of elements of physiological indicators of the potential yield of sweet cherry plantations of different designs, to introduce them into production and use them in further breeding

Keywords: fruit trees; stone fruit plant; horticulture; yield; innovative methods of reproduction; optimal breeding conditions

INTRODUCTION

Due to its agrobiological potential, Ukraine is a leader in global sweet cherry production. Adaptive horticulture is the leading principle of modern fruit production, which considers the maximum of optimally dosed factors of horticultural productivity. Currently, there are many technologies for growing sweet cherries in temperate climates. However, the disadvantage of most of the technologies traditionally used in Ukraine for growing sweet cherries was the late entry of trees into commercial fruiting and the complicated process of processing large trees in the orchard. High yields of sweet cherries are influenced by agronomic, management and natural and climatic factors. In such conditions, the optimal technology for ensuring sweet cherry yields is the use of small and medium-sized rootstocks in intensive plantations of sweet cherries. Therefore, the study of the effectiveness of rootstock technology implementation has been the most relevant topic in scientific institutions in recent years. The development of modern technologies for growing fruit trees was carried out by O.A. Kishchak and Yu.P. Kishchak (2021), T. Malyuk *et al.* (2021), B. Gulko (2020), J. Blažek *et al.* (2022), P. Drogoudi *et al.* (2020) and A. Küden *et al.* (2022).

In recent years of independent Ukraine, agricultural specialists tested numerous different rootstocks and layouts of sweet cherry trees. However, the optimal design of intensive plantations does not yet exist. The design of such plantations is determined by the variety, rootstock, and crown shape, and all these factors must be considered, as the determination of one affects the performance of the other. The study of increasing the yield of sweet cherries by rootstock of weak and medium-sized trees was carried out by J. Lanauskas *et al.* (2023). The design of plantations using this technology must meet certain standards: a straight trunk and a developed root system, the trunk and root must be healthy, the latter without significant distortions of the root collar, rootstocks must be of the same age and undamaged, with homogeneous species composition and quality.

Organic technology, which is applied without the use of synthetic chemical pesticides and mineral fertilisers, is one of the innovative technologies in modern horticulture, which was introduced by T. Herasko (2021). Based on this technology, sweet cherries are grown by calculating the balance of water regime, photosynthetic pigments, leaf area and biochemical composition of the fruit. The fruits of such cherries can be consumed without fear for the health of children and adults; however, organic cherries are not grown on an industrial scale because, from a practical point of view, they are not very efficient.

Given the current economic conditions and the development of gardening enterprises in Ukraine, production volumes are characterised by the yield of fruit crops. According to research by O. Kishchak *et al.* (2020), 50% of fertile lands have shifted climatic zones and desertification is observed in some central regions of Ukraine, which will subsequently lead to significant changes in fruit tree yields. Unseasonal frosts or too warm winters and other negative natural factors affect gross harvest rates. Therefore, the technology of sweet cherry cultivation, which considers environmental compliance or discomfort with certain weather factors, is one of the important issues for researchers.

O. Alekseeva and P. Bondarenko (2021) proves that the process of intensive cultivation of sweet cherries using weak rootstocks should consider the physiological structure of generative formations, their density and number, the number of fruit buds on these formations, the number of flowers on these buds. It is also indicated that the length of the generative insert should be no more than 30 cm, as it is under these conditions that the greatest productivity potential can be predicted.

Considering the above-mentioned, the research aims to study the effectiveness of clone grafting for intensive gardening in the central region of Ukraine.

MATERIALS AND METHODS

The field study was conducted at the farm in the village of Chaplyka, Pavlohradskyi district, Dnipro region. The climate of the study area is temperate continental, with an average winter temperature of -5...-6°C, summer temperature of +22...+23°C, with an average annual precipitation of 400 to 490 mm, and northeast and east winds. The soil of the study area is simple black soil with a high percentage of fertility (Drobitko *et al.*, 2022).

Two sweet cherry varieties were used in the study: Valeriy Chkalov (early ripening) and Krupnoplidna (late ripening) in a young plantation (3-6 vegetations). The first variety forms vigorous trees with large fruits. The second is a medium-sized tree with large fruits. Both varieties have high commercial characteristics. Seedlings of Magaleb cherry (Antipka) and Gisela 5 were used as rootstocks. The rootstocks of Magaleb cherry seedlings make the trees vigorous and resistant to drought and frost. The advantage of this rootstock is a reduction in fruit ripening and an acceleration of productivity after planting. This type of rootstock is widely used in the formation of orchards because of its ease of propagation, ease of budding and good growth of grafting components. Gisela 5 is a rootstock that reduces the vigour of tree growth, this type of rootstock is most popular in Europe. Although the use of Polish, Hungarian and American rootstock technologies in Ukraine does not allow for high yields in temperate climates, Ukrainian researchers are conducting studies to adapt these technologies to the Ukrainian climate. The advantage of this technology is the good growth of components at the grafting site and good angles of skeletal branches, which produce small root shoots. The growth vigour of trees grafted with Gisela 5 is reduced by 50%, and such cherries enter commercial fruiting early with a high level of efficiency. Trees become suitable for high-density and intensive planting. The disadvantages of this rootstock variant are the risk of damage to early flowering by spring frosts, the tree ages quickly due to high productivity, and the tree needs additional support due to the reduced root system and spindle-shaped crown.

The experimental study lasted for 1 year and had two variants: studying the effect of inserts of Magaleb cherry seedlings (Antipka) on the yield of cherry trees of the Krupnoplidna variety and studying the effect of Gisela 5 clone rootstocks on the yield of sweet cherries of the Valery Chkalov variety. The experimental plots had an area of 200 m^2 (5 m × 3 m and 5 m × 4 m, respectively), with 10 trees on each plot.

Each of the trees was selected through phenological observations, and the main indicators of yield prediction were also noted through these observations. These indicators include stem circumference, crown parameters, number and length of shoots, degree of flowering and useful ovary, the density of generative formations, average fruit weight and diameter. Leaf surface area was also taken into account as one of the parameters of the predicted yield, and the content of pigments chlorophyll *a* and carotenoids *b* was determined using a UNICO 2800 UV/VIS spectrometer. The length of the intercalary in all variants was 20 cm. The agronomic conditions of the research in all variants were identical. Statistical processing of the data obtained was carried out using Agrostat New and Minitab 16 computer programs.

RESULTS

To create intensive sweet cherry plantations in temperate climates, special attention should be paid to a comprehensive study of the main parameters of tree growth. Specifically, budding height and planting depth, quality of varieties, rootstocks, the density of varieties, types of crown formation, degree of pruning, and water and nutrient conditions. This study traced the interconnection of the elements of plantation design: variety and rootstock combinations, layout, and tree crown shape. Table 1 shows one of these parameters, namely, biometric parameters of tree crowns and boles depending on variety-rootstock combinations.

Table 1. *Biometric indices of crown and bole formation in sweet cherries Krupnoplidna on Antipka rootstock and Valery Chkalov on Gisela 5 rootstock*

Rootstock variants	Variety of sweet cherry	Plot size	The cross-sectional area of the bole, m^2	Crown projection area		Crown area	
				Actual, m^2	The utilisation of the feeding area, %	Actual, m^3	The utilisation of growth space, %
Antipka	Krupnoplidna	5 m × 3 m	254.3	8.4	63	8.3	52
		5 m × 4 m	326.7	8.8	80	9.8	59
Gisela 5	Valery Chkalov	5 m × 3 m	167.3	9.1	86	9.7	57
		5 m × 4 m	198.5	10.2	73	10.7	69

Source: *compiled by the authors*

In this study, when planting trees, the stem height indicator was used at the level of 50-70 cm, which is a standard value for industrial plantations. The Krupnoplidnaya variety outperformed the Valery Chkalov variety in terms of the cross-sectional area of the stem by almost 26%, and in terms of stem growth by 1.5 times, indicating that the Krupnoplidnaya sweet cherry variety was characterised by more intensive growth during the study period. It was proved that the assessment of tree growth vigour due to the development of living space in terms of the projection area and crown volume was 8-11% higher in 5 m × 4 m plots than in 5 m × 3 m plots. This suggests that the density of tree planting affects stem growth by increasing the feeding area of trees. The optimal tree height was 3.3-3.5 m, which was sufficient to ensure optimal radiation exposure of the plantations, and the row spacing was 5 m, which meets the established standards for orchard spacing. According to the indicators in Table 1, the allocated nutrition area for the 5 m × 3 m tree layout is 10.5 m, and for the 5 m × 4 m layout it is 14 m, i.e., the second variant of the layout is 19% more efficient on average in terms of space utilisation.

The vegetative growth of trees in a year can be assessed by the total annual growth of trees. This figure includes the number of annual growths on a tree, the average length of one growth, and the total length of annual growth of trees. Given that sweet cherries have a shoot-forming and shoot-regenerating ability of the buds, the number of annual growths is less than that of other stone fruit trees.

Therefore, for the cultivation of competitive intensive plantations, the annual growth rate of a tree is important. For stable, high-quality fruiting, which is ensured by the uniformity of fruit distribution throughout the crown, it is necessary to replace overgrown wood regularly.

Table 2 shows how the growth vigour changes depending on the influence of clonal rootstocks.

Table 2. *Annual growth of sweet cherry trees depending on variety and rootstock combinations*

Rootstock variants	Variety of sweet cherry	Plot size	The number of growths per tree, pcs	The average length of one growth, cm	Total annual growth	
					of 1 tree, m	1 ha, thousand meters
Antipka	Krupnoplidna	5 m × 3 m	163.6	39.6	64.8	43.2
		5 m × 4 m	191.4	45.6	87.3	43.6
Gisela 5	Valery Chkalov	5 m × 3 m	137.4	43.6	59.9	40.0
		5 m × 4 m	173.2	43.8	76.3	38.1

Source: *compiled by the authors*

Thus, according to the data in Table 2, it is proved that the insertion of mahaleb cherry seedlings (Antipka) on one tree of the Krupnoplidna variety formed an average of 166.7 growths per vegetation period, which is 19% more than the insertion of Gisela 5 clone rootstocks on trees of the Valery Chkalov variety. Comparing the arrangement of trees in the 5 m × 3 m and 5 m × 4 m plots, we can say that the formation of denser tree crowns, less prone to bareness, was observed in the 5 m × 4 m plot.

For effective fruiting, the average length of one growth should be more than 30 cm, a decrease in this indicator indicates insufficient vegetative growth and trees require pruning, and an indicator of more than 60 cm for tree growth is excessive, which leads to a decrease in the amount of fouling wood. In this study, the average length of one growth is 37.5-45.6 cm, which indicates a balance of growth and fruiting processes in the plantations. The growth vigour of sweet cherry trees depended to a small extent on the design of the plantations. Namely, trees of the Krupnoplidna variety had a total growth of 42.1-46.0 m/ha, and trees of the Valery Chkalov variety had a total growth of 34.1-40.6 thousand m/ha. In the 5 m×4 m plot, the total annual growth of the trees was 72.8 m, which is 21% more than the total growth in the 5 m×3 m plot, where the compaction of the plantations from 667 trees/ha to 1000 trees/ha reduced the annual growth by 24%.

The next indicator used to predict yields is photosynthetic activity. For trees grafted onto intercalators, the energy they accumulate during photosynthesis is used to form organs and crops. The process of photosynthesis fully depends on the area of the leaf plate on the shoots. It was found that this indicator on the leaves of bouquet branches was at the level of 43.7-45.5 cm^2 and did not depend on the variant of rootstocks. During the phenological observation, it was noted that sweet cherries of the Krupnoplidna variety had slightly larger leaves (70 cm^2) than trees of the Valery Chkalov variety (41 cm^2). All the above factors affect the size of the leaf surface, namely, its increase. Thus, the leaf surface area of Krupnoplidna sweet cherry increased by 23% after inoculation with Antipka, and that of Valery Chkalov by 21%. This increase in the number of leaves was due to an increase in the number of growths on the tree and the total annual growth (Table 3).

Table 3. *Leaf area and leaf index depending on the planting design*

Rootstock variants	Variety of sweet cherry	Plot size	Leaf area		Leaf index, m^2 leaf area	
			1 tree, m^2	1 ha, thousand, m^2	per 1 m^2 of crown projection surface area	per 1 m^3 of the crown area
Antipka	Krupnoplidna	5m × 3m	54.3	36.2	6.4	6.6
		5m× 4m	81.4	40.7	9.2	8.3
Gisela 5	Valery Chkalov	5m × 3m	53.5	35.7	5.9	5.5
		5m× 4m	77.2	38.6	7.6	7.2

Source: *compiled by the authors*

Considering the leaf area of a 5 m × 3 m planting density of 667 trees/ha, this figure decreased by 20%, compared to a 5 m × 4 m plot with a density of 500 trees/ha. Leaf index refers to the level of leaf coverage of tree crowns per unit projection area or crown volume. This index is also 15% higher in the 5 m × 4 m layout, which is explained by better crown illumination and a larger feeding area due to improved water and nutrient conditions. Krupnoplidna sweet cherries have a 1.2 times higher leaf index than Valery Chkalov sweet cherries due to the more compressed pyramidal shape of the tree crown. Thus, to improve yields, it is necessary to form a sufficient leaf area.

The main photosynthetic pigments studied in this experiment were chlorophyll *a* and *b*. The content of the former in the leaves ranged from 3.50 to 5.50 mg/g of dry matter, i.e., 57-62% of the total pigment content in the dry matter of the leaves; and the content of the latter was on average 2.8 times lower. The content of carotenoids is 3.0 times lower compared to chlorophyll. Such indicators correspond to the physiological optimum of sweet cherries (Table 4).

Table 4. *Content of photosynthetic pigments in sweet cherry leaves depending on tree crown zones*

Rootstock variants	Variety of sweet cherry	Plot size	Chlorophyll *a*, mg/g		Chlorophyll *b*, mg/g		Carotenoids, mg/g	
			periphery	centre	periphery	centre	periphery	centre
Antipka	Krupnoplidna	5 m × 3 m	4.35	5.50	1.46	1.93	1.54	1.77
		5 m × 4 m	3.72	4.95	1.31	1.80	1.30	1.53
Gisela 5	Valery Chkalov	5 m × 3 m	3.68	4.96	1.19	1.87	1.33	1.54
		5 m × 4 m	4.05	4.26	1.34	1.58	1.29	1.47

Source: *compiled by the authors*

As can be seen from Table 4, the ratio of chlorophyll *a* to chlorophyll *b* averages 3.04, and 2.72 in the central part of the crown. These values are within the physiological norm for sweet cherries. However, there is an increase in the proportion of *b*, which is an indicator of the adaptation of shade leaves to low-light conditions. According to the layout and rootstock variant, the Krupnoplodnaya sweet cherry variety can be distinguished on a 5 m × 3 m plot. It is known that a lack of light leads to a decrease in the thickness of the leaf blade and the number of layers of mesophyll-containing chloroplasts. Therefore, the specific gravity of dry matter of leaves from the crown periphery in this area averaged 75.1 g/m^2 leaf surface, which is 33% higher than that of leaves in the crown centre. Thus, the increase in specific gravity is due to the thickening of the leaf blade, not the proportion of dry matter in the leaves. Thus, this indicator proves that leaves with sufficient light levels outnumber shaded leaves in terms of chlorophyll *a* and *b* content, which allows compensation for the lack of photosynthetic pigments in the central crown zones. This fact once again proves that the content of photosynthetic pigments and their ratio ensures the passage of fruiting processes in sweet cherries.

Up to 80% of the sweet cherry fruit yield is formed in bouquet branches, which are laid on branches of two years and older, and the remaining 20% is formed at the base of annual shoots. The formation of bouquet branches is a long-term process that results in special generative formations. The durability and productivity of these formations depend on the factors discussed above in this study: lighting conditions, photosynthesis rates in leaves, and the age of the generative formation. The analysis of the density of generative formations on the wood of different ages in this study showed that the density of generative formations decreased with increasing age. Thanks to this analysis, it was possible to estimate the yield potential of the plantations. On average, 19.4 bouquet branches per 1 m were formed on two-year-old wood, and 17.4 pcs/m on three-year-old wood, which is 10% less. Starting from the age of four, the number of generative formations decreased by 31% (Table 5).

Table 5. The density of bouquet branches on the wood of different ages depends on the grafting option and placement scheme

Rootstock variants	Variety of sweet cherry	Plot size	The density of branches, pcs/m		
			2-year	3-year	4-year
Antipka	Krupnoplidna	5 m×3 m	19.0	17.5	10.5
		5 m×4 m	20.0	18.0	11.5
Gisela 5	Valery Chkalov	5 m×3 m	19.0	16.5	12.0
		5 m×4 m	20.0	17.0	13.5

Source: *compiled by the authors*

Thus, as can be seen from Table 5, there are no differences in the density of generative formations by rootstock variant, only in the combination of Antipka and Krupnoplidna, worse preservation of bouquet branches was observed on a four-year-old tree compared to Valery Chkalov sweet cherry, which is explained by the early ripening of this variety and spring frosts that were recorded during the experiment. According to the layout, it was found that the 5 m×4 m plot had 14% more generative formations at the age of two and three years than the 5 m × 3 m plot. On trees of four years of age, the density of bouquet branches did not depend on the layout.

The last two indicators that show the formation of the productivity of the varieties of these sweet cherries are the number of flowers per generative bud and the quality of the fruit. On average, the trees formed 2.77 flowers per fruit bud. Depending on this indicator, both sweet cherry varieties showed a tendency to increase yields in terms of fruit quality (Table 6). This suggests that higher yields can be achieved by introducing clonal rootstocks and by introducing cherry seedlings. Also, it should be noted that the average fruit weight was 5% higher in the 5 m × 4 m plot. These results confirm the influence of the feeding area on fruit size. The fruits of Krupnoplodnaya sweet cherry had an average weight of 7.3 g and 23.8 mm in diameter, and the fruits of Valery Chkalov sweet cherry had an average weight of 10.4 g and 28.0 mm in diameter.

Table 6. Structure of predicted yields by rootstock variant and placement scheme

Rootstock variants	Variety of sweet cherry	Plot size	Number of bouquet branches, pcs	Number of flowers per fruit bud, pcs	The yield of sweet cherry plantations, t/ha
Antipka	Krupnoplidna	5 m × 3 m	944.4	2.59	4.5
		5 m × 4 m	789.6	2.60	5.1
Gisela 5	Valery Chkalov	5 m × 3 m	1521.2	3.12	5.2
		5 m × 4 m	1146.3	3.19	5.5

Source: *compiled by the authors*

Thus, as can be seen from this research, both sweet cherry varieties on Antipka and Gisela 5 rootstocks have good yields in temperate climates. According to a set of indicators of actual and specific yields, it was proved that this technology is optimal in improving fruiting performance. The yield indicators obtained in this study meet not only the requirements of the state standards of Ukraine in the agricultural industry but also the international standards of the United Nations Economic Commission for Europe. Thus, this study proved that the genotype of the variety has the same influence on the physical parameters of fruit quality as the construction elements of rootstock plantations, intermediate inserts, and tree layout.

DISCUSSION

Today, the implementation of optimal agricultural practices requires improving the technical and organisational capabilities of growing planting material in a shorter time frame, while preserving the biological characteristics of crops and varieties. Maintaining the potential yield of plantations under current environmental conditions is virtually impossible due to the uncontrolled impact of these natural conditions on fruit yields. Therefore, the entire process of plantation care should be aimed at improving the production process of trees.

Achievements in the agricultural industry are fragmented, with some advanced studies assessing potential yields based on several factors: the intake and absorption of photosynthetically active radiation, moisture availability of plantings, soil fertility and plant uptake of nutrients, while some studies only consider the impact of anthropogenic factors. This diversity in research does not allow for the creation of a single technology for realising the yield potential of plants. According to S. Szilágyi *et al.* (2022) and H. Sarisu (2021), this process requires a comprehensive study. For example, the authors prove that the methodology of integral assessment of the realisation of yield potential by breeds and varieties is based on determining the degree of influence of individual weather factors on yield. That is, for industrial agriculture, it is important to determine the predicted yield based on a comprehensive analysis of the elements of the yield structure or the process of plant productivity formation.

This was the research aims – to predict the potential yield of the KrupnQoplidna and Valeriy Chkalov sweet cherry varieties using clone rootstocks and Magaleb cherry seedlings, where each of the rootstock variants was used to adjust the potential of sweet cherries, adapting it to temperate climate conditions and increasing demand in the international market.

In contrast to traditional sweet cherry growing technologies, the main requirements for rootstocks on intensive planting trees, according to J. Ortega-Vidal *et al.* (2021) and K. Németh-Csigai *et al.* (2023) is to reduce the volume of crowns due to a decrease in tree growth force, which will allow to compact the planting, adapt to the soil and climatic conditions of the growing area, increase the rate of fruiting and increase the yield of high quality, simplify the reproduction procedures, reduce root shoots and increase disease resistance. And as this study proves, this technology successfully copes with these requirements. This is confirmed by the high predicted yields.

The main countries where the search for modern technologies for growing cereals began were Germany, the Czech Republic, the USA, Italy, and France. In Ukraine, these technologies are just beginning to develop, but the first results of their implementation are noticeable.

One such organic technology is implemented without the use of synthetic chemical pesticides and mineral fertilisers (Mero *et al.*, 2023). T. Herasko (2021) proves the effectiveness of this technology by studying the impact of the physiological state of sweet cherries on their yield. In his study, the author shows how the water regime, the content of photosynthetic pigments in the leaves and the biochemical composition of the fruit affect yield indicators. Preserving the organic characteristics of the soil is considered the basis of organic technology in horticulture. Blackening contributes to the maintenance of the soil in the garden, namely, maintaining the required level of beneficial soil microorganisms, optimal soil temperature and moisture. This study showed that after introducing sod in the form of mowed natural grasses into the aisles of an unirrigated garden, the soil cools down to 28°C, compared to 37°C in the control plot (black fallow), meaning that the use of natural grasses as sod maintains a moderate soil temperature, which allows for sufficient moisture to be maintained. And the analysis of biologically active substances in sweet cherry leaves indicates that the content of sugars, titratable acids, phenolic substances, ascorbate, and glutathione is preserved compared to those trees whose soil was not subjected to sodding. The author notes that the use of this technology is a concern for the environment and healthy eating. In addition, this technology is aimed at the European market, where organic sweet cherries meet standards without the use of synthetic chemical pesticides and mineral fertilisers. However, this technology is not used on an industrial scale in Ukraine due to the lack of scientific research and the low efficiency of this technique in terms of accelerating and increasing sweet cherry fruiting. And the question of the optimal soil maintenance system for an organic orchard remains with the grower. Instead, the use of rootstock technology allowed to increase the yields of the Krupnoplidna and Valeriy Chkalov varieties.

Another technology that can be used in modern agriculture to achieve predictable yields is seed stratification. This technology makes it possible to control the process of tree germination from the very beginning and accelerate the time of seed maturation. In their study, S. Tabakov *et al.* (2020) and R. Marini (2020) applied the stratification technology to such sweet cherry varieties as bird cherry, Antipka cherry, and common cherry. All these varieties are actively used for rootstock technology, but before using them as rootstocks, it is necessary to check their properties as cherries. The stratification period for these cherries lasted 110-140 days for Bird cherry; 90-120 days for Antipka cherry; 120-180 days for common cherry. Stratification is the process of internal ripening of stone fruit seeds, which involves placing the seeds in a room with an average monthly temperature of 4°C, pre-mixed with any substrate (sand, sawdust, peat) and water. During stratification, the seeds absorb moisture evenly, which helps them to undergo internal maturation and germination. The complexity of this technology is timely sowing, as the germination process is rapid, and the weather conditions must be suitable for the biological properties of the seeds. The sweet cherry seeds were sown in autumn and treated with growth stimulants: gibberellic acid, cytokinin, ethylene, and thiourea. After the seedlings germinated in spring, they were placed according to the 7 m × 5 m scheme, the author of the article notes the inappropriateness of such placement, because, at an older age under such conditions, the trees will lose 50-60% of solar energy and nutrients, because cherries slowly absorb the feeding area. The study of this article proves that the 5 m × 4 m layout is more optimal for better production of photosynthetic products by trees.

The creation of a sufficient area of the assimilation apparatus is extremely important in the formation of a high yield and quality of fruits. According to the studies of E. Vignati *et al.* (2022), L. Kapoor *et al.* (2022), and A.J. Simkin *et al.* (2020), with an increase in the ratio of leaf area to the number of fruits on the tree, all indicators of sweet cherry fruit quality increased. It is noted that 32 cm^2 leaf surfaces are required to increase the weight of 1 g of fruit. The data obtained in the study of the article confirm this fact, namely, the leaves of trees in the 5 m × 3 m arrangement had 54% less leaf surface area than the leaves of trees in the 5 m × 4 m arrangement. Therefore, the compaction process should preserve all the physiological properties of sweet cherries, i.e., be reasonable.

The budding technology is becoming increasingly widespread in the global nursery industry. This technology is based on replacing a part of the rootstock bark with a part of the bark with a cuttings eye. This can be done from early May to late August, regardless of the degree of bark lag. This technology has gained popularity due to its ease of implementation and high scion survival rate. Scion survival is one of the most important elements of the structure of plant productivity formation. High-quality budding results in a higher survival rate of the eyes than in traditional rootstock grafting. Thus, in the studies of T. Arsov *et al.* (2020), sweet cherries, the rootstocks of which were treated with the budding technique, gave high fruit quality indicators. In modern market conditions, this indicator is responsible for fruit size, colour, density, stem length and taste. As noted above, the use of rootstock technology allows the achievement of the predicted yield with high-quality fruits, and the budding method will ensure the assimilation of the rootstock by the trees.

CONCLUSIONS

Modern technologies for intensive sweet cherry cultivation involve considering all physiological processes (occurring inside the plant) and external factors such as climate, soil, and irrigation conditions. The transition to intensive sweet cherry cultivation, using weak rootstocks on vigorous plant varieties and vice versa, requires considering such technologies as thickening tree layouts and developing varieties with high genetic yield potential. Consideration of these patterns gives the desired results in predicting sweet cherry yields.

Thus, it was possible to prove that both plant varieties produced enough yield depending on the potential of the variety. However, the trees of the Valery Chkalov variety were characterised by a greater number of increments and total annual fruit growth compared to the Krupnoplidna sweet cherry variety. Trees of the variety Valery Chkalov are characterised by greater vigour of tree growth in terms of a set of indicators, however, in a few years the crowns of such trees reach large sizes, become branched and the quality of the fruit decreases. Sweet cherries become smaller in diameter than is customary in today's market conditions, and profitability decreases as a result. Thus, it has been proven that the use of Gisela 5 clone rootstock inserts balances the physiological potential of the Valeriy Chkalov variety and maintains high-quality fruiting. In turn, the Krupnoplidna variety also showed a high fruiting potential (5.1 t/ha) with a smaller amount of annual growth. This is explained by the fact that under the influence of the insertion of Magaleb cherry seedlings (Antipka), this variety begins to bear fruit earlier than the Valery Chkalov cherry variety and passes the age periods of tree development faster.

That is, under the conditions described in this study, the natural potential of the varieties is somewhat adjusted, but the yield does not deteriorate. The prospect of further research may be additional field studies over several years to study the yield potential of these sweet cherry varieties on the specified rootstock variants in temperate climates.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Аналіз сучасних технологій вирощування сортів черешні в умовах помірного клімату

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Анотація. Актуальність дослідження зумовлена необхідністю оптимізації систем вирощування плодових культур з урахуванням погодних умов. Метою досліджень є відпрацювання технології щеплення інтенсивних насаджень черешні на малих та середніх підщепах. Провідним методом у досягненні мети дослідження став польовий дослід. Основними результатами дослідження є: наведено провідні технології підвищення врожайності сортів черешні залежно від впливу стресових факторів середовища; обґрунтовано використання технології клонової підщепи в насадженнях черешні в умовах помірного клімату. За комплексом показників формування продуктивності прогнозували врожайність насаджень різних конструкцій. А саме, виявлено схему сортопідщепних поєднань інтеркалярного розміщення, його довжину та параметри комплексу росту рослин; визначено показники фізіологічної активності, росту, продуктивності, якості плодів та економічної ефективності в інтенсивних насадженнях черешні. Встановлено, що застосування цієї технології дозволить підвищити врожайність та покращити якісні показники плодів черешні за рахунок виведення сортів з компактною кроною, що дозволить ущільнити насадження. Проаналізовано, що кліматичні умови є головним чинником у процесі формування врожаю. Визначено перелік стресових факторів помірного клімату, що впливають на врожайність черешні. Доведено, що впровадження технології клонової підщепи є найбільш ефективним для вирощування інтенсивних насаджень черешні в умовах помірного клімату. Практична мета досліджень – визначення та перевірка комплексу елементів фізіологічних показників потенційної врожайності насаджень черешні різних конструкцій, впровадження їх у виробництво та використання в подальшій селекції

Ключові слова: плодові дерева; кісточкова рослина; садівництво; урожайність; інноваційні способи розмноження; оптимальні умови вирощування

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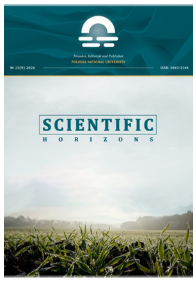

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Research of quality indicators of different types of wholegrain flour

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Abstract. The concept of modern nutrition involves the presence of the maximum amount of nutrients, including vitamins, essential amino acids, carotenoids, natural antioxidants, minerals, phenolic and tannin compounds, organic acids, and dietary fibre, which is why the food industry is interested in developing wholegrain products based on crops such as wheat, rye, barley, triticale, buckwheat, corn, and rice. The purpose of the study is to evaluate wholegrain flour using modern production technologies and control its quality, which will lead to a new level of development in the Ukrainian food industry and ensure increased profitability of the flour milling and baking industries.

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Methods used in the study: theoretical – analysis, synthesis, comparison and generalisation; experimental – identification and measurement to determine the physicochemical, organic, grinding, flour-milling and baking quality indicators of wholegrain wheat flour. Characterising the experimental data of different types of wholegrain flour, it was established that the content of dry matter, crude protein, crude fat, crude fibre or fibres, mineral content, and easily hydrolysed carbohydrates (starch, hemicellulose) were in the range of 84.7-88.8%, 10.2-16.3%, 0.9-1.7%, 2.3-4.8%, 1.2-3.2%, and 77.5-84.2%, respectively. Indicators such as ash content and flour size directly depended on the grinding scheme and the integrity of all anatomical grain particles. The technology of wholegrain wheat flour production combines the advantages of existing milling methods with minimising the adverse effect on the qualitative and quantitative gluten content, which varied from 21% to 36% in wholegrain flour samples, and the gluten deformation index ranged from 53.8 to 81.7 units. The materials of the study are of practical significance and indicate the need for further research, since when assessing the quality indicators and examining the characteristics of wholegrain wheat flour, attention should be devoted to the further development of optimal technology for the production of bread from this raw material

Keywords: wheat grain; baking properties; nutritional value; gluten; chemical and technological parameters

INTRODUCTION

Changes in the structure of food consumption in Ukraine and the expansion of the range of bakery, confectionery and culinary products made from flour require a broader understanding of its quality indicators and monitoring of the safety of food raw materials. More and more caterers are opting for wholegrain bread as it contains all the nutrients the body needs. The relevance of the issue of providing high-quality wholegrain flour is conditioned upon the current situation: a decline in grain quality and the need to find new approaches; development of technological methods and solutions that allow producing raw materials with high consumer properties. Wholegrain flour retains all the natural nutritional value of grains and provides consumers with important biologically active substances. According to D.O. Zhygunov (2017), one of the biggest challenges facing the flour and grains industry is the launch of new, high-quality and safe products. The nutritional value of wholegrain flour is about 12% protein; 2% fat, including 0.4% saturated fatty acids; 70% carbohydrates, including 2% sugar; and 1-2% fibre. M.F. Kravchenko *et al.* (2022) report that the priority in the development of functional grain products is using different crops with chemical composition correction: buckwheat, oatmeal, barley, rice, soybeans, which have high nutritional value but still have low consumer demand. Currently, the "8 Grains" multicomponent bread mix is gaining popularity in Ukraine, containing 56.4% soft wheat flour, 17.6% barley flour, 14.1% oat flour, 3.5% rye flour, 1.4% buckwheat flour, 1.4% corn flour, 1.4% durum wheat flour, 1.4% rice flour, 1.4% millet flour, and 1.5% flaxseed.

D. Marchenkov *et al.* (2021) provide information on modern flour production technologies, including chemical bleaching, stabilisation and the addition of preservatives and leavening agents, which reduce the biological and nutritional value of bakery products by extracting most vitamins, protein components, macro- and microelements from grain raw materials. These ingredients are mostly contained in the grain hull, therefore, in high-grade flour, they are 2-3 times less. O. Zakharchuk *et al.* (2023) state that in the production of high-grade flour, more than 70% of electricity is consumed by the grinding and decanting system since conventional graded grain milling is based on the stepwise mechanical separation of endosperm, germ and hull. Refined flour has some adverse effects on healthy eating, including weight gain, gastrointestinal diseases, diabetes, reduced metabolism and gluten content.

According to O. Dragan *et al.* (2021), wholegrain flour is produced only by grinding grain, thus all the properties of grain are preserved, it can be rye, wheat, multigrain, spelt, corn, barley, buckwheat, oat, rice, deodorised soya, flaxseed or any other specific purpose flour, provided that the wholegrain part is crushed and not sieved. Flour must correspond to the requirements of international standards: ISO 5530-1:2013 (2013) and ISO 5530-2:2012 (2012), which regulates the moisture content, quantitative and qualitative gluten content, falling number, ash content, whiteness, vitreous content, and percentage of the main nutrients. DSTU 2209-93 (1993) applies to various types of flour, including by-products and waste from flour milling. In addition, the quality characteristics of wheat flour meet the requirements of TC U (Technical Conditions of Ukraine) 10.6:30816688:001-202; wholegrain rye flour meets the requirements of DSTU 8791:2018 (2018); multigrain flour meets the requirements of TC U 15.6-13929625-001:2011, usually a composition of wheat, oat, millet, buckwheat, and rice. Wholegrain rice flour is gluten-free and contains half the amount of crude fat, and helps to normalise metabolic processes and improve memory and brain function. Buckwheat flour contains a large amount of crude protein, Zinc, and Copper. Wholegrain flaxseed flour in bread production has enveloping properties that lead to the normalisation of stomach acidity.

O. Ivanishcheva & O. Pahomska (2021) report on promising developments in wholegrain flour technology: Institute of Food Chemistry of the National Academy of Sciences of Ukraine – flour "Zdorovye", according to TC U 156-02128514-006-2005; OJSC "Dobrodiya" – wholegrain flour according to TC U 15.6-0092737-006-2002; CJSC "Zhmenka" – wholegrain fine flour "Extra" according to TC U 15.636594696-001-2009. For the domestic market, LLC "Grain Base of Ukraine" produces coarse flour with a production capacity of 15 tonnes per day, providing the population with high-quality food.

The purpose of the study is to evaluate the current technologies for the production and quality monitoring of wholegrain flour, which will lead to a new level of the Ukrainian food industry and ensure increased profitability in the bakery sector.

THEORETICAL OVERVIEW

Wholegrain flour is made from unhulled seeds that are milled together with the hull and grain germ. Despite the coarseness of the resulting product, it is called wholemeal flour, or single-grind flour. In her work, N.V. Vasylenko *et al.* (2018) state that to assess the quality of flour in practice, a classification is given that is divided into 5 groups: general technological; physical and technological; chemical and technological, indicators of protein-protease and carbohydrate-amylase complexes, physical properties of dough; baking indicators and safety of raw materials.

A. Wójtowicz *et al.* (2020) report that wheat flour is classified according to the main biochemical and physical characteristics that determine nutritional value and consumer value. The characteristics are determined by the composition and structure of the flour particles and the consumer (technological) benefit. Flour classification is divided into types, species and grades. J. Lin *et al.* (2019) describe the types of grain crops by biochemical and anatomical characteristics used for flour production. According to S. Ma *et al.* (2022), the main difference between wholegrain and varietal flour is that the former contains bran and germ, while the latter consists only of the kernel endosperm. The endosperm consists mainly of starch and crude protein. Bran and germ consist of vitamins, minerals, crude protein, crude fat and crude fibre. M. Gómez *et al.* (2020) estimated that wholegrain flour contains carbohydrates, vegetable crude fibre, crude protein, crude fat, pectin, vitamins E, A, B, PP, H, Phosphorus, Selenium, Magnesium, Zinc, Ferrous, Iodine, Sodium, Calcium, Potassium, Chromium and Copper. Wholegrain flour varies significantly from ordinary flour in terms of its physical and mechanical properties and chemical composition, as the germ, husk and endosperm are milled together, thereby increasing the content of crude fibre by 10 times, calcium by 2 times, phosphorus by 3 times, magnesium by 5 times, iron by 3 times, vitamin PP by 3 times, and vitamins B_1 and B_2 by 2 times.

Wholegrain flour consists of large particles of grain endosperm, fruit hulls and germs that are not uniform in size; the size is limited by residues on wire mesh sieves No. 067 to no more than 2%, silk fabric No. 38 and polyamide fabric No. 41/43 PA to no less than 35%. W. Gao *et al.* (2020) inform that an important indicator of wholegrain flour quality is organoleptic characteristics and crunch: colour – white with yellow or grey colour and visible particles of seed hulls; crunch – the presence of a sandy feeling on the teeth; smell – pleasant aroma, in the presence of a sour or musty smell, it is concluded that the flour may be old, spoiled or stored improperly; taste – fresh, slightly sweet, without bitter or sour taste. S. Pradana-López *et al.* (2022), report that organoleptic indicators are used to determine the degree of infestation, the presence of cobwebs, larval peel, if these signs are not detected during the initial inspection, detailed sieving is conducted. The qualitative standardisation of flour in terms of ash content is established by the ratio of bran to endosperm, as the germ contains much more ash than the endosperm. The work of P. Skřivan *et al.* (2021) found that for each type of flour, there are ash content standards, not more than for: high-grade wheat – 0.55%, semolina – 0.6%, 1st grade – 0.75%, 2nd grade – 1.25%, sown rye – 0.75%, wholegrain – 1.45-2%.

Gluten is represented by a group of proteins found in the stocks of wheat, barley, rye and oats. The beneficial properties of wheat gluten include the presence of 18 types of essential amino acids, including methionine, lysine and threonine. According to A. Cappelli *et al.* (2020), the percentage of gluten in wholegrain flour is 18-22%, in the highest grade – 32%, in the first grade – 30%, in the second grade – 25%. The quality of gluten is determined by its firmness, elasticity and extensibility. Gluten is divided into three groups according to its extensibility: strong (8-10 cm), medium (11-16 cm) and weak (>16 cm). The flour falling number determines the taste, volume and appearance of bakery products and is measured by the mechanical impact of a laboratory mixer that destroys starch at high temperatures. The Grain X Hagberg-Perthen Falling Number Meter can be used to quickly and accurately measure α-amylase activity in flour, thus avoiding sprouting and enzyme activity. The work of S. Navrotskyi *et al.* (2019) reports that the optimal falling time, depending on the variety, is 260-280 s for whole wheat, 400 s for high-grade wheat, 350 s for first-grade wheat, 340 s for second-grade wheat, 105 s for whole rye.

MATERIALS AND METHODS

The following methods were used to examine the quality of wholegrain flour: theoretical methods – analysis, synthesis, analogy, comparison and generalisation; research methods – identification and measurement to determine physicochemical, organoleptic, milling and baking parameters. The information base of this study was established by regulations, food quality standards, scientific and analytical materials of official publications. An essential task of the State Food and Consumer Service of Ukraine is to track the flow of bakery food products, protect consumer rights, control the safety and quality of wholegrain flour, provide new methods for establishing a single production cycle and improve them. According to the FAO, national policies designed to increase productivity, food security and supply are therefore focused on the efficient use and processing of grain raw materials.

The study included flour from different producers made from soft wheat grain grown in 2020 in different regions of Ukraine with an average crude protein content of 10-14%. The object of the study was the experimental samples of flour with a shelf life of 10 months, packed in paper bags of 1000±1.5-2% g: No. 1 – wholegrain wheat flour of wholemeal mill grinding; No. 2 – wholegrain wheat flour of wholemeal mill grade; No. 3 – wholegrain wheat flour of spelt mill grinding; No. 4 – wholegrain wheat flour of spelt mill grinding; No. 5 – organic wholemeal wheat flour; No. 6 – wholemeal wheat flour; No. 7 – special wholemeal wheat flour; No. 8 – wholemeal mill flour; No. 9 – wholemeal wheat flour. The requirements were set for the quality of wholegrain flour supplied to the production process in terms of the following indicators: technological – moisture, colour, smell, taste, crunch, pest infestation, the content of fine grain fraction; milling – moisture content, specific gravity, ash content, grinding, actual nutrient composition; baking properties – gluten content and quality, falling number, dispersed composition.

The quality of wholegrain flour was standardised according to the state standard DSTU 3768:2019 (2019). To determine the commercial quality of wholegrain flour, the following methods were used: sampling; colour and smell determination; percentage of dry matter. The quality of wholegrain flour was measured by determining the amount and quality of gluten, the gluten deformation index (GDI) according to DSTU ISO 13690:2003 (2009) and according to DSTU ISO 21415-2:2009 (2009). Several special laboratory tests in biology edited by V.V. Vlizlo *et al.* (2012) were used: total nitrogen content converted to crude protein by the Keldahl method; crude fat by the method of extraction with organic solvents, crude fibre or dietary fibre; crude ash, BEA (nitrogen-free extractive substances), which are represented by a group of easily hydrolysed carbohydrates). Mycotoxins are generated in many grains by microscopic mould fungi that develop during long-term storage. According to DSTU EN 12955-2001 (2001), the presence of mycotoxins Aflatoxin, T-2 toxin, and deoxynivalenone (DON) was determined in wholegrain flour using a Sunrise enzyme-linked immunosorbent assay. Bread quality tests were performed to examine the functional activity of wholegrain flour: bread volume, porosity, and specific volume of bread.

The results were analysed statistically, reliable conclusions were drawn and comparisons were made between the wholegrain samples. The data obtained on the chemical composition of wholegrain flour was summarised, and as a result, it was possible to draw fairly reliable conclusions about milling, storage conditions, the safety of use, basic physical and chemical parameters, commercial qualities, and characteristics of baked bread.

RESULTS

The quality of wholegrain flour is significantly influenced by the processing technologies for different types of grains, which are separated for mechanical processing using millstones and rollers. Two technologies are distinguished: the stone mill and the vertical mill. Their essence is to grind grain between millstones of solid stone. The advantage of these methods is the preservation of nutrients, natural taste and aroma, and a homogeneous end product. Grain threshing using two rollers differs from the previous grain processing techniques as it separates the grain into three parts – gluten, flour, and bran – which are mixed in the required quantities. The process of shredding with crushing rollers, while retaining nutrients, is less efficient than other methods.

To increase the moisture content and saturation of wholegrain flour, the grain is soaked and heat-treated. The advantage of the maceration process is the reduction of anti-nutrients in the grain, such as phytic acid, tannins or tannins, trypsin inhibitors and alkyl resorcinols. The presence of anti-nutrients in whole grains can interfere with the normal absorption of nutrients. Maceration – is the process of restoring grain by soaking it in water, acid or alkaline solutions for a specific period and then drying and milling it. Maceration is usually performed at low or high temperatures and in the presence of enzymes. Notably, maceration can increase flavour intensity and improve aroma. Grain heat treatment – an increase in the temperature of the raw material just before milling using drying shafts, special ovens or industrial dryers. Due to the different technical and biochemical characteristics of different wheat varieties, the parameters of hydrothermal treatment of wheat grain vary from those of other crops, with the optimum moisture content being 12-14%. The experiment determined the food parameters of wholegrain flour, such as moisture content, gluten quality and quantity, fibre deformation index (FDI), falling number (FN), and flour size, the data are presented in Table 1.

Table 1. *Quality indicators of the tested wholegrain flour samples*

No.	Product name	Moisture content, %	Gluten		FN, sec	Size, %	
			%	FDI, units		sieve No. 067	sieve No. 38
1.	Wholegrain wheat flour, mill-ground, wholemeal flour	12.64	27.4	81.8	375	6	60

Table 1, Continued

No.	Product name	Moisture content, %	Gluten		FN, sec	Size, %	
			%	FDI, units		sieve No. 067	sieve No. 38
2.	Wholegrain wheat flour of the wholemeal milling	13.16	21.2	71.3	333	0.4	49
3.	Spelt wholegrain wheat flour, mill-ground, wholemeal flour	12.45	36.5	85.6	388	3	56
4.	Spelt wholegrain wheat flour for wholemeal milling	12.56	32.4	81.1	354	1	50
5.	Organic coarse wholegrain wheat flour	14.24	24.8	68.1	311	-	30
6.	Coarse wholegrain wheat flour	10.44	25.7	79.2	336	0.4	51
7.	Extra coarse wholegrain wheat flour	13.2	23.4	75.9	330	-	50
8.	Milestone wholegrain wheat flour	12.79	15.8	53.7	274	16	30
9.	Wholegrain wheat flour	11.88	21.7	72.6	323	0.6	62

Source: *compiled by the authors*

The gluten content and FDI of wholegrain flour are important in determining the structural and mechanical properties of the dough and baking properties, which are standardised at no less than 18%. The highest gluten content was observed in flour samples 3 and 4 – 36.5% and 32.4%, respectively. Therewith, in samples 1, 5, 6 and 7, the gluten content was in the range of 24.8-27.4%, and the lowest crude gluten content was observed in samples 2 and 9 – 21.2% and 21.7%. However, only one of the flour samples, No. 8, contains a low gluten level of 15.8%, which is not regulated by the standard. The qualitative composition of gluten, expressed in conventional units of FDI, varied according to the quantitative composition. As a result of the evaluation of the tested samples of wholegrain flour for moisture content, ash content, gluten, size at the passage through sieve No. 067, and size at the passage through sieve No. 38, it was determined that they were in the range of 10.4-14.2%, 1.1-1.6%, 21-36%, 0.4-16%, 30-62%, respectively.

It is recommended to evaluate the size of wholegrain flour; the finer it is ground, the higher the content of damaged starch grains, which are more likely to be affected by enzymes, thus, the dough made from wholegrain flour is more actively thinned, and the bread produced has a sticky crumb and a smaller volume. The size of the coarse grinding of the upper part of the flour is controlled by the residue on sieve No. 067 and the passage speed on sieve No. 38. These indicators differed significantly in the flour samples tested. Thus, in samples 1 and 3, the percentage residue on sieve No. 067 is within 3-6%, in sample 8-16%, and in samples 2, 4, 5, 6, 7 and 9, within 0.4-1%. The percentage of fine flour that passed through sieve No. 38 was highest in samples 1, 2, 3, 6, 7 and 9, ranging from 50-60%. Therewith, for samples 5 and 8, the content of the respective fractions did not exceed 30%.

The chemical composition of flour depends on the grain grade, climatic and agronomic conditions of cultivation, flour grade and milling scheme, in particular, wholegrain flour is close to the chemical composition of the wheat grain from which it is made, as presented in Table 2.

Table 2. *Chemical composition in absolute dry matter, %*

No.	Product name	Protein	Fat	Fibre	Ash	NES
1.	Wholegrain wheat flour, mill-ground, wholemeal flour	11.16	1.37	2.37	1.73	83.37
2.	Wholegrain wheat flour of the wholemeal milling	15.83	1.07	2.43	2.59	78.08
3.	Spelt wholegrain wheat flour for wholemeal milling	10.49	0.9	2.78	1.62	84.21
4.	Spelt wholegrain wheat flour for wholemeal milling	13.72	1.14	3.65	2.13	79.36
5.	Organic coarse wholegrain wheat flour	11.66	1.62	4.84	3.15	78.73
6.	Coarse wholegrain wheat flour	16.33	1.22	2.76	1.17	77.53
7.	Extra coarse wholegrain wheat flour	14.26	1.64	2.35	2.79	78.96
8.	Milestone wholegrain wheat flour	10.21	1.18	2.33	2.2	84.08
9.	Wholegrain wheat flour	13.04	1.3	2.5	2.65	80.51

Note*: NES – nitrogen-free extractive substances*
Source*: compiled by the authors*

Characterising the experimental data of wholegrain flour, which is characterised mainly by energy raw materials, containing 84.7-88.8% dry matter, 10.2-16.3% crude protein, 0.9-1.7% crude fat, 2.3-4.8% crude fibre, 1.2-3.2% ash, 77.5-84.2% NES, represented mainly by 65-75% starch. Therewith, the average nutritional value of 1 kg of wholegrain flour in terms of absolute dry matter is 1.35 feed oat units, 90-140 g of digestible protein, depending on the type of flour. In addition, the chemical composition of flour depends on the composition of the grain from which it is made and its grade. The higher the grade of flour, the higher the starch content. The content of other carbohydrates, and fat, ash and protein increases with the grade of flour. In particular, wheat flour contains a wide range of macro- and microelements: Phosphorus (P), Calcium (Ca), Magnesium (Mg), Zinc (Zn), Ferric (Fe), Copper (Cu) and other minerals that are important for maintaining the vital functions of the human body, as detailed in Table 3.

Table 3. *Content of nutrients on an absolutely dry matter basis*

No.	Product name	P, g/kg	Ca, g/kg	Mg, g/kg	Fe, mg/kg	Zn, mg/kg	Cu, mg/kg
1.	Wholegrain wheat flour, mill-ground, wholemeal flour	3.66	0.5	37.91	36.5	18.67	5.41
2.	Wholegrain wheat flour of the wholemeal milling	3.92	0.4	37.01	37.03	19.91	5.96
3.	Spelt wholegrain wheat flour, mill-ground, wholemeal flour	4	0.48	32.48	36.03	21.09	14.23
4.	Spelt wholegrain wheat flour for wholemeal milling	4.23	0.54	39.78	36.79	22.54	19.65
5.	Organic coarse wholegrain wheat flour	4.66	0.69	41.44	48.76	24.7	6.34
6.	Coarse wholegrain wheat flour	3.57	0.57	39.76	38.25	18.29	6.55
7.	Extra coarse wholegrain wheat flour	3.57	0.67	37.37	42.83	19.29	6.32
8.	Milestone wholegrain wheat flour	3.1	0.54	32.27	45.28	21.74	17.38
9.	Wholegrain wheat flour	3.97	0.43	37.36	55.57	24.32	20.73

Source: *compiled by the authors*

Flour consists mainly of organic and a small amount of inorganic (mineral or ash) substances, which are concentrated mainly in the aleurone layer, hulls and germ. Characterising the experimental data on the macro- and microelemental composition of different types of wholegrain flour, it was established that it contains Phosphorus – 3.1-4.7 g/kg, Calcium – 0.43-0.67 g/kg, Magnesium – 32.4-41.4 g/kg, Ferrous – 36.5-55.6 mg/kg, Zinc – 18.3-24.7 mg/kg, and Copper – 5.4-20.7 mg/kg. There is a difference in mineral composition between wholegrain flour varieties due to different milling and conditioning techniques. Mycotoxins are poisonous metabolic products of about 160 moulds that develop on the surface of grain and feed. The most toxic is aflatoxin B_1, which has carcinogenic, teratogenic and mutagenic effects. As part of the study, the safety of this food raw material was assessed, as it is easily contaminated, as presented in Table 4.

Table 4. *Mycotoxin content (aflatoxin, DON, T-2)*

No.	Product name	Aflatoxin (total), mg/kg	DON, mg/kg	T-2, mg/kg
1.	Wholegrain wheat flour, mill-ground, wholemeal flour	-	0.0005	0.001
2.	Wholegrain wheat flour of the wholemeal milling	-	-	-
3.	Spelt wholegrain wheat flour, mill-ground, wholemeal flour	-	-	-
4.	Spelt wholegrain wheat flour for wholemeal milling	-	-	-
5.	Organic coarse wholegrain wheat flour	-	-	-
6.	Coarse wholegrain wheat flour	-	-	-
7.	Extra coarse wholegrain wheat flour	-	-	-
8.	Milestone wholegrain wheat flour	-	-	-
9.	Wholegrain wheat flour	-	-	-
Standardisation according to DSTU 3768:2009		⩾0.005	⩾0.1	⩾0.1

Source: *compiled by the authors*

The maximum permissible levels of mycotoxins are: not more than 0.005 mg/kg for aflatoxin, not more than 0.1 mg/kg for DON, not more than 0.1 mg/kg for T-2. As a result of the experiment, it was established that the sample of wholegrain wheat flour (wholemeal) contains 0.0005 mg/kg DON, 0.001 kg/kg T-2, which limits its use for baby food and pasta. No mycotoxins were detected in the other wholegrain samples. The results of bread production from the tested wholegrain flour samples are presented in Table 5.

Table 5. *Physico-chemical characteristics of bread made from wholegrain flour*

No.	Product name	Bread volume, cm^3	Porosity, %	Specific bread volume, cm^3/g
1.	Wholegrain wheat flour, mill-ground, wholemeal flour	372	63.7	1.8
2.	Wholegrain wheat flour of the wholemeal milling	432	66.3	2.1
3.	Spelt wholegrain wheat flour, mill-ground, wholemeal flour	498	68.6	2.3
4.	Spelt wholegrain wheat flour for wholemeal milling	515	72.1	2.5
5.	Organic coarse wholegrain wheat flour	451	70.3	2.2
6.	Coarse wholegrain wheat flour	585	72.7	2.7
7.	Extra coarse wholegrain wheat flour	470	70.4	2.2
8.	Milestone wholegrain wheat flour	260	47.4	1.3
9.	Wholegrain wheat flour	447	68.9	2.1

Source*: compiled by the authors*

The baked bread was characterised by a developed and uniform porosity, a deep and smooth crust surface without side accents, and a pleasant taste and aroma. Flour sample No. 6 was defined by the largest bread volume of 585 cm^3, high porosity of 72.7% and low ash content, as the bran was separated and not mixed with the flour during production. Flour samples No. 3, 4 and 7 had a high bread volume and porosity of about 70%, which was due to a high gluten content of more than 24% and flour size in the range of 50-56% when passing through sieve No. 38. Flour sample No. 8 did not form a gluten crust, had the smallest volume of bread among the tested samples, low porosity (47%) and the lowest gluten level.

DISCUSSION

The flour examined was produced using stone and roller milling methods. The grinding size is related to the baking properties of the flour, its swelling rate and water absorption capacity. The selected milling methods have a significant impact on the quality of flour, especially wholegrain flour, the rheological properties of the dough and the characteristics of the bread. The size of the coarse grinding of the upper part of the wholegrain experimental flour was controlled by the residue on sieve No. 067 and the passage speed on sieve No. 38. Uneven grain size can reduce the baking performance of flour. According to J. Bressiani *et al.* (2019), the need to standardise wholegrain wheat flour by size and estimate the size of wholegrain flour particles from 194.9 to 830 μm is emphasised. Higher-grade flours usually have a more uniform particle size distribution (consisting of particles of more uniform size and shape) than lower-grade flours. The particle size of high-grade flour is between 30 and 40 microns, while wholegrain flour is more commonly between 30 and 670 microns.

When preparing flour-based dishes, bakery and confectionery products, the amount of flour used depends on its moisture content, which is based on 14.5%. The moisture content of the wholegrain flour samples was within the permissible limits, with the highest value recorded in sample No. 7 at 14.2%. The research of J. van Rooyen *et al.* (2022) demonstrated that soft wheat grain is quickly saturated with water, but moisture content characterises the nutritional value of the grain and its suitability for storage and processing. Wheat is considered a suitable raw material for long-term storage if it is stored in dry form and has a mass fraction of dry matter of at least 86%. For long-term storage of wholegrain flour, it is necessary to maintain a temperature of 5-15°C and relative humidity of 60-70%, as grain and flour storage is adversely affected by sudden fluctuations in temperature and relative humidity.

Wholegrain flour produced using different milling technologies differed significantly in organic quality, thus, it is important to assess the FDI indicator. The lower the FDI content, the stronger the gluten and the shorter the stretch; the higher the FDI, the weaker and more malleable it is. The gluten content of the wholegrain flour samples ranged from 21% to 36%, with the FDI ranging from 53.8 to 81.7 units. Therewith, sample No. 8 of wholegrain mill wheat flour demonstrated an unusually low gluten level of 16%. J.C. Cancilla *et al.* (2022) report that according to world standards, soft wheat is regulated by classes: for class 1, the gluten content is 30-32%, class 2 – 26-28%, class 3 – 22-23%, and class 4 – 16-18%; and the FDI index for class 1, 2 of soft wheat ranges from 43-77 units, for classes 3 and 4 – 18-102 units. The gluten index of durum wheat by class is 28% for class 1, 25% for class 2, 22% for class 3, and 18% for class 4. The gluten index for durum wheat should be in the range of 18-102 units. Bread producers have different approaches to the choice of raw materials, some select high-quality wheat and spelt to produce wholegrain flour, which is much more expensive due to its significantly higher baking properties, while others use cheaper flour. As described by J. Kuang *et al*. (2022), the elasticity and resilience of dough depends on the gluten content. The amount of gluten in flour affects the protein value, organoleptic properties of raw materials, keeping the form of semi-finished products, and the preservation of the form of products during drying and cooking. Flours with tearable gluten are unsuitable for baking products with forms, such as tubes or pasta, as these products boil quickly and do not retain their original appearance. Food processors distinguish three groups of flour by gluten: Group I is defined by good quality – 45-75 units; Group II by satisfactory strength – 20-40 units; Group III by unsatisfactory strength – 0-15 units.

The chemical composition of wholegrain flour was examined for dry matter, crude protein or protein, crude fat or lipids, crude fibre or fibres, minerals, and NES, but particular attention should be paid to the carbohydrate content. The total carbohydrate content corresponds to the sum of crude fibre and NES, which is in the range of 79.8-89%, where non-starch polysaccharides are represented by crude fibre, and starch and sugar are represented by NES. According to C.J. Seal *et al*. (2021), grains are a complex mixture of different forms of carbohydrates distributed in different amounts in grain fractions, and the carbohydrate content in wholegrain flour was in the range of 81.7-75.9%, starch – 55-60%, total sugar – 3.5-4%, crude fibre – 2.1-3.3%.

Mineral elements have no energy value but are important nutrients for the development and normal functioning of the body. Minerals are concentrated in the grain hull and are largely removed during conventional milling, thus, monitoring macro- and microelements in wholegrain flour is an important stage of research. The macro- and microelement composition of the experimental wholegrain flour was as follows: Phosphorus – 3.1-4.7 g/kg, Calcium – 0.43-0.67 g/kg, Magnesium – 32.4-41.4 g/kg, Ferrous – 36.5-55.6 mg/kg, Zinc – 18.3-24.7 mg/kg and Copper – 5.4-20.7 mg/kg. According to the research of W. Biel *et al*. (2021), wholegrain wheat flour is rich in minerals: Potassium – 15.8 g/kg, Magnesium – 29.3 g/kg, Phosphorus – 40.4 g/kg, Ferrous – 20.6 mg/kg, Manganese – 170 mg/kg, Copper – 47.5 mg/kg, Selenium – 23.1 mg/kg, Zinc – 24.7 mg/kg. Consumption of bread made from wholegrain flour covers the needs for B_3, B_5, PP by one quarter, as the content of these vitamins is B_1 – 19.8 IU, B_5 – 20.2 IU, PP – 26.7 IU.

Compared to conventional wheat, spelt contains more protein, fat, fibre, vitamins and minerals, and the nutrients in spelt are highly soluble in water, thus, being easily and quickly absorbed by the body. According to the physical and chemical parameters of the bread, sample No. 4 (wholegrain wheat flour milled from spelt) was defined by a total volume of 515 cm^3, porosity of 72.1% and specific volume of 2.5 cm^3/g. Following O. Pysarets *et al*. (2020), wholegrain spelt flour is a valuable functional raw material in the technology of bakery products production, but it has significant differences in rheological properties from conventional wheat flour, which is why it requires certain technological measures to improve the quality of finished products. Products made from spelt flour have a smooth surface, dark golden colour and regular shape, specific volume of 2.4 cm^3/g, and porosity of 68%. Spelt flour dough takes longer to knead and has better stability, but when heated, the dough weakens and thins out more, which helps to keep it fresh longer.

To enrich bread and bakery products, it is recommended to use a combined mixture of millet, buckwheat, oat flour, oat flakes and wheat germ. The inclusion of protein products in the dough increases both the protein content and the content of minerals, vitamins B and PP, which improves the quality of the product, improves its organoleptic and physicochemical characteristics, and extends the shelf life. As argued by L. Ghelardini *et al*. (2022), wheat germ flakes in the amount of 8-12% by weight of wholegrain flour increase the protein content by 22.8%, carbohydrate content by 4 times, fat content by 3.5 times, and fibre content by 15 times. Consumption of one such loaf of bread per day will satisfy the daily requirement for vitamins and minerals.

CONCLUSIONS

Ukraine's bakery industry is one of the main sectors of the food industry to ensure stable production of bread, bakery and other flour products in volumes that meet national food security standards. The benefits of consuming wholegrain flour have a positive impact on health, as they help maintain normal gastrointestinal function, and optimal blood sugar levels, and balance the diet with essential ingredients. The popularity of whole grains is growing every year, and more and more people are actively including whole grain products enriched with dietary fibre, protein, vitamins and minerals in their daily diet.

The monitoring of the Ukrainian market demonstrated no significant differences in the quality of wholegrain wheat flour, thus, a national standard should be developed to enable its wider use in the food industry and healthy food technologies. The analysis of experimental data obtained from different types of experimental flour demonstrated that the content of dry matter, crude protein, crude fat, crude fibre, minerals and

NES was within the range of 84.7-88.8%, 10.2-16.3%, 0.9-1.7%, 2.3-4.8%, 1.2-3.2% and 77.5-84.2%, respectively. The qualitative and quantitative gluten content of wholemeal flour varies from 21% to 36%, and the FDI ranges from 53.8 to 81.7 units. The results of the safety assessment of this raw material demonstrated that the sample of wholegrain flour (wholemeal flour) contained DON – 0.0005 mg/kg, T-2 – 0.001 kg/kg, therefore, it is restricted for use in baby food and pasta, in particular, no mycotoxins were detected in other flour samples.

The study of the quality of different types of wholegrain flour is an important area in the food industry, as the variety of production methods and uses can affect the quality of the final food product. Indicators such as ash content and flour size specifically depend on the milling method and the completeness of all anatomical particles. For a more accurate assessment of the quality of wholegrain flour, further research is needed using various methods and relevant factors: product composition, cooking methods, and taste preferences. The quality of flour produced by different milling equipment differs in terms of nutritional, organic and technical characteristics.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Анотація. Концепція сучасного харчування передбачає наявність максимальної кількості поживних речовин, зокрема вітамінів, незамінних амінокислот, каротиноїдів, природних антиоксидантів, мінеральних речовин, фенольних та дубильних сполук, органічних кислот, харчових волокон, тому харчова промисловість проявляє великий інтерес до розробки цільнозмеленого зерна на основі злакових культур – пшениці, жита, ячменю, тритікале, гречки, кукурудзи, рису. Метою дослідження є оцінка цільнозмеленого борошна за сучасних виробничих технологій та контроль їх якості, що призведуть до нового рівня розвитку української харчової промисловості та забезпечать підвищення рентабельності борошномельної та хлібопекарської галузей. Методи, що використовувались у процесі дослідження: теоретичні – аналізу, синтезу, порівняння та узагальнення; дослідні – ідентифікаційний та вимірювальний з визначення фізико-хімічних, органічних, подрібнювальних, борошномельних й хлібопекарських показників якості цільнозмеленого пшеничного борошна. Характеризуючи експериментальні дані різних видів цільнозмеленого борошна, встановлено, що вміст сухої речовини, сирого протеїну, сирого жиру, сирої клітковини або волокон, мінеральної частини, легкогідролізованих вуглеводів (крохмаль, геміцелюлоза) знаходилися в межах 84.7-88.8 %, 10.2-16.3 %, 0.9-1.7 %, 2.3-4.8 %, 1.2-3.2 %, 77.5-84.2 % відповідно. Такі показники, як зольність і крупність борошна, безпосередньо залежали від схеми помелу, цілісності всіх анатомічних частинок зерна. Технологія виробництва цільнозмеленого пшеничного борошна поєднує переваги існуючих способів помелу з мінімізацією негативного впливу на якісний й кількісний вміст клейковини, зокрема у зразках цільнозмеленого борошна він варіювався від 21 % до 36 %, індекс деформації клейковини – від 53.8 до 81.7 одиниць. Матеріали статті складають практичну значимість й вказують на необхідність подальших досліджень, тому що проводячи оцінку показників якості та вивчивши характеристики цільнозмеленого пшеничного борошна треба звернути увагу на подальшу розробку оптимальної технології виробництва хліба з даної сировини

Ключові слова: зерно пшениці; хлібопекарські властивості; харчова цінність; клейковина; хіміко-технологічні показники

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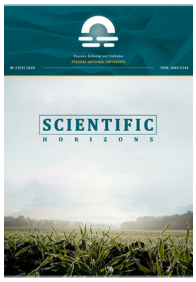

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Economic and biological characteristics and productivity analysis of sunflower hybrids

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Abstract. Evaluation of the biological characteristics of sunflower hybrids and their potential to improve the qualities of the plant under study that are useful for agricultural development is considered relevant. The research aims to carefully and in-depth evaluate the biological characteristics of sunflower hybrids to obtain information on the possibility of improving the qualities of the plant under study that is useful for agricultural development. During the experiment, the properties of such sunflower hybrids as Ukrainian *F1* (control sample), P62LL109 *Pioneer* (Classic), LG5377

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(*Limagrain*), ES Bella (*Euralis Semans*) and NK Rocky (*Syngenta*) were investigated. Each of these plants is listed in the State Register of Plant Varieties of Ukraine. The methods used in this research work include the production method, weighing and measuring, visual, laboratory and chemical, and mathematical. It was determined that the best indicators of productivity and economic characteristics are observed in three hybrid species, namely Ukrainian F1 (the best morphological characteristics, the highest weight of 1000 seeds, and hulling level), NK Rocky (*Syngenta*) (the highest percentage of fat and oil yield per 1 ha) and P62LL109 (*Pioneer*) (the highest weight of seeds per basket and bulk weight, the lowest hulling level, the highest yield). This may be useful for agricultural enterprises that may be interested in growing new sunflower hybrids with improved productivity and economic characteristics. The results of the study may become an impetus for further research of existing and creation of new sunflower hybrids that will be most useful for agricultural development

Keywords: southern chernozems; agriculture; grain profitability; early ripening group; oil content; yield

INTRODUCTION

The development of new varieties and uninterrupted production of sunflower seeds and other oilseeds, both in Ukraine and globally, is still a pressing issue, given the wide range of factors, including the significant demand for raw materials needed for oil production; climate and weather changes; and changes in the structural components of phytocoenoses. It is also important to consider the adaptive capacity of certain varieties or hybrids and, of course, the active spread and development of plant diseases and pests inherent in sunflowers.

Studies on similar issues were analysed to better understand the level of progress in this area of research. O. Andriienko *et al.* (2020) examined the impact of sowing density on sunflower yield in the Zaporizhzhia region. The results of the study showed that in years with favourable weather, yields increased by 8.6% with an increase in sowing density from 40,000 to 70,000 plants per hectare. In years with unfavourable weather, increasing planting density had no significant effect on yield (Tymchyshyn *et al.*, 2021). In addition, it was found that different sunflower varieties respond differently to changes in sowing density.

O. Andriienko and K. Vasylkovska (2020) studied the effect of plant density on sunflower yield in farms in the Kirovohrad region. The results showed that the optimal planting density of sunflowers in the Ukrainian steppe depends on the specific hybrid and year of cultivation. But, in general, 40-45 thousand plants per hectare is optimal.

It is also worth considering the results of a study conducted by S. Kalenska *et al.* (2020) on the morphological characteristics of plants and yields of sunflower hybrids in the northern part of the forest-steppe zone of Ukraine. The results show that rainfall and high temperatures during the growing season had a positive effect on the yield of hybrids. In addition, correlation analysis showed that plant height had a strong positive relationship with yield, while the number of seeds per head had a moderate positive relationship.

V.M. Lukomets *et al.* (2021) studied current trends in sunflower breeding and genetic improvement. Attention was paid to the main achievements in sunflower breeding, in particular high-yielding hybrids, varieties with high resistance to diseases and pests, as well as hybrids with improved seed and oil qualities. Modern breeding methods and the use of genetic engineering to improve sunflower characteristics are also described.

It is also worth considering the study by H.V. Pantsyreva (2020), which investigated the peculiarities of the formation of legume productivity. The results of the data analysis showed that in the Ukrainian right-bank forest-steppe and steppe regions, the highest productivity of legumes can be achieved by using fertilizers and certain cultivation methods. For example, the use of large amounts of nitrogen has a positive effect on crop productivity, while a decrease in the amount of fertilizer leads to a decrease in yield.

The practical significance of the results lies in the fact that high-quality seed has a significant impact on the productivity and personal quality characteristics of a particular sunflower hybrid, which is economically beneficial for every agricultural enterprise in Ukraine (Nesterchuk, 2017; Shahini *et al.*, 2022a). The research subject is the determination of the processes of sunflower productivity formation in the climatic and geochemical conditions of the Kherson region. The research aims to study the influence of hybrids' biological properties on the level of plant quality and yield and the quality of sunflower seeds. To achieve the goal of this study, the following tasks were defined: to evaluate the existing varietal and hybrid composition of sunflowers in terms of compliance with the complex action of biotic and abiotic factors, as well as to determine the potential of their productivity, study the effect of the length of the growing season on the long-term improvement of the technical qualities of sunflower and increase the productivity of this plant; to determine the effect of vegetation density on the duration of the growth and development phases of sunflower; to study the effect of individual biological properties of certain sunflower hybrids on quality indicators and yield.

MATERIALS AND METHODS

The research was carried out both in the field and in the laboratory on the territory of the Kopani experimental farm, Kherson region. Field studies were conducted in 2021 in the fields of the northern part of the Kherson region and the area of the sown plot of southern black soil was 100 m^2. The area of the accounting plot was 50 m^2. The studied sunflower hybrids were planted in four rows in a continuous arrangement on one experimental plot. The average seed density was chosen namely 45 thousand units per 1 hectare. The sunflower's predecessor was cereals, in particular winter wheat. Mathematical processing of the results obtained in the course of the work was carried out according to the Student's criterion and using a computer program called Agrostat.

The research objects were selected sowing materials of early ripe hybrids of sunflower plants, namely: ES Bella (*Euralis Semans*), NK Rocky (*Syngenta*), P62GG109 Pioneer (*Classic*), LG5377 (*Limagrain*) and Ukrainian F1 (All-Ukrainian Scientific Institute of Selection). Each of the selected hybrids is listed in the State Register of Plant Varieties of Ukraine and is adapted for active cultivation.

Description of the hybrids used in the study:

Ukrainian F1 (Control). Features: the originator of the variety is VNIS (All-Ukrainian Scientific Institute of Selection). Ukrainian F1 belongs to the early ripe sunflower hybrids. The vegetation period ranges from 103 to 109 days inclusive, which allows farms to grow this hybrid throughout Ukraine. The main advantage of the Ukrainian F1 plant hybrid is its rapid and intensive development in the initial stages of its growth, also known as a quick start. These hybrids can accelerate the development of their root system, while at the same time absorbing the maximum amount of nutrients and moisture dissolved in the soil (Neshev *et al.*, 2022). Subsequently, this provides the plant with increased resistance to stress. Data on the main characteristics of the hybrid are presented in Table 1.

Recommended plant density for sunflower harvesting: 1. Under moderate moisture conditions: from 50 to 55 thousand/ha. 2. Under adequate moisture conditions: from 65 to 70 thousand/ha. Data on the hybrid's resistance to diseases are presented in Table 2.

Table 1. *Main characteristics, morphology, and agronomy*

Origin	Ukrainian Scientific Institute of Breeding
Vegetation period	From 103 to 109 days
Crop height	From 172 cm to 180 cm
Oil contents	From 49% to 52%
Ripening group	Early ripening
Capitula diameter	From 21 cm to 25 cm
Capitula angle	Semi-angled
Shedding resistance	High
Drought resistance	High
Yield potential	5.2 t/ha
Hybrid type	Trilinear
Capitula type	Convex

Source: *compiled by the authors*

Table 2. *Disease resistance*

Phomopsis	*Botrytis cinerea Pers.*	*Puccinia helianthi Schw.*	*Sclerotica sclerotiorum*	*Phota oleracea Sass.*	*Plastopara helianthi Hov.*
7 marks	7 marks	9 marks	7 marks	7 marks	7 marks

Source: *compiled by the authors*

These hybrids also can accelerate the development of their root system, while at the same time absorbing the maximum amount of nutrients and moisture dissolved in the soil. Subsequently, this provides the plant with increased resistance to stress. NC Rocky (*Syngenta*). Commercially known as NK Rocky. L-linoleic type of oil content. The highest yields are observed in the early maturity group. This indicator does not decrease in the later stages of sowing (Dosio *et al.*, 2023). Data on the main characteristics of the hybrid are presented in Table 3.

Table 3. *Main characteristics, morphology, and agronomy*

Origin	***Syngenta***
Vegetation period	105 days
Crop height	From 150 to 160 cm
Oil contents	53%
Ripening group	Early ripening
Drought resistance	8 marks
Yield potential	5 t/ha
Herbicide protection system	Traditional
Hybrid type	Simple

Source: *compiled by the authors*

Recommended plant density for sunflower harvesting: 1. Under insufficient moisture conditions: from 35 to 40 thousand/ha. 2. Under adequate moisture conditions: from 45 to 55 thousand/ha. Data on the hybrid's resistance to diseases are presented in Table 4.

It is worth noting that if a farm wants high sunflower yields in the long term, it is necessary to place the plants in rows evenly and take care of the plants according to approved sowing technologies, namely, to observe crop rotation, effectively control weeds and pests and prevent thickening of crops.

LG5377 (*Limagrain*). The originator of LG5377 is the French company "*Limagrain*". It is a hybrid with high yield potential. The high weight of 1000 seeds help to increase yield and product quality (Céccoli *et al.*, 2022). Data on the main characteristics of the hybrid are presented in Table 5.

Table 4. *Disease resistance*

***Sclerotica sclerotiorum* of stem**	***Sclerotica sclerotiorum* of capitula**	***Phomopsis***
8 marks	8 marks	7 marks

Source: *compiled by the authors*

Table 5. *Main characteristics, morphology, and agronomy*

Origin	***Limagrain***
Vegetation period	97 days
Height	From 150 to 160 cm
Oil contents	49%
Ripening group	Early ripening (up to 100 days)
Capitula diameter	From 15 to 19 cm
Mass of 1000 seeds	From 70 to 75 gr
Yield potential	4.9 t/ha
Initial growth energy	9 marks
Herbicide protection system	Traditional
Yield stability	8 marks
Stress resistance	8 marks
Hybrid type	Simple;
Resistance to *Orobanche cumana Wallr.*	None
Cold resistance	9 marks

Source: *compiled by the authors*

Recommended plant density for sunflower harvesting: 1. Under insufficient moisture conditions: from 45 to 55 thousand/ha. 2. Under adequate moisture conditions: from 50 to 60 thousand/ha. Data on the hybrid's resistance to diseases are presented in Table 6.

Table 6. *Disease resistance*

Phoma betae Frank.	*Sclerotium bataticola Taub.*	*Phota oleracea Sass.*	*Sclerotica sclerotiorum* **of stem**	*Sclerotica sclerotiorum* **of capitula**	*Phomopsis*	*Plastopara helianthi Hov.*
7 marks	8 marks	8 marks	8 marks	9 marks	9 marks	9 marks

Source: *compiled by the authors*

Hybrid LG5377 is characterized by resistance to stress and moisture deficit, which makes it popular among farmers who grow sunflowers in conditions of water shortage. LG5377 is also highly resistant to lodging and disease. P62LL109 (*Pioneer*). The P62LL109 sunflower hybrid is high-yielding and disease resistant. In addition, the high oil content of this hybrid makes it suitable for growing for use in the food industry (Ahmed *et al*., 2021a). Data on the main characteristics of the hybrid are presented in Table 7.

Table 7. *Main characteristics, morphology, and agronomy*

Origin	***Pioneer***
Crop height	From 150 to 160 cm
Oil contents	50%
Ripening group	Average-ripening
Mass of 1000 seeds	From 40 to 60 grams
Vegetation period	From 95 to 105 days
Drought resistance	8 marks
Yield potential	5 t/ha
Resistance to *Orobanche cumana Wallr.*	A-E
Growth technology	Traditional
Hybrid type	Simple

Source: *compiled by the authors*

Recommended plant density for sunflower harvesting: 1. Under insufficient moisture conditions: from 45 to 55 thousand/ha. 2. Under adequate moisture conditions: from 50 to 60 thousand/ha. Data on the hybrid's resistance to diseases are presented in Table 8.

Table 8. *Disease resistance*

Phota oleracea Sass.	*Phomopsis*	*Sclerotica sclerotiorum dBy.*
6 marks	7 marks	7 marks

Source: *compiled by the authors*

Excellent adaptability to different soil and weather conditions allows this hybrid to perform well in any region, and the low number of leaves on the P62LL109 plant allows for a higher sowing density. ES BELLA (*Euralis Semans*). ES Bella hybrid is one of the most productive sunflower hybrids on the market. It has high resistance to *Orobanche cumana Wallr* and diseases, making it the best option for growing in the southern regions of Ukraine (Andriienko *et al*., 2020). Data on the main characteristics of the hybrid are presented in Table 9.

Table 9. *Main characteristics, morphology, and agronomy*

Origin	***Euralis Semans***
Vegetation period	From 100 to 105 days
Crop height	From 150 to 160 cm
Oil contents	From 49% to 51%
Ripening group	Early ripening
Capitula diameter	22 cm
Capitula angle	Downwards
Drought resistance	8 marks

Table 9, Continued

Origin	*Euralis Semans*
Yield potential	5.3 t/ha
Resistance to *Orobanche cumana Wallr.*	Highest in the early-ripening segment (A-G++)
Hybrid type	Moderately intense

Source: *compiled by the authors*

Recommended plant density for sunflower harvesting: 1. Under insufficient moisture conditions: from 55 to 60 thousand/ha. 2. Under adequate moisture conditions: from 60 to 65 thousand/ha. Data on the hybrid's resistance to diseases are presented in Table 10.

Table 10. *Disease resistance*

Sclerotinia sclerotiorum	*Phomopsis*	*Phota oleracea Sass.*
8 marks	8 marks	9 marks

Source: *compiled by the authors*

The ES Bella hybrid is of interest for oil production due to its high oil content. It is characterized by maximum yield potential and a quick start.

A biochemical soil analysis was conducted on a 100-hectare plot at the Kopani Research Farm in Kherson Oblast. The results of the analysis showed that the site has chernozem soils, which differ from chernozem soils in other areas of the Kherson region. A high nitrogen (N) content of 190 mg/kg was found in the soil of the experimental site. This indicates that the use of nitrogen fertilizers may be necessary, but there is a risk of weathering of the humus layer and groundwater contamination if the norm is exceeded.

In general, the soils of the experimental plot have sufficient nutritional value, average biochemical composition, and favourable conditions for growing various crops.

However, additional fertilization and soil fertility improvement measures may be required to improve sunflower cultivation at this site.

The following fertilizers were used to grow sunflowers on southern black soil:

1. Ammonium. They contain a large amount of nitrogen, which is essential for plant growth. Ammonium fertilizers can be used in granular or powdered form, and they dissolve quickly in the soil. In this case, ammonium nitrate was used.

2. Potash. Potassium is necessary to maintain plant resistance to stressful conditions and increase yields. Potassium chloride was used in this study.

3. Phosphorus. Phosphorus is an essential element for plant root growth. In this experiment, superphosphate was used.

It is worth noting that sunflower's need for fertilizer can vary depending on weather conditions (Shahini *et al*., 2022b). For example, if the soil is wet, the amount of certain macro- and microelements available to the plant may decrease, so more fertilizer may be needed in this case. Also, if there is a drought during the sunflower growing season, the plants may need additional irrigation to ensure normal growth and development (Aslam *et al*., 2021).

As for the fertilization scheme, fertilizers were applied according to the needs of the plant and its growth stage, by hand. During this study, three fertilizations were carried out. The first application of fertilizer was made 21 days after planting. Nitrogen fertilizers, such as ammonium nitrate, are most effective at this stage. The second fertilization is carried out at the stage of tassel formation (early July). Potash and phosphorus fertilizers were applied. The third feeding was carried out at the stage of seed growth (early August). In this case, potash fertilizers were used. The fertilizer application rates per hectare of sunflower that were used during this research are presented in Table 11.

Table 11. *Fertilizer application rates per hectare of sunflower*

Nitrogen	Phosphorus	Potassium
90 kg/ha	70 kg/ha	90 kg/ha

Source: *compiled by the authors*

It is worth noting that during this study, a variety of farming equipment was used for sunflower cultivation, including cultivators, rakes, and ridged seeders. In the case of southern soils, where drought is a problem, work was sometimes carried out at night when the soil was moister. The frequency of mechanical work depended on the stage of sunflower development and weather conditions (Zhang *et al*., 2021). The first treatment was carried out after sowing, and the subsequent treatments were carried out 14-21 days after planting.

As for climate and weather conditions, all data is presented in Table 12.

Table 12. Climatic conditions of the region

Climate type	Temperate continental
Moisture	Low
Winter	Soft and low snow
Summer	Hot and dry
Precipitation during the year	Uneven
Average annual rainfall	In the north of the right bank, from 400 mm to 430 mm per year, and in the coastal zone from 300 mm to 325 mm per year
Humidification coefficient	0.3, which means that the evaporation rate is higher than the precipitation rate
Average wind speed	From 3.5 to 5 m/s
Average annual temperature	9.8°C
Annual rainfall	From 355 mm to 440 mm

Source: *compiled by the authors*

As for the sunflower harvest, the key aspects of its cultivation were the weight of 1000 seeds, the weight of seeds per basket, the volume weight of seeds, oil content and husk.

RESULTS AND DISCUSSION

During the experiment, significant variability in sowing and yield properties was recorded among the early maturing sunflower hybrids selected for the study. During the study period, the field germination rate of the seed material reached 94.9%, which depended on the viability and weather conditions during the period limited to sowing to germination. In addition, field germination also depended on biological characteristics.

The lowest rates of plant survival and germination at the end of the growing season were recorded in the early maturing sunflower hybrid ES Bella (*Euralis Semans*). These indicators amounted to 93.6% and 94%, respectively. In the early maturing sunflower hybrids P62LL109 (*Pioneer*) and NK Rocky (*Syngenta*), the lowest number of plants that fell out after sowing and at the end of the growing season was found, namely 2.5% and 2.7%. Also, as of 2021, the largest number of plants after sowing and at the end of the growing season survived in the early ripe sunflower hybrid P62LL109 (*Pioneer*), namely 95.4%. Somewhat fewer plants survived for the same period in the early maturing sunflower hybrid NK Rocky (*Syngenta*), namely 95.2%, but compared to the results of other hybrids, these figures are still high. The reason for the different germination rates of seeds of early maturing sunflower hybrids is the influence of various factors on the seed during harvesting, drying and storage. Based on the results of all these factors, varietal, sowing and yield properties of seeds of early ripe sunflower hybrids are formed. The survival of the hybrids at the end of the growing season depended on the soil and climatic conditions of the area where these plants were grown. Also, weather conditions had a significant impact on such criteria as germination and survival of early ripe sunflower hybrids at the end of the growing season.

The phase of the emergence of the 8th pair of true leaves occurred with a slight difference: in the hybrid LG5377 (*Limagrain*) – on the twenty-first day, Ukrainian F1 (control) and ES Bella (*Euralis Semans*) – on the twenty-second day, and in sunflower hybrids P62LL109 (*Pioneer*) and NK Rocky (*Syngenta*) on the twenty-third day after emergence.

The hybrid LG5377 (*Limagrain*) entered the bud stage the fastest, namely on the 52nd day after germination. In the studied plots, the buds of sunflower hybrids Ukrainian F1 (control) and ES Bella (*Euralis Semans*) appeared on the 53rd day, and the buds of hybrids P62LL109 (*Pioneer*) and NK Rocky (*Syngenta*) appeared the latest, on the 54th and 55th day after germination, respectively.

Flowering in the hybrid LG5377 (*Limagrain*) began on the 68th day after germination, and in plants of the early maturing sunflower hybrid Ukrainian F1 (control) flowering began on the 69th day. Plants of hybrids P62LL109 (*Pioneer*) and ES Bella (*Euralis Semans*) were characterized by an even later flowering period with the beginning of flowering on the 70th day. The later period was observed in the sunflower hybrid NK Rocky (*Syngenta*), the beginning of flowering which occurred on the 71st day after germination.

The shortest period from germination to full ripeness was recorded in the hybrid LG5377 (*Limagrain*), which was 102 days. Plants of hybrids ES Bella (*Euralis Semans*) and P62LL109 (*Pioneer*) were characterized by a slightly shorter period, namely 104 and 106 days, respectively. The longest period was in sunflower hybrids Ukrainian F1 (control) and NK Rocky (*Syngenta*), namely 107 and 109 days, respectively.

Thus, considering all the above, it can be established that in the early stages of the life cycle of early maturing sunflower hybrids, namely before the flowering phase, the highest growth intensity was in the hybrids Ukrainian F1 (control) and LG5377 (*Limagrain*). In other hybrids, the growth rate was average at the initial stage of development.

In the case of crops, it is necessary to have information about the elements that make up the crop to have a balanced impact on plant productivity. Some of the most important morphobiological signs of any plant growth are stem height, leaf area, number of leaves, and head diameter. Observing them provides information on the state of plant development.

Table 13 presents the data obtained during the survey.

Table 13. *Biometric parameters of sunflower hybrids were obtained during the experiment*

Sunflower hybrids	Stem height, cm	Stem diameter, mm	Capitula diameter, cm	Leaf count, pcs.
Ukrainian F1 (control)	172.7	23.6	23.9	33.7
NK Rocky *(Syngenta)*	162.8	22.2	23.5	32.4
LG5377 *(Limagrain)*	159.5	20.8	19.8	29.9
P62LL109 *(Pioneer)*	160.6	23.1	22.6	33.1
ES Bella *(Euralis Semans)*	158.1	21.7	21.3	28.9

Source: *compiled by the authors*

Following the results, among all hybrids, the tallest plants were recorded in the Ukrainian F1 (control) hybrid (172.7 cm). This hybrid is also characterized by the largest diameter of the basket (23.9 cm), stem diameter (23.6 mm) and the largest number of leaves (33.7 pcs). The shortest plants were recorded in sunflower hybrids LG5377 (*Limagrain*) and ES Bella (*Euralis Semans*), 159.5 cm and 158.1 cm, respectively. It was also found that they have the smallest basket diameter (19.8 cm and 21.3 cm), stem diameter (20.8 mm and 21.7 mm), and the lowest number of leaves (29.9 pcs and 28.9 pcs). The sunflower hybrids NK Rocky (*Syngenta*) and P62LL109 (*Pioneer*) showed average biometric parameters. All the results are presented in Table 14.

Table 14. *Data on crop structure and seed quality were obtained*

Sunflower hybrids	Mass of 1000 seeds, g	Mass of seeds from one capitula, g	Volume weight of grain, g	Huskiness, %	Oil content, %
Ukrainian F1 (control)	71.7	83.4	384.8	23.9	49.9
NK Rocky *(Syngenta)*	66.5	84.2	392.1	21.8	52.6
LG5377 *(Limagrain)*	71.0	78.1	385.7	23.2	49.2
P62LL109 *(Pioneer)*	66.2	84.8	393.9	21.4	50.8
ES Bella *(Euralis Semans)*	69.0	81.3	389.0	22.4	50.5

Source: *compiled by the authors*

The weight of 1000 grains is one of the most important aspects of sunflower yield formation and has a wide range of fluctuations, depending on the biological characteristics of a particular hybrid. In the hybrid Ukrainian F1 (control), this indicator is the highest and reached an average of 71.7 g. Also, this indicator was high in the hybrid LG5377 (*Limagrain*) (71.0 g). Plants of hybrids NK Rocky (*Syngenta*) and P62LL109 (*Pioneer*) had the lowest performance in this aspect – 66.5 g and 66.2 g, respectively. As for the weight of seeds per basket, this indicator was the highest in hybrids NK Rocky (*Syngenta*) and P62LL109 (*Pioneer*), namely 84.2 g and 84.8 g. The lowest result was found in the hybrids ES Bella (*Euralis Semans*) and LG5377 (*Limagrain*) (81.3 g and 78.1 g). All results are presented in Table 15.

Table 15. *Yields of early ripe sunflower hybrids, as of 2021*

Sunflower hybrids	Mass of 1000 seeds, g	Mass of seeds from one capitula, g	Yield, t/ha	± to control, t/ha
Ukrainian F1 (control)	71.7	83.4	3.89	-
NK Rocky *(Syngenta)*	66.5	84.2	4.05	+0.16
LG5377 *(Limagrain)*	71.0	78.1	3.47	=0.42
P62LL109 *(Pioneer)*	66.2	84.8	4.14	+0.27

Table 15, Continued

Sunflower hybrids	Mass of 1000 seeds, g	Mass of seeds from one capitula, g	Yield, t/ha	± to control, t/ha
ES Bella *(Euralis Semans)*	69.0	81.3	3.64	-0.25

Source: *compiled by the authors*

The volumetric weight of the grain characterizes the weight of seeds in each volume (in Ukraine – the weight of seeds per 1 litre). This indicator was the highest in the hybrids NK Rocky (*Syngenta*) and P62LL109 (*Pioneer*) and amounted to 392.1 g and 393.9 g, respectively. The lowest grain weight was in the hybrids Ukrainian F1 (control) and LG5377 (*Limagrain*) (384.8 g and 385.7 g). The highest index of seed hulling was observed in two hybrids, namely Ukrainian F1 (control) and LG5377 (*Limagrain*) (23.9% and 23.3%, respectively). The lowest index was observed in hybrids NK Rocky (*Syngenta*) and P62LL109 (*Pioneer*), namely 21.8% and 21.4%.

The oil content in the presented hybrids ranged from 49.2% to 52.6% inclusive. The highest oil content was recorded in the plants of hybrids NK Rocky (*Syngenta*) and P62LL109 (*Pioneer*) and it was 52.6% and 51.8%. The lowest index was recorded in hybrids LG5377 (*Limagrain*) and Ukrainian F1 (control), 49.2% and 49.9%, respectively. All results are presented in Table 16.

Table 16. *Oil yields from 1 hectare of early ripe sunflower hybrids*

Sunflower hybrids	Yield, t/ha	Oil contents, %	Oil yield per 1 ha, t/ha	± to control, t/ha
Ukrainian F1 (control)	3.89	49.9	1.67	-
NK Rocky *(Syngenta)*	4.05	52.6	1.83	+0.16
LG5377 *(Limagrain)*	3.47	49.2	1.47	=0.20
P62LL109 *(Pioneer)*	4.14	50.8	1.80	+0.13
ES Bella *(Euralis Semans)*	3.64	50.5	1.59	-0.08

Source: *compiled by the authors*

Following the results of the biochemical analysis of the southern chernozem soil at the experimental site, the soil pH is 6.8, which is optimal for most cultivated plants. The humus content was 4.2%, which is quite high and indicates that the soil is in good condition. The P_2O_5 and K_2O content in the soil is 150 mg/kg and 210 mg/kg, respectively, which are also good indicators for the growth of various cultivated plants. It was also found that the soil of the site contains enough macro- and microelements necessary for plant growth, such as calcium (Ca), magnesium (Mg), iron (Fe), copper (Cu), zinc (Zn) and manganese (Mn). The presence of these elements in the soil is sufficient for growing a wide range of crops. All the results of the biochemical analysis are presented in Table 17.

Table 17. *Results of biochemical soil analysis*

pH	Humus	N	P_2O_5	K_2O	O_2	CO_2	H_2CO_3	Fe	Mn	Cu	Zn	B
6.8	3.5%	0.11%	0.15%	0.19%	0.3 mg/kg	0.05 mg/kg	0.2 mg/kg	40 mg/kg	4 mg/kg	2 mg/kg	10 mg/kg	0.5 mg/kg

Source: *compiled by the authors*

These indicators indicate that the soils in the study area have an average level of humus, nitrogen, and phosphorus, with a high level of potassium. Dissolved oxygen, CO_2 and H_2CO_3 have low values. The content of trace elements in the soil is at a satisfactory level, with particularly high levels of iron and zinc. The effect of ammonium, potassium and phosphorus fertilizers on sunflower growth and productivity was studied on all five hybrids selected for this research (Giannini *et al*., 2022).

The results showed that the application of ammonium fertilizers had a positive effect on the growth and productivity of all sunflower hybrids, except for P62GG109 *Pioneer* (Classic). The hybrids ES Bella (*Euralis Semans*) and LG5377 (*Limagrain*) showed the best results compared to the control group. The application of phosphate fertilizers had a positive effect on the formation of the sunflower root system. The best effect was seen in the hybrids NK Rocky (*Syngenta*) and P62GG109 *Pioneer* (Classic). The least pronounced effect of phosphorus fertilizers was in hybrids LG5377 (*Limagrain*) and Ukrainian F1 (control).

Potash fertilizers had a positive effect on all sunflower hybrids, except for Ukrainian F1, where the effect was less pronounced. The greatest improvement in plant health and resistance to stressful conditions was observed in hybrids ES Bella (*Euralis Semans*) and NK Rocky (*Syngenta*). Thus, the results of the study indicate that the application of ammonium, potassium and phosphorus fertilizers had a positive effect on the growth and productivity of the plants under study.

However, in addition to fertilizers, the development of sunflower hybrids in 2021 was also influenced by early autumn after a dry summer. Such conditions contributed to the early formation of the root system and stimulated plant growth. However, in late summer, the weather became wet, leading to disease and pest outbreaks. All hybrids developed fungal diseases on the leaves when the optimum amount of precipitation was exceeded: hybrids ES Bella (*Euralis Semans*) and LG5377 (*Limagrain*) were the most resistant to these diseases, while hybrid P62GG109 *Pioneer* (Classic) was the least resistant to them.

Weather conditions play an important role in sunflower cultivation, as the crop requires sufficiently high temperatures and precipitation to produce a rich harvest (Chandrashekar and Krishnadoss, 2022). Low temperatures and frequent frosts in March and April 2021 resulted in delayed sowing and germination. In addition, high precipitation in March and April resulted in flooding of some ploughed fields and delayed ploughing. In May and June, high temperatures and sufficient rainfall provided favourable conditions for sunflower growth. However, in early July, the region was hit by a severe drought, which negatively affected plant development and productivity. Nevertheless, despite the negative factors, as of 2021, the amount of precipitation required for plant growth and development was generally sufficient. Temperature conditions were also favourable for the crops. All early maturing sunflower hybrids emerged on the fourteenth day after sowing and did not depend on any biological characteristics of the hybrids.

In the studies of sunflower hybrids ES Bella (*Euralis Semans*), NK Rocky (*Syngenta*), P62GG109 *Pioneer* (Classic), LG5377 (*Limagrain*) and Ukrainian F1 (All-Ukrainian Scientific Institute of Selection), some changes in growth and yield related to weather conditions were recorded. The most vulnerable to drought were hybrids P62GG109 *Pioneer* (Classic) and Ukrainian F1 (control). At the same time, the hybrids ES Bella (*Euralis Semans*), NK Rocky (*Syngenta*) and LG5377 (*Limagrain*) showed increased resistance to drought and slight yield losses compared to the first two hybrids.

Considering the results obtained, it can be concluded that the hybrids ES Bella (*Euralis Semans*), NK Rocky (*Syngenta*) and LG5377 (*Limagrain*) showed the most stable productivity when growing sunflowers in this experimental plot. Since it was found that the application of ammonium, potassium and phosphorus fertilizers has a significant impact on the growth and productivity of sunflowers, it is necessary to calculate the optimal amount of fertilizer for each hybrid individually, considering its characteristics and requirements for soil and climate.

Based on the data obtained, it can be concluded that there is an inverse relationship between the weight of 1000 seeds and the bulk weight and size of the seeds: larger seeds had a lower bulk weight and weight of 1000 seeds, and smaller seeds had a higher bulk weight. In addition, small seeds had a lower hulling index and higher oil content.

The results of other studies are also worth considering. M.A. Ahmed *et al.* (2021b) considered the heterosis of sunflower seeds. Seed yields were higher in hybrids with dominant or superdominant genes. As for the oil content, it had a positive and significant heterosis for all hybrids when compared to plants with mothers of better genetic structure. Significant differences between genotypes were also observed in terms of average seed yield and fatty acid traits. Heterosis indices for the studied aspects were significant in almost all hybrids. It was determined that the non-additive and additive effects of genes are actively involved in the inheritance of all traits. Dominant variances (σ2D) were higher for oil quality and grain yield of sunflower compared to additive variances (σ2A).

Another study that deals with the genetic aspect is the research work of H.G.M.D. Ahmed *et al.* (2022), who examined the molecular characteristics of hybrid sunflower varieties and their authenticity. The results showed that 10 hybrids are authentic, i.e., their genetic characteristics match the description provided by the manufacturer. In addition, the molecular characterization, using SSR markers, allowed us to identify different alleles present in the hybrids, which can be useful for further improvement of breeding programs.

It is also worth mentioning the results of a study conducted by A. Radanović *et al.* (2018). They examine the genetic structure of sunflowers from ancestors to modern hybrids. The genetic characteristics of sunflowers, including genomes, chromosomes, genetic markers, physiological and biochemical characteristics, and factors affecting the development of sunflowers are described in detail. The mechanisms of formation of new combinations of genes used in breeding to create new, more productive sunflower hybrids were analysed.

A. Sher *et al.* (2022) focused on studying the effects of different irrigation sources on sunflower yield and oil quality. The study was conducted using different sunflower hybrids and three irrigation sources (rainfall, ordinary water, and saltwater). The results showed that using ordinary water for irrigation increased yields and improved oil quality. In contrast, the use of salt water reduced yields and oil quality. The amount of precipitation did not have a significant effect on yield and oil quality.

It is also worth considering the study by V. Tyagi *et al.* (2020), which determined the heterotic effects of different combinations of cytoplasm in sunflower hybrids grown under different irrigation conditions. The results showed that hybrids combining corn and pea cytoplasm were the most productive. It was also found that hybrids with corn cytoplasm were less sensitive to water deficit, while hybrids with sunflower cytoplasm were more sensitive.

M. Ghaffari *et al.* (2021) evaluated the resistance and yield of sunflower hybrids using genotypic analysis. The results showed that sunflower hybrids planted in different regions of Iran had different yields. The analysis of genotype-environment interaction also helped to identify the most stable and productive sunflower genotypes under different conditions. In general, the study by M. Ghaffari *et al.* (2021) showed that the stability and yield of an average sunflower hybrid vary widely in different conditions but can be predicted by analyzing the genotype and environment.

In general, considering the above studies and comparing them with this research, similarities in the final results can be seen. This can be useful for breeding to grow more productive sunflower hybrids in Ukraine, as well as for increasing the efficiency of growing this crop in this region.

CONCLUSIONS

Based on the research results, it can be concluded that each of the presented early maturing sunflower hybrids produced a grain yield that largely depended on the biological characteristics of a particular hybrid. It is also worth noting that the weather conditions favourable for the research made it possible to study the genetic potential of the experimental objects, giving the plants everything, they needed for intensive growth and development. As a result of the research, it was found that the highest yields among early maturing sunflower hybrids were shown by P62LL109 (*Pioneer*) and NK Rocky (*Syngenta*) (4.14 t/ha and 4.05 t/ha). During the study, it was also found that the field germination rate of the seed of early-ripening sunflower hybrids is within 94.9%. As for the morphological parameters, they are the highest in the Ukrainian F1 hybrid (control) (height – 172.7 cm; stem diameter – 23.6 mm; basket diameter – 23.9 cm; the number of leaves per stem – 33.7 pcs).

Regarding the characteristics of seeds, the weight of 1000 grains is also the highest in this hybrid (71.7 g). However, the weight of seeds from one basket was the highest in hybrids P62LL109 (*Pioneer*) and NK Rocky (*Syngenta*), namely 84.8 g and 84.3 g. The volumetric weight of grain was also the highest in these two hybrids (P62LL109 (*Pioneer*) – 393.9 g; NK Rocky (*Syngenta*) – 392.1 g). The highest level of huskiness is inherent in the sunflower hybrid of the early maturing group Ukrainian F1 (control) and hybrid LH5377 (*Limagrain*), namely 23.9% and 23.2%, respectively. The lowest indicators in this aspect were recorded for hybrids P62LL109 (*Pioneer*) and NK Rocky (*Syngenta*) (21.4% and 21.8%). Regarding fat content, the highest percentage was observed in hybrids P62LL109 (*Pioneer*) and NK Rocky (*Syngenta*), namely 50.8% and 52.6%, and the lowest – in hybrids Ukrainian F1 (control) and LG5377 (*Limagrain*) (49.9% and 49.2%).

The hybrids P62LL109 (*Pioneer*) and NK Rocky (*Syngenta*) yielded the highest yields of 4.14 t/ha and 4.05 t/ha. The oil yield per 1 ha was also the highest in these two hybrids: P62LL109 (*Pioneer*) – 1.80 t/ha; NK Rocky (*Syngenta*) – 1.83 t/ha. The highest indicators of profitability and economic efficiency were also presented by sunflower hybrids NK Rocky (*Syngenta*) and P62LL109 (*Pioneer*).

Considering all the results obtained in the course of writing this paper, to improve seed quality and increase the yield of sowing material, it is worth sowing certified seeds of high-quality sunflower hybrids Ukrainian F1 (control), NK Rocky (*Syngenta*) and P62LL109 (*Pioneer*) at the optimal sowing density of 45 thousand units per 1 hectare and regularly and timely carry out all necessary agronomic measures, which will increase the quality of the final product and increase the final net profit for the agricultural enterprise.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Аналіз господарсько-біологічних особливостей та продуктивності гібридів соняшнику

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Анотація. Оцінювання біологічних особливостей гібридів соняшнику та їх потенційні можливості для підвищення корисних для розвитку сільського господарства якостей досліджуваної рослини вважається актуальним. Метою даної наукової роботи є уважне та поглиблене оцінювання біологічних особливостей гібридів соняшнику задля отримання інформації, що стосується можливості підвищення корисних для розвитку сільського господарства якостей досліджуваної рослини. В ході експерименту було досліджено властивості таких гібридів соняшнику, як Український *F1* (він же контрольна проба), П62ЛЛ109 *Pioneer* (Класичний), ЛГ5377 (*Limagrain*), ЕС Белла (*Euralis Semans*) та НК Роккі (*Syngenta*). Кожна з перерахованих рослин занесена у Державний реєстр сортів рослин України. Серед методів, які були використані в даній науковій роботі, є виробничий метод, вимірювально-ваговий, візуальний, лабораторно-хімічний, а також математичний. Було визначено, що найкращі показники продуктивності та господарських особливостей спостерігаються у трьох гібридних видах, а саме Український F1 (найкращі морфологічні показники, найвища маса 1000 насінин та рівень лушпинності), НК Роккі (*Syngenta*) (найвищий відсоток жиру та вихід олії з 1 га) і П62ЛЛ109 (*Pioneer*) (найвища маса насінин з одного кошика та об'ємна маса, найнижчий рівень лушпинності, найвищий рівень врожаю). Це може бути корисно для сільськогосподарських підприємств, які можуть зацікавитися у вирощуванні нових гібридів соняшнику з покращеними показниками продуктивності та господарських особливостей. Результати дослідження можуть стати поштовхом для подальшого дослідження наявних і створення нових гібридів соняшника, які будуть максимально корисні для розвитку сільського господарства

Ключові слова: південні чорноземи; сільське господарство; рентабельність зерна; ранньостигла група; олійність; врожайність

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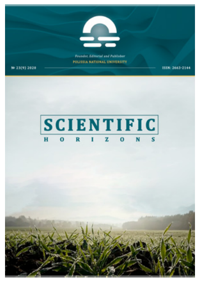

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Assessment of ecosystem functions of public green spaces in the city of Berezhany, Ternopil region

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Abstract. Researching the possibilities of using modern approaches and tools for evaluating the ecosystem services of green spaces is relevant and requires theoretical justification and applied research, especially in the context of the importance of ensuring the sustainable development of Ukraine. Therefore, the purpose of this study was to work out the procedure of quantitative and cost evaluation of ecosystem services of green spaces for public use and search for opportunities to present the received information to stakeholders. For this, an inventory of green spaces was carried out with the measurement of their biometric and sanitary indicators. For quantitative and cost assessment of the ecosystem functions of plantations and individual trees, the i-Tree Eco toolkit was used, and the Google My Maps application was used for their visualization. The conducted study helped obtain information about individual ecosystem functions of green spaces (reduction of pollutants, carbon absorption and sequestration, oxygen production volumes and regulation of surface water flows). As part of this utility, the annual ecosystem function for the absorption of 770 kilograms of harmful compounds (ozone, carbon monoxide, nitrogen dioxide, and particles of various sizes) was calculated, which is estimated at UAH 128,648,000 annually; reduction of air pollution by 7.43 metric tonnes of gross carbon sequestration (19 kg per 1 plant), with an estimated cost of UAH 41,028,000 and a reduction of water runoff by 684.9 cubic meters, which is estimated at UAH 47,042 of annual utility. Furthermore, as of the moment of the study, the researched green spaces retain carbon in their tissues, which creates an ecosystem benefit in the amount of UAH 1,493,009 thousand (€36,901). The highest indicators of ecosystem usefulness are inherent in park stands, while the trees and bushes of the central part of the city are more effective in absorbing pollutants. Trees capable of achieving significant biometric indicators in local conditions are characterized by greater

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ecosystem productivity. The conducted study creates conditions for better awareness of the ecosystem value of green spaces, but its popularization is also important. The practical value of the results also lies in the possibility of bringing them to authorities, enterprises, and organizations, activists and other stakeholders, which will create conditions for improving environmental awareness, promoting the security and protection of tree stands, improving management and making informed decisions in the field of green construction

Keywords: monetization; utility; tree and shrub services; i-Tree Eco; urban landscapes; environmental awareness

INTRODUCTION

A promising modern area of scientific research of urban landscapes is the search for new opportunities and approaches to the assessment of ecosystem functions of green spaces. Therefore, the analysis of advanced global practices and the possibilities of using the latest tools in this field, together with the implementation of applied research on obtaining information on the volumes and assessment of ecosystem services of tree-shrub vegetation, is characterized by relevance.

It is common knowledge that urbanization processes in most cases lead to negative changes in the environment (Nyelele *et al.*, 2019). Specifically, according to Wolf *et al.* (2020), simultaneously with the growth and development of settlements, a consequent deterioration of climatic, hydrological, and biotic conditions of the urban environment occurs, which adversely affects the health of residents of settlements. Furthermore, according to other scientists, such as Wong *et al.* (2018), due to built-up density, urban landscapes experience higher levels of pollution, biodiversity loss, and social inequality compared to rural areas. Under such conditions, green spaces become important for cities, which, according to the conclusions of Rötzer *et al.* (2019) can not only mitigate the consequences of this negative impact but improve the condition of urban landscapes and create optimal conditions for human habitation. These properties of tree and shrub plantations, or the benefits they can provide for the environment, are called ecosystem functions or ecosystem benefits of green spaces.

The study of various possibilities and approaches to the quantitative measurement and valuation of the ecosystem functions of trees and shrubs, according to researchers (Bidolakh *et al.*, 2023), is characterized by relevance, as evidenced by the constant increase in the number of scientific publications in this filed (Velasco-Muñoz *et al.*, 2022) and the growing interest of the international community (Yang & Khan, 2021; Esperon-Rodriguez *et al.*, 2022; Gaglio *et al.*, 2023) in the implementation of the results of these studies in the practice of ensuring the sustainable development of settlements. At the same time, in Ukraine, according to the author (Pryshchepa, 2019), this process takes place much more slowly and, according to the conclusions of scientists (Havrylenko & Tsyhanok, 2019), there is an urgent need to develop methodological and applied principles for evaluating the ecosystem functions of green spaces, considering the benefits they produce for the environment and society. Therefore, the study of the possibilities of using modern approaches and tools for evaluating the ecosystem services of urban plantations for the conditions of Ukraine is relevant and requires further theoretical substantiation and applied research.

As the object of this study, the methodology of obtaining information about individual ecosystem functions of green spaces for their quantitative and cost evaluation was chosen. The purpose of this study was to investigate the possibilities of determining the ecosystem benefits of public green spaces using the i-Tree Eco toolkit and the possibility of presenting the obtained information to local authorities, the academic community, public organizations, environmental activists, and other stakeholders. To fulfil this purpose, the main tasks were set as follows: to measure the biometric indicators of the tree-shrub vegetation together with the development of the methodology for the performance of works to determine the quantitative and value indicators of ecosystem functions; performing an analysis of the received information in terms of various ecosystem services, categories of plantations, species composition, and other indicators, as well as working out the possibility and perspectives of presenting the obtained results.

LITERATURE REVIEW

An important requirement today in the context of the balanced development of settlements around the world is their sustainable development. In such operating conditions, according to scientists Wong *et al.* (2018), green infrastructure is the basic concept of using an ecosystem approach to enhance the sustainable development of urban landscapes. According to the research by various authors (Castro-Díez *et al.*, 2019), tree and shrub plantations, as an integral element of urban ecosystems, provide critically important ecosystem functions for the safe existence and well-being of residents, such as improving air quality by removing pollution and reducing noise, protecting and purifying water, protecting and stabilizing the soil, improving and regulating the microclimate, mitigating the consequences of urbanization, improving the biological interchange of the matter, preserving biodiversity, etc. Apart from socio-economic benefits, phytolandscapes, according to Castro-Díez *et al.* (2019) and Nyelele *et al.* (2019), produce intangible benefits, such as cultural and educational services, aesthetic values; activation of mental processes, awareness of one's own identity, etc.

Back in the 1990s, many participants in various international conventions recognized the ever-growing need for international scientific assessment of ecosystems. Therefore, in 2005, scientists and activists developed the international program "Millennium Ecosystem Assessment" (Millennium Ecosystem Assessment, 2005), the purpose of which was to obtain scientifically sound information about changes in ecosystems with the investigation of their impact on people's well-being to develop appropriate measures. The participants of the program determined that currently there are enough opportunities to preserve and even improve the quality of ecosystems, by replacing some services they provide with others, or by ensuring a positive synergistic interaction between them. However, in practice, the ecosystem services of urban landscapes are rarely considered during actual urban design and urban infrastructure planning due to the lack of sufficient fundamental research and recommendations in this area (Song *et al.*, 2020).

In the conditions of the need to ensure the sustainable development of settlements, the awareness of the underestimated role of green spaces in creating a comfortable and safe living environment for their residents should stimulate the implementation of regular measures regarding the caring attitude, protection, qualitative and quantitative reproduction of spaces in urban landscapes (Bidolakh *et al.*, 2023). In turn, to improve the awareness of the usefulness of trees and shrubs for urban ecosystems, it is important to investigate the value of phytolandscapes in this regard and to present the obtained results both to specialists involved in green economy, and to governing bodies and a wide scope of consumers of ecosystem services, which are all residents of settlements (Vallecillo *et al.*, 2019). Under such conditions, in the absence of a direct financial expression of ecosystem services produced by green spaces, degradation and loss of these objects due to their underfinancing is observed (Havrylenko & Tsyhanok, 2019). Many researchers in various parts of the planet (Croci *et al.*, 2022) testify to the constant growth of the demand for the assessment of ecosystem services of green spaces around the world.

Notably, the material part of the utility of plantations, such as wood products, pulp, by-products, leaf mass, etc., according to Castro-Díez *et al.* (2019) is much easier to estimate since many mechanisms have already been developed in this area. While the quantification and evaluation of the environmental benefits and services of green spaces stays a current hot topic, so does its implementation in urban design and planning (Song *et al.*, 2020). Furthermore, as noted by scientists (Steenberg *et al.*, 2017), to ensure constant and regular support of ecosystem services, the process of quantifying them and investigating the vulnerability of green spaces is important. According to other scientists (Wolf *et al.*, 2020), in general, urban planning and management of green spaces should strategically promote the development of trees and shrubs as a social determinant of public health, while quantitative understanding of complex synergies, trade-offs and dependencies on the interaction of different components of urban landscapes, according to Castro-Díez *et al.* (2019), is essential for achieving the sustainable provision of ecosystem services.

According to researchers (Wong *et al.*, 2018), the overall increase in the global sustainability of settlements is only possible if the ecosystem services of green spaces are increased, along with the simultaneous reduction of the environmental load on urban landscapes. In this process, a vital component is the awareness of both the benefits of each individual plant and the plantation as a whole, because each individual tree can affect the microecosystem, and in different plantations, these effects can extend to the neighbouring built environment (Franceschi *et al.*, 2022). The results of research by other scientists (Song *et al.*, 2020) proved that diverse types of urban green spaces are extremely heterogeneous, characterized by different plant groups, structure, and biodiversity, and have different purposes, which is also reflected in their ecosystem functions. In this context, evaluating the usefulness of public plantings, it should be noted that according to the Rules for the maintenance of green areas in populated areas of Ukraine (Order No. 105, 2006), these phytolandscapes are located on the territory of parks and gardens of various locations and purposes, squares, boulevards, on slopes, embankments, and other areas that have free access for recreation. Therefore, this category of plantations should be of maximum benefit to the inhabitants of settlements, who regularly use these ecosystem functions without always comprehending their value.

Evaluating the prospects of current research in the field of evaluating the ecosystem functions of green spaces, one should note the importance of further investigating the processes of introducing ecosystem payments (Gaglio *et al.*, 2023), improving decision-making by stakeholders, mechanisms for returning investments (Roman *et al.*, 2020), optimizing the structure and composition of urban green spaces to maximize the provision of ecosystem services (Song *et al.*, 2020), practical studies on the dependence of ecosystem functions on individual plant species and their biological metric parameters (Wolf *et al.*, 2020). A separate major area of research is the methodological substantiation of the procedure for obtaining and using information about the ecosystem functions of green spaces, including the involvement of modern tools for performing work and presenting the obtained results. In this area, there is a lot of work on improving the procedure for obtaining information about biometric indicators of plants during their inventory, by involving global positioning systems (GPS), methods of remote sensing of the earth (RSE), geographic information systems (GIS), modern mapping systems and services, electronic maps, geoportals, etc. (Bidolakh & Lakyda, 2019). One of the promising areas of research in this field is also the involvement of a special i-Tree Eco toolkit for investigating certain ecosystem services of green spaces and their replacement cost (Song *et al.*, 2020). However, this toolkit is not widely used to investigate the ecosystem functions of trees and bushes in Ukraine and needs a more detailed approval regarding suitability for the conditions of Ukraine, efficiency and feasibility of use in this area of research.

MATERIALS AND METHODS

As an experimental base of the study, green spaces of public use growing in the territory of the city of Berezhany, Ternopil region, were used. The field collection of materials was performed during June-August 2022 in the territory of the central part of the city of Berezhany (1.64 ha), Pryzamkovyi park (3.6 ha) and the city square on the Ternopilska street (0.6 ha). The total area of the study base was 5.84 ha. Its location can be described by the following values of geographic coordinates: north latitude within 49.445481°–49.447314° and east longitude within 24.937804°–24.946753°. In total, 390 trees and bushes were included in the inventory at this facility.

For the researched public green spaces, an inventory was performed during the growing season according to the instructions for the inventory of green spaces in populated areas of Ukraine (Order..., 2014). Simultaneously with the implementation of the recommendations of this instruction, the biometric indicators of trees and shrubs were additionally measured to determine their ecosystem functions per the recommendations of the USDA Forest Service (2021) for their assessment using i-Tree Eco tools. Such indicators include geolocation of each tree and bush; land use category; plant height from the ground surface to the base of the crown and from the beginning of the crown to the top of the plant; the dimensions of the projection of the crown in two mutually perpendicular directions; the percentage value of the lost and dead parts of the crown (if any), as well as the illumination of the plant from four sides and from above.

Species of tree-shrub plants were established according to the definition of Dobrochaeva & Prokudin (1999). The age of the plants was determined by morphological characteristics. The diameters at breast height (DBH) of trees and bushes were measured using an aluminium measuring fork according to the rules of forest inventory, and in some cases a tape measure was used. Plant height was determined with Anuchin's altimeter. Geolocation of trees and bushes was performed using the Garmin GPSMap64s receiver in the geographic coordinate system. USDA Forest Service recommendations (2021) were used to determine the land use category, the percentage value of the lost and dead part of the crown, and the illumination of the crown. Clarifying and correcting the locations of plants, based on the results of their geolocation with a GPS receiver, was performed according to the methodology (Bidolakh & Lakyda, 2019), which helped increase the accuracy of the final coordinates of the park's plants.

After collecting field materials, they were processed according to the recommendations of the USDA Forest Service (2021) and entered into the i-Tree Eco tools software. After processing the information entered into the software, the results of the assessment of individual ecosystem functions of green spaces (reduction of the amount of pollutants, carbon absorption and sequestration, volumes of oxygen production and regulation of surface water flows) of each tree in particular and the plantation as a whole were obtained. These indicators were obtained in quantitative, qualitative, and cost terms and displayed in the form of tables, reports, and graphs. The geoinformation database created in I-Tree Eco tools (combination of the obtained indicators of each tree and bush along with their locations) was exported in KML format to prepare an electronic map of ecosystem services of green spaces. This map was placed in open interactive access on the Google My Maps resource to inform all stakeholders about the ecosystem functions of public green spaces in the city of Berezhany, Ternopil region.

RESULTS AND DISCUSSION

The results of the research of the public green spaces in the territory of the city of Berezhany, Ternopil region, suggested that the examined phytolandscapes are represented by 34 tree and shrub species, among which the most numerous are *Aesculus hippocastanum* L. (share of 14.1% of the total number of plants), *Tilia cordata* Mill. (13.8%), *Acer platanoides* L. (12.8%), and *Fraxinus excelsior* L. (10.0%). The listed tree species together account for more than half of the plants in the plantations by quantitative indicator, while the rest of the tree-shrub species are represented by a share of no more than 6%. Large-sized plants have the greatest influence on the functioning of the landscapes under study (Table 1), most of which are representatives of the green spaces of Pryzamkovyi Park and the square on the Ternopilska street, thanks to a considerable area of nutrition on the largest biometric indicators in the stand composition.

Table 1. *Summary information about plant specimens with the highest biometric indicators*

ID	Botanical name	Latitude, degrees	Longitude, degrees	Landuse	DBH, cm	Crown Dieback, %	Height, m	Base height, m	Top height, m	Crown (NS), m	Crown (EW), m	Mmissing crown, %	Light exposure, category
231	*Quercus robur*	49.4463	24.9438	park	136	48	27	15	12	33	26	38	5

Table 1, Continued

ID	Botanical name	Latitude, degrees	Longitude, degrees	Landuse	DBH, cm	Crown Dieback, %	Height, m	Base height, m	Top height, m	Crown (NS), m	Crown (EW), m	Mmissing crown, %	Light exposure, category
131	*Quercus robur*	49.4458	24.9438	park	107	43	19	5	14	13	16	33	1
155	*Salix alba*	49.4465	24.9429	park	106	48	20	0	20	8.2	7.9	48	3
236	*Quercus robur*	49.4462	24.944	park	106	38	28.5	10	18.5	15	22	18	4
347	*Salix alba*	49.4471	24.9437	park	92	48	16	2	14	16	9	38	4
252	*Fraxinus excelsior*	49.4458	24.9442	park	90	18	33	4	29	14.2	12.9	18	3
381	*Salix alba*	49.447122	24.938562	park	90	3	31	4	27	14	12	3	5

Notes: *light exposure is evaluated according to five criteria. Number of sides of the tree receiving sunlight from above (maximum of five). Top of tree is counted as one side*
Source: *developed by the author of this study based on their own research*

The estimated area of the projection covers of the crowns of trees and bushes (according to I-Tree Eco tools) is 2.743 hectares, which is 47.0% of the total area of the territory under study and, according to the calculations of I-Tree Eco tools, corresponds to 23.89 ha of leaf area. The given information allows determining that, under the given experimental conditions, the leaf area of public green spaces in the city of Berezhany with a canopy density of about 0.5 exceeds the area of such an object by 4.1 times, and the area of projection coverage of tree and shrub crowns by approximately 8.7 times. This information can indicate the efficiency of the use of space by green spaces because their crown develops in horizontal and vertical planes. Therewith, under the given conditions of the study, thanks to the development of the crown of trees and bushes in the vertical plane, the leaf area of phytolandscapes increases almost nine times compared to the area of the horizontal projection cover of plants.

Assessment of the impact of varied species on the production of ecosystem services largely depends on their leaf area. Therefore, to determine the dominant species in relation to the ecosystem functions of the plants under study, we calculated the dominance index, which was calculated as the product of the share of plants in the stand composition and the area of their leaf surface and is presented in the form of a diagram in Figure 1. Notably, this distribution proves only the existing influence of vegetation on the ecosystem services of urban landscapes through its leaf surface. The high values of the dominance indicator are not at all an indicator that these trees are critical for the ecosystem and require special attention in the further green management. However, these tree species currently dominate the structure of public green spaces in the city of Berezhany due to their predominance in composition and larger crown sizes.

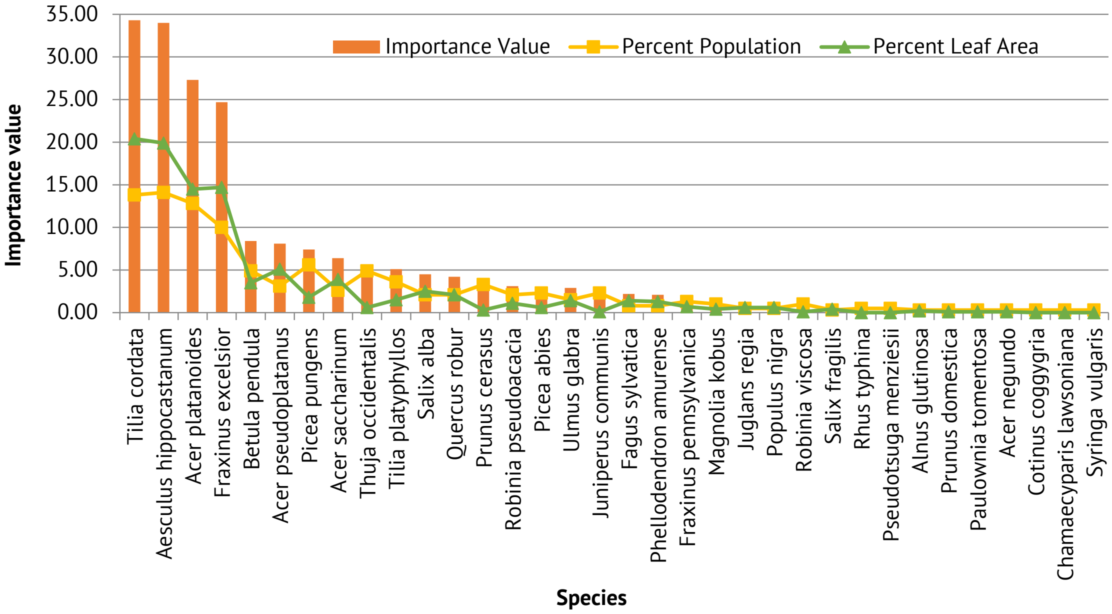

Figure 1. *Importance value by species*
Notes: *the "Importance value" indicator is calculated as the product of the "Population" and "Leaf Area" percentage values*
Source: *developed by the author of this study based on their own research*

Analysing the distribution of the public green spaces under study in the context of DBH classes (Fig. 2), one should note the predominance of middle-aged stands. Therewith, the most numerous DBH classes in terms of the number of trees and bushes were 30.5-45.7 (26.7% of the total number of plants), 15.2-30.5 (25.9%), 7.6-15.2 (16.0%) and 45.7-61 (14.6%). The predominance of large trees with large diameters for such species as *Quercus robur* L., *Salix fragilis* L. and *Aesculus hippocastanum* L. is also of note.

Figure 2. *Species distribution by DBH class*
Source: *developed by the author of this study based on their own research (2022)*

Characterizing the sanitary condition of stands based on the results of the conducted study, there is a difference in the approaches to the assessment of this indicator according to the national methodology of the inventory of green plantations (Order..., 2014) and the recommendations of the USDA Forest Service (2021). Thus, according to the Ukrainian inventory method, the sanitary condition of the public stands under study is characterized by three categories of quality condition, and according to the results of the conducted study, 53% of the plants are classified as good, 41% as satisfactory, and 6% as unsatisfactory. At the same time, the USDA Forest Service (2021) method, after data processing according to the i-Tree Eco tools program, divides trees and shrubs into seven status categories. After data processing, the following results were obtained for assessing the sanitary state of green spaces: Excellent – 3.1%; Good – 49.5%; Fair – 27.9%; Poor – 15.6%; Critical – 2.3%; Dying – 1.5%, Dead – 0%. The given results indicate the importance of taking measures to improve the health of 47.4% of the stands under study, of which 3.8% require immediate measures to treat trees. Analysing the species distribution of the sanitary state of plants, the worst indicators are typical for coniferous species, and specifically for *Picea abies* L. (22.2% in a critical and dying state) and *Thuja occidentalis* L. (10.5% in a dying state).

Based on the results of processing the information entered into the program, data was obtained regarding the assessment of individual ecosystem services of green spaces: reduction of the number of pollutants, absorption and sequestration of carbon, volumes of oxygen production and regulation of surface water flows of each tree in particular and plantations in general. In this study, the reduction in the number of pollutants was calculated based on the analytical data of the i-Tree Eco tools program regarding the absorption by trees and bushes of sulphur dioxide (SO_2), ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), as well as particles with a size of less than 2.5 μm (PM2.5) and 2.5-10 μm (PM10). Analysing the obtained data (Fig. 3), the largest volumes of absorption and the highest value of the ecosystem service are inherent in sulphur dioxide (SO_2).

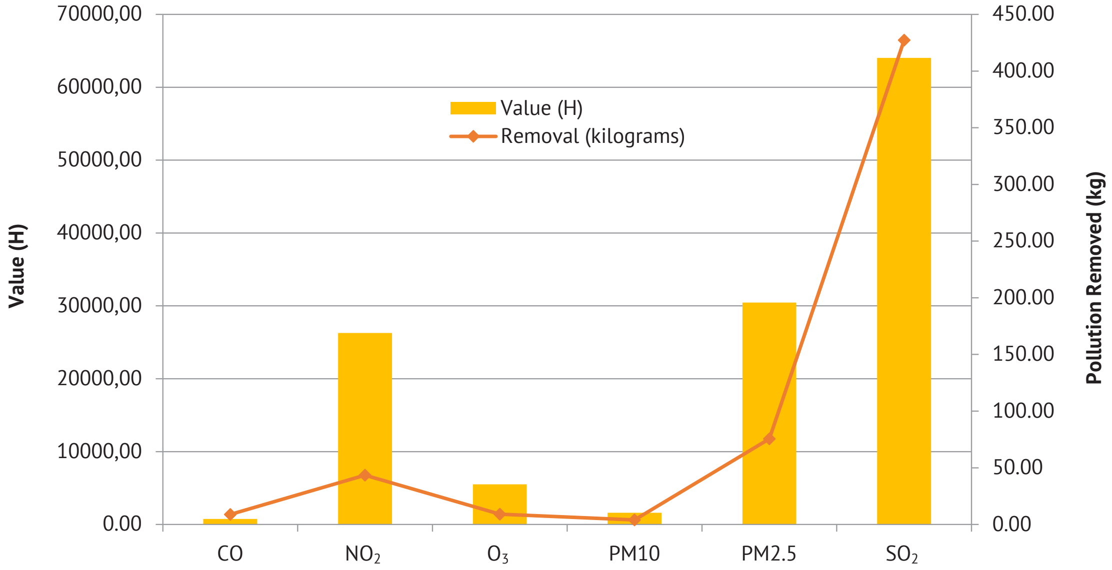

Figure 3. *Quantitative and cost assessment of the annual absorption of pollutants for public green spaces in the territory of the city of Berezhany, Ternopil region*

Notes: *on the diagram, the graph shows the annual amounts of absorption of pollutants, and the bars show the same indicators in value terms*

Source: *developed by the author of this study based on their own research (2022)*

In general, according to the data of the I-Tree Eco Tools program, it was established that the researched public green spaces can absorb 770 kilograms of harmful compounds (ozone, carbon monoxide, nitrogen dioxide, and particles of different sizes) annually in their biomass, and accordingly reduce air pollution. According to the methodology of the USDA Forest Service (2021), the investigated public green spaces in the city of Berezhany perform an ecosystem service to reduce air pollution in the amount of UAH 128,648 thousand annually in terms of the indicators under study.

Evaluating other annual ecosystem functions of public green spaces in the city of Berezhany (Table 2), the phytolandscapes under study can absorb and *sequester carbon*. This service becomes increasingly useful in the face of global climate change, where green spaces can sequester carbon from carbon dioxide in their tissues, thereby creating conditions for mitigating these changes. The results of data processing proved that the green spaces under study can annually provide 7.43 metric tonnes of gross carbon sequestration, with the estimated cost of this service for the urban ecosystem in the amount of UAH 41,028,000 (€1010.5). Notably, per plant, this indicator is 19 kg of annual carbon sequestration with the associated utility of UAH 105.2 (€2.6).

Table 2. *Summarized information on the ecosystem benefits of public green spaces in the territory of the city of Berezhany, Ternopil region*

Category	Trees (pcs.)	Gross Carbon Sequestration		Avoided Runoff		Pollution Removal		Carbon Storage	
		(metric t/yr)	(H/yr)	(m^3/yr)	(H/yr)	(metric t/yr)	(H/yr)	(metric ton)	(H)
Pryzamkovyi park									
Total by object	228	4.89	26,993.56	480.01	32,969.44	0.48	72,537.08	208.99	1,154,804.84
Recalculation for 1 plant	1	0.021	118.39	2.105	144.60	0.0021	318.15	0.917	5,064.93

Table 2, Continued

Category	Trees (pcs.)	Gross Carbon Sequestration		Avoided Runoff		Pollution Removal		Carbon Storage	
		(metric t/yr)	(H/yr)	(m^3/yr)	(H/yr)	(metric t/yr)	(H/yr)	(metric ton)	(H)
Square on Ternopilska street									
Total by object	43	0.92	5,077.12	81.09	5,569.48	0.07	11,936.41	21.02	116,130.71
Recalculation for 1 plant	1	0.021	118.07	1.886	129.52	0.0016	277.59	0.489	2,700.71
Green spaces in the central part of the city									
Total by object	119	1.62	8,957.56	123.80	8,503	0.22	44,174.35	40.19	222,074.26
Recalculation for 1 plant	1	0.014	75.27	1.040	71.45	0.0018	371.21	0.338	1866.17
Aggregated data on public green spaces									
Total by public green spaces	390	7.43	41,028.24	684.90	4,7041.92	0.77	128,647.84	270.20	1,493,009.81
Recalculation for 1 plant	1	0.019	105.20	1.756	120.62	0.0020	329.87	0.693	3,828.23

Notes: *the table shows the annual utility data for the indicators "Gross Carbon Sequestration", "Avoided Runoff" and "Pollution Removal" and the cumulative utility as of 2023 for the indicator "Carbon Storage"*
Source: *developed by the author of this study based on their own research by processing them in the i-Tree Eco tools program*

The analysis of the provision of this ecosystem service in terms of different stands (Fig. 4) showed a considerable predominance of park stands due to the greater number of trees and better sanitary conditions. At the same time, the green spaces of the square along the Ternopilska street can provide annual carbon sequestration volumes almost comparable to the stands in the central part of the city with almost half the number of plants, which is explained by the larger number of large trees growing in the square. That is, the volumes of carbon sequestration depend to a considerable extent on the biomass and sanitary condition of plants and increase during the growth and development of trees and bushes, which is also confirmed by the results of analogous studies (Lin *et al.*, 2020).

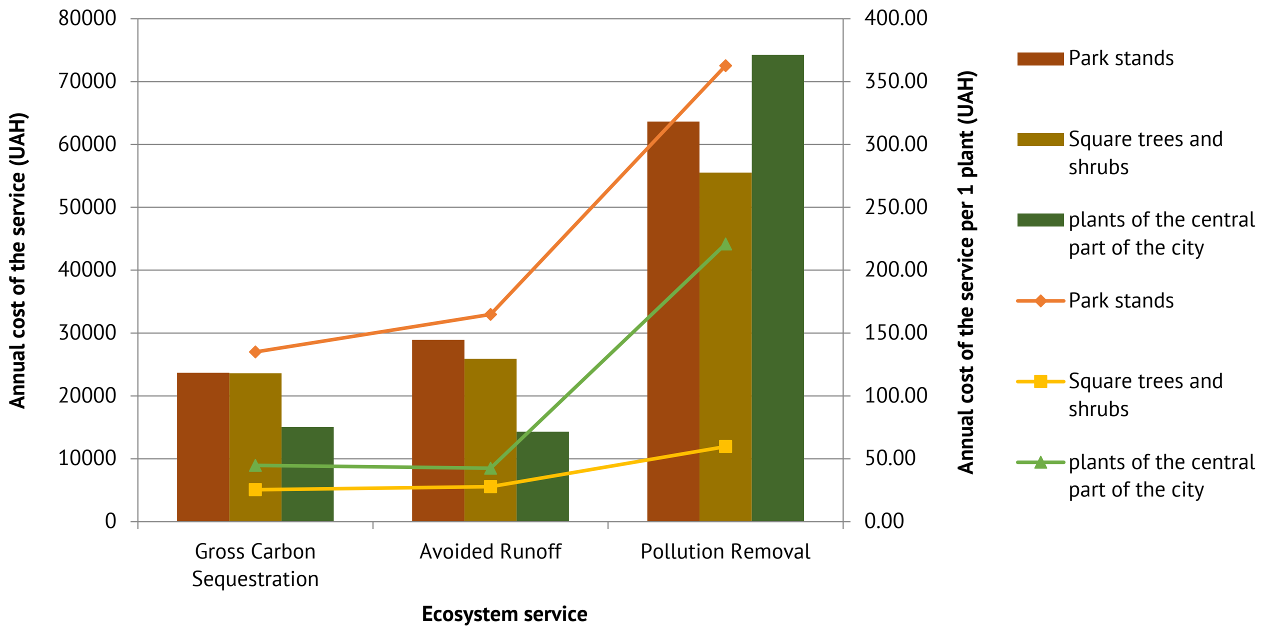

Figure 4. *Summarized data on the annual ecosystem benefits of public green spaces in the territory of the city of Berezhany, Ternopil region*
Notes: *the graph shows the annual costs of ecosystem services for different types of stands, and the columns show the same indicators per 1 plant*
Source: *developed by the author of this study based on their own research (2022)*

Another ecosystem function investigated in this study was *the ability of green spaces to regulate water flow*. This service is valuable to the urban environment as trees and shrubs reduce and improve surface water runoff. Specifically, green spaces perform protective, anti-erosion, and water-regulating functions. Investigated public tree and shrub stands in the territory of the city of Berezhany, Ternopil region, can reduce water flow by 684.9 m^3 annually (Table 2). Such an ecosystem service in monetary terms, according to the results of data processing in I-Tree Eco Tools, is estimated at the amount of UAH 47,042 (€1158.7) of annual utility. Analysing the features of water flow regulation in the section of the studied urban landscapes, the highest volumes of performance of this ecosystem service are inherent in park stands (Fig. 4). The average plant in the shared areas of the central part of the city fulfils this ecosystem function by about 50% in smaller volumes compared to trees and shrubs that grow in parks and squares. In this case, according to the conclusions of scientists who performed analogous studies (Mosyaftiani *et al.*, 2022), higher indicators of biometric parameters, which, in this study, are inherent in plants growing in parks and squares, have the greatest impact on water flow regulation.

Apart from the above-examined ecosystem services that can be evaluated in annual terms, there are the benefits of trees and shrubs that they produce during their life cycle. One of these functions is the ability of plants to accumulate and store carbon in their tissues during their growth and development. According to the results of the I-Tree Eco Tools evaluation, the public green spaces under study have already accumulated 270.2 metric tonnes of carbon in their tissues, which corresponds to 1,008.4 metric tonnes of carbon dioxide. This ecosystem usefulness is estimated by the program in the amount of UAH 1,493.01 thousand. (€36.9 thousand). The analysis of the productivity of carbon absorption in the species distribution (Fig. 5) proved that the most effective in this regard are *Aesculus hippocastanum* L. (retains in its tissues 29.8% of the total amount of absorbed carbon in the section of the experimental study base), *Fraxinus excelsior* L. (14.0%), *Tilia cordata* Mill. (11.2%) and *Acer platanoides* L. (12.8%). The listed species are also the most numerous in the stand composition and have high biometric indicators, which can serve as an explanation for their maximum efficiency in relation to this ecosystem service. This statement is also consistent with the results of other researchers who investigated this issue (Nowak, 2017).

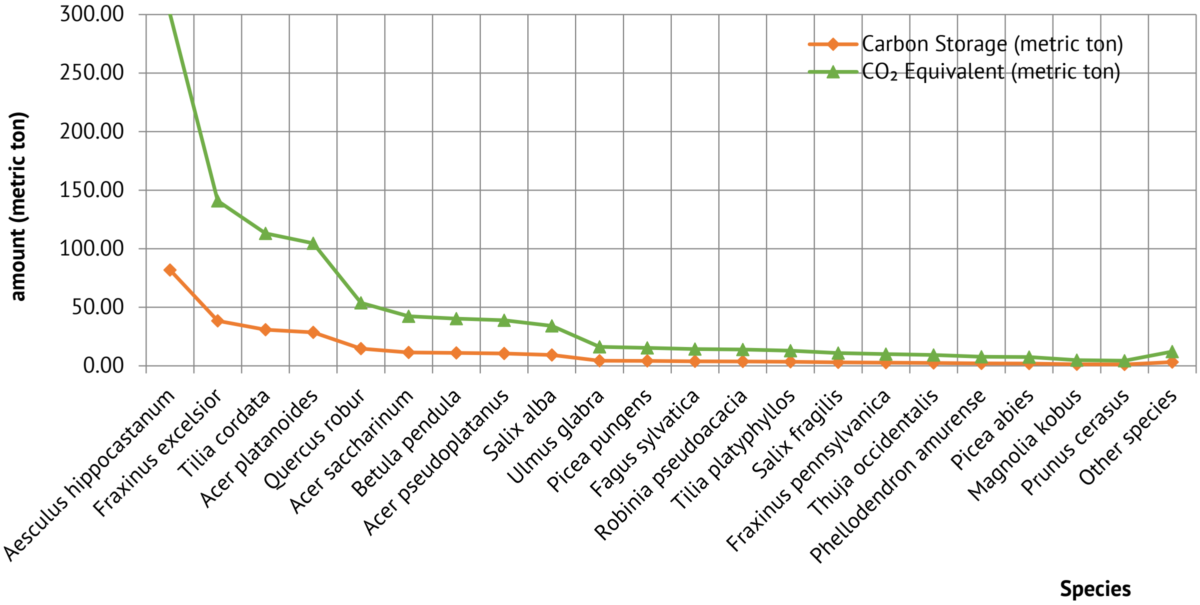

Figure 5. *Volumes of absorbed carbon and CO_2 equivalent in the section of tree-shrub species by plantations of public use in the territory of the city of Berezhany, Ternopil region*

Notes: *on the diagram, tree-shrub species that have an absorption volume of less than one metric tonne are grouped under the "Other species" group*

Source: *developed by the author of this study based on their own research (2022)*

A comparative analysis of the ecosystem productivity of green spaces in the section of the investigated objects proved that the most effective in this regard are park stands, which can create ecosystem services in the amount of UAH 132.5 thousand (€3275) annually, which is UAH 581 (€14.4) averaged per plant. The annual averaged ecosystem productivity of the considered tree-shrub stands in the park is higher than that of individuals growing in the square and in the central part of the city by 8.1% and 12.2%, respectively. Furthermore, park stands can absorb and store carbon in their tissues during their lifetime, which in terms of value is estimated, as of today (2023), in the amount of UAH 1,154.8 thousand (€28,542). According to this indicator, the average ecosystem productivity of park plants substantially exceeds analogous values of plants growing in the square and the central part of the city by 83.2% and 171.4%, respectively.

The conducted study offers a better insight into the part of the ecosystem services of public green spaces. However, for a wide scope of users to get acquainted with this information, the stage of its presentation and delivery to stakeholders is also important. As evidenced by the results of many scientists (Nedkov *et al.*, 2017; Bidolakh *et al.*, 2023), assessment and mapping of ecosystem services provide valuable spatial information to support decision-making, planning activities, ensuring the sustainable development of urban ecosystems, climate regulation, and increasing environmental awareness of society. Displaying information about the ecosystem services of each tree and bush of the researched stands in the form of an electronic map using the application (Google MyMaps, 2023), according to the methodology described above, made it possible to provide open access for everyone and create conditions for a better understanding of the value of each plant and the volume of its individual ecosystem productivity (Fig. 6). Another approach to promote the ecosystem services of trees and shrubs at the local level could be to attach information plates to plants and create special information stands with information on the ecosystem services of green spaces in both quantitative and monetized terms.

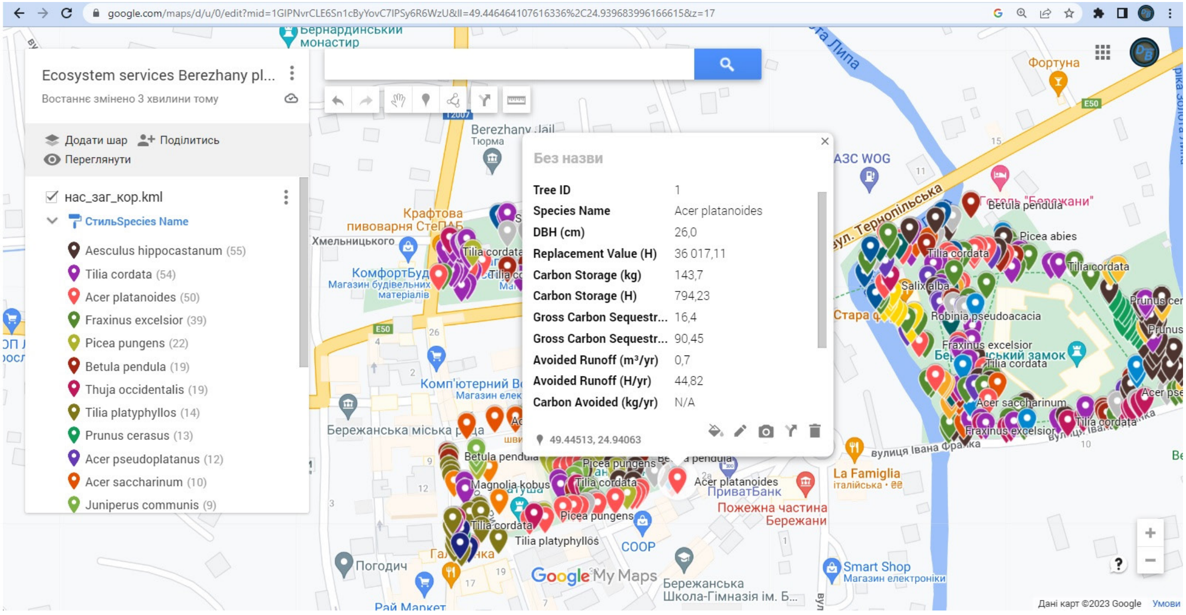

Figure 6. *Interactive map of the amount and cost of ecosystem services of public green spaces in the territory of the city of Berezhany, Ternopil region*
Source: *developed by the authors of this study based on (USDA Forest Service, 2021; Google MyMaps, 2023)*

In general, the conducted study helped determine in quantitative and cost terms part of the ecosystem services of public green spaces (reduction in the amount of pollutants, absorption and sequestration of carbon, volumes of oxygen production, and regulation of surface water flows) and display them in the form of an interactive map. This approach, according to (Burkhard & Maes, 2017), improves the decision-making process in the field of environmental protection activities and creates conditions for improving the environmental awareness of the population.

Comparing the conclusions obtained in this study with the results obtained by other scientists, it is worth noting the unanimity of scientists from different countries (Croci *et al.*, 2022; Včeláková *et al.*, 2023) regarding the importance of conducting analogous applied studies of the maximum possible number of ecosystem services for various types of green spaces in all corners of the world. Many experts (Mosyaftiani *et al.*, 2022) also recommend using modern tools for this process, including i-Tree Eco Tools for researching ecosystem services of green spaces. Therewith, the obtained study results are interpreted by various authors (Yang & Khan, 2021) in the plane of the most effective delivery of information about the ecosystem functions of green spaces to users of ecosystem services, authorities and scientists, including similarly to the findings this study obtained by visualizing them on maps (Bidolakh & Lakyda, 2019). Ultimately, according to researchers (Cimburova & Barton, 2020; Stoeckl *et al.*, 2023), such studies should contribute to the overall greening of social development and the improvement of environmental awareness of residents of settlements, which is also relevant for ensuring the sustainable development of urban landscapes of Ukraine.

CONCLUSIONS

The conducted study helped work out the procedure for obtaining and evaluating quantitative and value indicators of ecosystem services using the i-Tree Eco tool, using the example of public green spaces in the city of Berezhany, Ternopil region. The findings created conditions for demonstrating the value of green spaces for urban ecosystems and the importance of conducting analogous studies to ensure the sustainable development of ecosystems.

The obtained results proved that the ecosystem usefulness of the researched green spaces in monetized terms amounts to UAH 216,718 thousand (€5356) annually in terms of the investigated indicators (reduction of the number of pollutants, absorption and sequestration of carbon, volumes of oxygen production, and regulation of surface water flows). Therewith, the average value of the annual cost of ecosystem services of each tree-shrub plant in terms of the above-mentioned indicators is UAH 557 (€13.8). Furthermore, evaluating the ability of the investigated green spaces to absorb and store carbon in their tissues during their lifetime, the value assessment of this ecosystem utility as of today (2023) is UAH 1,493,009,000 (€36901).

The results of the analysis of the ecosystem productivity of different plant stands (park, square, and green spaces in the central part of the city) showed the highest indicators for park stands given the higher values of their biometric indicators. Tree and shrub plants of the square on the Ternopilska street in the city of Berezhany is slightly inferior to the investigated park stands in terms of their indicators. Green spaces in the central part of the city, even with lower average biometric indicators, are more effective in absorbing pollutants. In terms of species, trees that can achieve considerable biometric indicators in local conditions of urbanized landscapes are characterized by greater ecosystem productivity. For the city of Berezhany, Ternopil region, such trees should include *Quercus robur* L., *Aesculus hippocastanum* L., *Fraxinus excelsior* L., *Tilia cordata* Mill., and *Acer platanoides* L.

To familiarize more people and popularize the ecosystem value of trees and bushes, we have proposed the creation of electronic interactive maps with unrestricted access for all stakeholders, as well as the installation of information boards and stands with information about the ecosystem services of green spaces. The practical value of the results of this and analogous studies also lies in the possibility of presenting the obtained results to local authorities, enterprises, and organizations related to green management, scientific and public organizations, activists, and other stakeholders. Such an approach will create conditions for improving the awareness of the value of green spaces to ensure the sustainable development of urban ecosystems and society, improving their security and protection, improving management and creating conditions for making informed decisions in the field of green construction, improving the environmental awareness of residents of settlements and achieving other ecologically oriented results.

Notably, the chosen topic has considerable prospects for further research in the context of obtaining information about the ecosystem services of other plant stands, expanding the list of ecosystem functions for research and evaluation, researching the possibilities of involving innovative tools for performing analogous works, expanding the scope of applications and improving the methods of presenting the obtained results to popularize the usefulness of green plantations for urban ecosystems.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Оцінювання екосистемних функцій зелених насаджень загального користування у м. Бережани Тернопільської області

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Анотація. Дослідження можливостей використання сучасних підходів та інструментарію для оцінювання екосистемних послуг зелених насаджень вирізняється актуальністю та потребує теоретичного обґрунтування та прикладних досліджень, особливо в умовах важливості забезпечення сталого розвитку України. Тому метою цієї роботи є опрацювання процесу кількісного та вартісного оцінювання екосистемних послуг зелених насаджень загального користування та пошук можливостей представлення отриманої інформації для зацікавлених осіб. Для цього проведено інвентаризацію зелених насаджень з вимірюванням їх біометричних та санітарних показників. З метою кількісного та вартісного оцінювання екосистемних функцій насаджень та окремих дерев використано інструментарій i-Tree Eco, а для їх візуалізації додаток Google My Maps. Виконані дослідження дали змогу отримати інформацію про окремі екосистемні функції зелених насаджень (зменшення кількості забруднюючих речовин, поглинання та секвестрація вуглецю, обсяги продукування кисню та регулювання поверхневих водних стоків). У складі цієї корисності обчислено щорічну екосистемну функцію щодо поглинання 770 кілограм шкідливих сполук (озон, оксид вуглецю, діоксид азоту та частки різного розміру речовин), що оцінюється на суму 128,648 тис. грн щорічно; зменшення забруднення повітря на 7,43 метричних тони валового обсягу секвестрації вуглецю (19 кг у перерахунку на 1 рослину), із оціненою вартістю у розмірі 41,028 тис. грн та зменшення водного стоку на 684,9 м. куб, що оцінюється на суму 47,042 грн щорічної корисності. Окрім того, досліджені зелені насадження станом на момент дослідження утримують у своїх тканинах вуглець, що створює екосистемну корисність на суму 1493,009 тис. грн (€ 36901). Найвищі показники екосистемної корисності характерні для паркових насаджень, а дерева та кущі центральної частини міста є ефективнішими у відношенню поглинання забруднюючих речовин. Більшою екосистемною продуктивністю характеризуються дерева, які здатні досягати значних біометричних показників в місцевих умовах. Проведені дослідження створюють умови для кращого усвідомлення екосистемної цінності зелених насаджень, проте важлива також її популяризація. Практична цінність результатів полягає також у можливості їх доведення до органів влади, підприємств та організацій, активістів та інших зацікавлених осіб, що створить умови для покращення екологічної свідомості, сприяння захисту та охороні насаджень, удосконаленню менеджменту та прийняття обґрунтованих рішень у сфері зеленого будівництва

Ключові слова: монетизація; корисність; послуги дерев та кущів; i-Tree Eco; урболандшафти; екологічна свідомість

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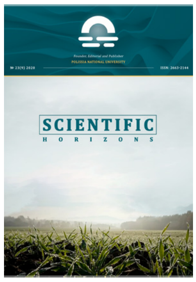

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Environmental problems from rainfall runoff

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Abstract. The state of surface water objects requires constant attention, since on the one hand – they are the sources of fresh water, and on the other hand – the wastewater receivers. Whole range of factors influence the state of surface waters: climatic characteristics, hydrology, soil features and water quality. The relevance of this topic is due to the difficult socio-ecological situation in the river basins of Ukraine; during decades, the aquatic ecosystems have been considered and used only as an economic resource for industrial and agricultural production and the discharge of pollutants, which has led to a rapid decrease in the ecological potential of natural water objects. The purpose of the study is to analyze the natural and anthropogenic impacts on the formation of surface runoff, to determine mathematical dependencies for an adequate calculation of volumes of surface runoff, considering the anthropogenic impacts, which changes the natural features of hydrographs in watercourses and the quality of surface waters. To determine the volumes of surface runoff, it is used the methods that are based both on the direct instrumental measurements and on the construction of various digital models. In the course of the study, it has been identified the main factors influencing the formation of anthropogenic floods, as well as the most typical pollutants, which are present in the surface runoff from the areas with residential construction and artificial coating. The article proposes a number of improvements to the existing mathematical dependencies based on the theory of isochrones for a more accurate display of the processes that form the surface runoff. The resulting mathematical model can be used for predicting the surface runoff from various surfaces, both natural and those that have undergone changes as a result of anthropogenic impact, which in the future can become the basis for the development of environmental measures

Keywords: surface wastewater; contaminants; isochrone theory; drainage basin; ground water

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INTRODUCTION

Surface runoff water that enter water ponds and watercourses (most often without treatment) is one of the main reasons for the deterioration of their condition. The solution of this problem is difficult due to the peculiarities of the regime of formation of surface runoff and its entry into surface water objects, which differ significantly from the conditions for the formation of domestic and industrial wastewater. Therefore, building a model that reflects all the factors affecting the qualitative and quantitative characteristics of surface runoff is of great importance.

The state of surface water objects, compared with the end of the twentieth century, has experienced significant impacts; this applies to both an increase in the mineralization of surface waters and pollution with biogenic compounds. The intensification of agricultural production has led to an increase of pesticide and mineral fertilizer residues in the surface waters, namely: nitroammophos, diammofos, potassium nitrate and others. These are the most common pollutants from the category of pesticides for the surface water: DDT, chlorophos, metaphos. The article by S. Pokhrel (2020) is devoted to this topic, in which the author examines the negative impact of such pollutants on the aquatic biogeocenoses, in particular, the destruction of phytoplankton by pesticides, which is the producer of primary production, which (as a result) leads to a loss of ecosystem stability.

In the work of the group of authors such as A. Butkovskyi *et al.* (2021), it is also described the consequences of pollution of surface water ponds with pesticides such as bentazone, 2-methyl-4-chlorophenoxyacetic acid (MCPA), metalaxyl, propiconazole and imidacloprid. At the same time, the authors proposed methods to prevent pesticide leaching with the surface runoff, namely: the use of vermiculite, pumice, water-absorbing polymer (SAP) for the retention of pesticides belonging to the group of water-soluble ones. On the other hand, the development of organic farming leads to a reduction in the use of mineral fertilizers and plant protection products, which has a direct impact on the quality of wastewater. In the work by M. Trenciansky *et al.* (2022), it is shown a decrease in the pollution of surface wastewater after switching to organic farming. The results of reduction of substances such as nitrates and chlorides became the most significant ones. However, with a prolonged use of organic fertilizers, it was observed an increase in bacterial pollution of surface runoff, in particular, with the coliform bacteria.

The development of cities and the expansion of infrastructure causes significant changes in the processes of formation of surface runoff. This theme is described in detail in the article by K. Sokur and L. Palamarchuk (2021). In the article, it has been carried out a cluster analysis of rainfall, which can be classified as very strong and dangerous according to their nature. As a result of the study, it has been revealed that the runoff from an entirely built-up area is 100-300% more that the runoff formed in the area with a lack of artificial coatings and with minimal buildings. The problem of increased flood runoff during the heavy rainfall is described in the article by T. Morales-Pinzon *et al.* (2015). In particular, the authors of the article argue that the pollution accumulated during the rainless period is rinsed off the surface of urban coatings and significantly worsens the state of surface runoff.

Climate change also contributes to the formation of surface runoff. Thus, in the work by O.V. Stepova and V.V. Roma (2018), the results of changes occurring in the climatic conditions are given, namely: an increase in the average annual temperature and fluctuations in the annual rainfall. This direction is very important, and as the authors of the article have shown, in addition to changes in the formation of surface runoff, climatic characteristics (in particular, the temperature value) affect such indicators as the level of dissolved oxygen and indicators of the presence of organic compounds, namely: biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Separately, it is worth noting that the state of surface wastewater can also affect the quality of groundwater. For example, in the work by W. Morsy and Z. El-Fakharany (2012), based on the statistical analysis and mathematical modeling, it has been determined that the pollution of surface runoff can lead to an increased risk of migration of plume pollution, resulting in a deterioration in groundwater quality.

Thus, the surface runoff can affect both the state of surface water objects and the quality of underground aquifers; thus, determining the volume of surface runoff is very important. The purpose of this work is to improve the existing methods for calculating the volume of surface runoff that enters the water ponds and water courses with rain and meltwater. This will make it possible to predict the possible consequences of the influence of surface wastewater on the state of surface and groundwater objects, as well as to determine possible ways to minimize these consequences.

MATERIALS AND METHODS

The calculation of river runoff is an important part of hydrology. It can be based both on the traditional methods for measuring the level and flow of water, and on the mathematical modeling methods. In the case of direct instrumental measurements, the flow meters of various designs are used, which are compared with the water levels in the watercourse. To obtain correct data on the volume of runoff, the obtained data is subjected to various types of mathematical analysis. If possible, the data obtained during the operation of hydrotechnical structures (such as locks, gates and others, installed on regulated watercourses) are used to determine the volume of river flow.

The formulas used can be classified into two main types: empirical formulas (which in general consider the basic regularities of the formation of surface runoff) and genetic formulas (which is based on the theoretical foundations of the formation of runoff on slopes and in waterways. The reduction and volumetric methods are the most widely used empirical methods. The reduction formulas are based on a schematic representation of slope and waterway hydrographs (Medvedeva & Shakirzanova, 2015). In the methods related to mathematical modeling, it is possible to distinguish genetic and probabilistic-statistical approaches, which are combined to some extent. The probability-statistical methods are based on the principle of grouping runoff's characteristics into statistical series (or combinations), which are studied by the methods of mathematical statistics and probability theory. The ability to track changes both in space and time is an important advantage of probabilistic-statistical methods. With the help of these methods, it is possible to obtain general interdependencies.

Particular attention has been paid to research on how the floods form and what consequences they have for calculating the maximum runoff, layers, runoff's time and hydrographs. All these properties can be determined as a result of direct field studies. With the lack of observations, they are based on the concept of general principle of the formation of spring floods. It is typical for the genetic methods to study river runoff to rely on the cause-and-effect relationships. At the same time, much attention is paid to the study of water systems, their classification, implementation of regional hydrological zoning. Genetic methods include the methods of hydrological analogy, hydrological interpolation, regional coefficients, water balances and dissection of runoff hydrographs by source (genetic dissection). Genetic methods may also include some runoff models (for example, runoff isochrones, deterministic models).

Genetic formulas and formulas of boundary intensity are based on the assumptions regarding the formation of surface runoff as a hydro-mechanical process. As a rule, such models consider several stages of runoff formation, starting from the first phase – the slope runoff, when the moisture is transformed from water intakes into a slope hydrograph; and then, due to the flow stratification and factors of waterway regulation related to the second phase of transformation, it becomes a waterway hydrograph. Adjustment for the individual characteristics of water intake is carried out by means of constructing an isochrone curve based on the empirical data. Separately, it is worth noting the advantage of such methods, which lies in the fact that they can be applied to water intakes, regardless of their size. In this study, the reduction formula specified in the Building Regulations SNiP 2.01.14-83 "Determination of calculated hydrological characteristics" (2014) was taken as a basis for the development of a mathematical model. It determines the maximum discharge of surface runoff during the spring snowmelt:

$$Q_{P\%} = \left[\frac{K_0 h_{P\%} \mu \delta \delta_1 \delta_2}{(A+A_1)^{n_1}}\right] A \, . \tag{1}$$

At the same time, the data obtained as a result of long-term observations of rivers-analogues are used for determining the values of coefficients included in equation 1, such as the parameter characterizing the friendliness of spring flood (K_0), the estimated layer of the total spring runoff ($h_{P\%}$), the coefficients considering the impact of water ponds (δ), the impact of afforestation (δ_1), the impact of wetland areas (δ_2).

RESULTS

Water resources on the territory of Ukraine are unevenly distributed. The volumes of surface runoff also change over time. In summer, it usually makes up 7-10% of the annual runoff, and in autumn and winter – it increases up to 15-16%. In low-water years, surface runoff can decrease to 40-60% of similar indicators based on the results of long-term observations (Rybalova & Melnik, 2021). Separately, it is worth noting the low quality of water in many watercourses, which makes it unsuitable even for the use for cultural and domestic purposes. It often happens that a watercourse has a negative water balance, which leads to a violation of hydrological regime of the river, and accordingly, makes it impossible to use this water for the needs of national economy.

Surface runoff is the main source of power for the rivers, namely the spring snowmelt, and in the summer period – the replenishment of river runoff occurs due to the groundwater. A number of factors influence the formation of surface runoff: land cultivation, deforestation, construction of housing and industrial facilities (including the environmentally hazardous ones). In addition to the fact that a change in the underlying surface affects the volume of surface runoff, this also leads to a change in the qualitative composition of wastewater. Therefore, the identification of dependencies that would most fully characterize the process of formation of surface runoff is an urgent problem. The equations for calculating the volume of rainfall runoff from a certain area should be based on the basic factors, which form the volume of runoff. They primarily include: local parameters, such as relief, intensity and duration of rainfall, the absorption capacity of soils and features of the regime of underground water and groundwater, the cross section of water-collecting relief by ravines and gullies The nature of land use is necessarily considered; for the ploughed up lands, it is worth considering the water consumption by agricultural crops, the timing of vegetative period. Based on the above-mentioned indicators, the maximum rainfall volumes can be represented in the simplest form using the equation:

$$q_{P\%} = 13.2 h_{в_{max,1\%}} \delta_{sn} \delta_E G_p^{0,5} \lambda_p K_{wa}, \tag{2}$$

where $h_{вmax,1\%}$ – the maximum value of water accumulation and with a supply of 1%, mm; δ_{sn} – a coefficient characterizing the soil nutrition (this parameter can vary from 0.9 for the areas, in which the water-catchment is characterized by the low level of soil nutrition; 1.05 – for the areas in which the water-catchment is characterized by an average level of soil pressure feeding; 1.25 – for the areas, in which the water-catchment is characterized by a high level of soil nutrition); δ_E – is the coefficient of water consumption accounting, which depends on the type of agricultural crops grown in the territory under consideration and the duration of vegetation period (this indicator ranges from 0.85 to 1); λ_p – the coefficient of transition from the provision of 1% to another given one; K_{wa} – the coefficient of reduction of maximum water accumulation; G_p – is a parameter that depends on the soil nutrition and the area subject to anthropogenic impact.

The value of G_p is determined according to the equation:

$$G_p = \left(\delta_{ld} P_p^{\chi} + \sqrt{\frac{\delta_l(1-\delta_{ld})}{A+30}}\right)\delta_e \,, \tag{3}$$

where δ_{ld} – the coefficient characterizing the scale of land development (calculated by the formula:); δ_l – the coefficient depending on the level of afforestation of the territory under consideration; δ_e – is an empirical coefficient reflecting the level of changes that occurred under the influence of anthropogenic or technogenic intervention (δ_e for the Dnieper basin and the northern part of Ukraine is 1.23); P_p – the parameter of feeding, its value depends on the type of soil and the depth of aquifers; χ – the indicator of the level of feeding parameter.

The equation for calculating the volume of rainfall runoff is structurally similar to the formula given in SNiP 2.01.14-83 "Determination of calculated hydrological characteristics" (2014). However, at the same time, there are several significant differences. For example, in SNiP, it is proposed to calculate the maximum drainage rate based on the runoff coefficient and the layer of precipitation that fell during the day. This dependence does not consider the fundamental factors such as the state of soil, as well as the terrain, the level of groundwater, the volume of water consumed by agricultural crops, the duration of vegetation period, melioration measures, the topographic features of the area under consideration, and other criteria. All characteristics are considered when forming the equation (1). Considering the larger number of parameters makes it possible to more accurately predict the volume of maximum runoff. This especially affects the calculations of flood runoff for small rivers and watercourses subject to the anthropogenic impact. However, the parameters of the above-mentioned equation do not fully consider the physics of the process of the flood flow formation. According to the analysis of the channel network of rivers in the upper and middle flow of the Dnieper region, the configuration of the river catchment basins can have quite diverse forms, while the equation (1) is based on the assumption that the rivers' basins have a rectangular form. Thus, in order to increase the reliability of calculations, it is necessary to add an empirical coefficient to formula (1) – a constructive-hydrographic one, with the help of which it would be possible to proceed to the modeling of realistic river basins.

The time of the channel running has main influence on the process of formation of flows of anthropogenic floods (the ratio of hydrographic length of the watercourse to the running speed). While the running speed is one of the most important indicators that can significantly affect the runoff transformation in the channel). The calculation formula considers the mutual dependence of time of the channel running and the parameter of the forming costs related to the unit of time. Determination of the maximum integral discharge of surface runoff is based on the isochrone theory. The work by C. Xi *et al.* (2021) is devoted to the application of this theory regarding the calculation of flooding. Methods of mathematical modeling based on the isochrone theory are reflected in the article by C. Cui *et al.* (2022).

According to the isochrone theory, the value of the maximum water accumulation is calculated on the basis of the ratio of the slope run time (τ_{srt}) to the channel run time (τ_{crt}). At the same time, if τ_{crt} is more than τ_{srt}, then the formation of the maximum occurs as a slow runoff, as a result of which the greatest water accumulation is observed. If τ_{crt} is less than τ_{srt}, the maximum is formed as a developed runoff. In this case, there is a maximum water accumulation (h_{vmax}), which is calculated through the coefficient of the layer of the largest water accumulation φ. Thus, water accumulation can be determined using the equation $h_в=\varphi*h_{vmax}$. Based on the above-mentioned dependencies, it is possible to conclude that the layer of slope runoff differs from the highest water accumulation ($h_{вmax}$). This difference is equal to the loss of flood runoff (R_{fr}), which (for convenience) will be determined using the coefficient of runoff loss in recession R_{fr}. It should be noted that the value of R_{fr} is always less than 1. When multiplying the runoff loss coefficient in recession by the maximum water accumulation, it will be obtained the value of the layer of slope runoff.

According to the theoretical scheme for the formation of flood runoff as a result of anthropogenic changes, the maximum water accumulation directly depends on the groundwater regime. This indicates that different levels of groundwater can generate different maximum water volumes, even if other factors (such as the volume of rainfall and soil conditions) are the same. Changes in the volumes of water accumulation through the groundwater levels are considered using the empirical coefficient ξ_{gw}. The coefficient of groundwater level indication (ξ_{gw}) considers the mechanical composition of the soil and the vegetation period. Anthropogenic changes that affect the nature of redistribution of the surface runoff are considered using the coefficient for accounting for the level of anthropogenic changes K_{ac}. Anthropogenic changes are usually expressed as an increase in the land occupied by agricultural production within a particular water-catchment area. This coefficient is determined by comparing the volumes of runoff from agricultural land and natural landscapes. Due to the variety of factors affecting the formation of composition of the surface wastewater, as well as the nature and degree of inorganic and organic pollution, the surface runoff is a priority indicator that should be considered among the components of various origins to determine the state of surface water. The proposed model does not consider the features of the water basin such as afforestation and waterlogging; these parameters are considered in the indicators of maximum water accumulation. For watercourses with the most regulated runoff due to the presence of ponds and lakes, the coefficient of accounting for the influence on lakes' runoff is introduced for the proposed methodology (Traskova, 2015).

Various territories of Ukraine, such as the upper and middle Dnieper and the northern part of Ukraine have a significant number of karst formations (geological formations that are formed during the process when the rocks is leached and dissolved by the surface water or groundwater). These formations make their additional contribution to the formation of surface runoff. Depending on the type of supply, these formations can lead to both an increase in the flood runoff and its significant decrease. This influence is considered in the calculation model using the empirical factor of accounting for the state of cavernous porosity δ_c. The degree and nature of pollution of surface runoff from the residential and commercial facilities varies and depends on the sanitary conditions of the water catchment area, the level of development of the territory and the meteorological characteristics of precipitation, namely: the duration and strength of precipitation, the duration of preliminary dry weather and the intensity of spring melting process, as well as the impact of rainwater pollution, which occur due to pollution of atmospheric air by the emissions from industrial enterprises and transport.

High concentrations in the surface runoff are observed at the beginning of rain; after reaching the maximum volume of runoff, as a rule, a significant decrease can occur. Irrigation waters and household wastewaters have a stable composition and high concentrations of pollutants. As a rule, these are the most characteristic pollutants: the suspended solids, oil products, BOD and COD indicators characterizing the presence of organic compounds in wastewater. The presence of suspended solids in the surface wastewater is due to the presence of soil particles carried from the open surfaces, the road surface components, dust, household waste and building materials that can be stored in open areas. The presence of oil products in the rainwater is a separate problem; they are formed as a result of leaks of fuel and lubricating fluids during the operation of vehicles and other machines and mechanisms. The specific components of the surface runoff from areas with residential development include: synthetic surfactants, heavy metal salts, phosphates, biogenic elements (primarily – nitrogen compounds, which can be present both in organic and in inorganic forms in the wastewater: ammonium, nitrate and nitrite nitrogen). The presence of such substances indicates an unsatisfactory sanitary and hygienic condition of the underlying surface or a violation of the tightness of sewer networks. Excessive bacteriological pollution of the surface runoff is also caused by the same reason.

Thus, in the course of the study, it has been improved the existing model for estimating the volume of surface runoff that enters the surface water ponds, both as a result of direct precipitation and during the floods caused by snowmelt. The features of pollution of water ponds by surface runoff are revealed: the most characteristic pollutants are determined, as well as the specific conditions (unevenness in time) regarding the concentrations of pollutants in rain and melted wastewater.

DISCUSSION

The problem of environmental pollution, namely the water objects, is one of the most urgent for today. A number of articles by both domestic and foreign authors are devoted to the study of influence of the surface runoff on the state of water objects. Thus, in the collection of articles formed on the basis of results of the first international-scientific and practical conference "Modern directions of scientific search", Chicago, USA, 2021, it was presented the work by Ukrainian authors O.V. Rybolova and L.V. Melnik (2021) devoted to the influence of rainwater runoff on the state of water objects. The authors in their work also used a method based on the calculation of environmental index to determine the state of surface waters. The rivers of the Kharkiv region, belonging to the basins of the Dnipro and Siverskyi Donets rivers, were chosen as the basis for the research. Based on the assessment of environmental index, it has been determined that almost all water objects (that were investigated) are classified as the quality class 4. This means that ecological state of these watercourses is bad. Small rivers appeared to be the most vulnerable to anthropogenic impact. The authors of the article have come to conclusion that urbanization is the most significant source of influence, which changes the normal formation of the natural flow of rivers due to the disturbance of natural relief and intervention in the underground horizons. Agriculture is another factor influencing the state of surface runoff. As a rule, the surface runoff from agricultural land contains biogenic elements, such as nitrogen and phosphorus compounds, which are part of the most mineral fertilizers. At the same time, the following factors has a great importance for the composition of surface runoff: the type of agricultural crops grown in certain areas, their yields, methods of land cultivation, in particular, whether the artificial irrigation is used. The conclusions of these authors are fully consistent with the results obtained in the course of research by the authors of this work.

Authors P. Smilii *et al*. (2021) conducted similar studies on the territory of the Zhytomyr region within the Pripyat river basin. Based on the obtained results, an assessment of water quality was carried out in three blocks: salt composition, block of ecological and sanitary indicators and block of indicators of toxic action. According to the results of such assessment, the integral ecological coefficient was determined. It is especially worth noting that the block of ecological and sanitary (trophic-saprobiological) indicators is the limiting indicator that most affected the value of integral-ecological index; this indicates that anthropogenic factors have the greatest influence on the state of water objects in the Pripyat river basin. The authors of publication I. Gopchak *et al*. (2021) made similar conclusions. The small rivers of the right-bank of Polissia became the subject of their research. As in the previous study, the block of ecological-sanitary (trophic-saprobiological) indicators was the characteristic that most influenced the overall ecological index. Thus, in comparison with the block of salt indicators, or the block of indicators of toxic action, the block of ecological and sanitary indicators has the highest values. This proves once again that the quality of surface water in Ukraine depends primarily on the quality of surface runoff, which suffers greatly from anthropogenic load.

Similar studies are being carried out in many countries around the world. For example, the work by M. Suchowska-Kisielewicz and I. Nowogonski (2021) is based on the studies conducted in Poland. The software complex "Storm Water Management Model" developed by the United States Environmental Protection Agency (EPA) was used to simulate the rainfall runoff. This software complex is based on number of hydrological parameters, namely: variable duration of precipitation and its amount, evaporation of water from the open surface of water ponds and watercourse, accumulation of precipitation (rainwater and snow), further snowmelt, leakage and filtration of rainwater and meltwater into the soil thickness, the risks of groundwater overflow into underground and surface sewer networks and structures and vice versa, as well as the specificity of movement of the rain and melt water flows along the underlying surface. Although the methods of researching the problem differ significantly from those ones adopted on the territory of Ukraine, the conclusions made by these authors coincide with the conclusions obtained in the course of this study.

The combined sewer systems are common problem for the state of surface waters, that is when both surface runoff waters and domestic-industrial wastewaters are collected in one network. This problem is primarily associated with the possibility of wastewater overflow during the most intense precipitation, when part of runoff is discharged into a surface water pond without treatment. On the other hand, the composition of pollutants contained in the domestic-industrial wastewater can be radically different from the pollutants in rainwater, which makes it difficult to clean them; in particular, this significantly impairs the operation of treatment facilities, the main treatment type of which is based on biological methods. The article by L. Soriano and J. Rubio (2019) is devoted to this problem, in which (using the example of the city of Zaragoza) the studies regarding the impact of surface wastewater on the state of the Ebro River were carried out. The article proposes a number of measures to improve the state of water resources within the city; first of all, the authors paid attention to improving the sanitary condition of the city, which largely depends on the composition of rainwater. This fully coincided with the opinion of the authors of this study.

If there is no possibility of continuous monitoring of the volume of surface runoff, it is very important to have a correct model for mathematical calculations of such quantities. Therefore, there are several different approaches to determine the volume of surface runoff, each of which tries to consider all existing factors as much as possible. Modern approaches to determining the volume of surface runoff are also based (in addition to the isochrone theory) on a geometric approach to the slope and/or channel runoff hydrograph. This approach is developed in their works by the teams of authors such as S. Wei *et al*. (2022) and L. Wang *et al*. (2021). In particular, empirical models have been proposed, which combine the descriptors of hydrograph and rainfall storage reservoir to make reasonable predictions depending on the types of individual hydrographs.

In an article by A.A. Dokus *et al*. (2019), it has been proposed to use mathematical model of runoff formation, which use both the main parameters of meteorological characteristics (snowfalls and precipitation) and runoff coefficients. The model was tested to determine the maximum modulus of spring flood runoff for rivers with a large catchment area located in different physical-geographical conditions in the Southern Bug river basin. However, this model can only be used for spring floods. Using it to predict the volume of surface runoff during rainfall is not possible. Although it showed a high accuracy for calculating spring floods. The method proposed by the authors of this article, based on the isochrone theory, can be used to calculate the volume of surface runoff, including during rains.

In the study by D. Deka and B.M. Das (2022), the precipitation model was built with specified parameters of intensity and duration in order to promptly drain rainwater from the streets of Guwahati, using the SWMM 5.1 software complex. The SWMM 5.1 software complex implements a technique based on the Gumbel distribution.

Based on the calculations obtained, the authors of the article have come to conclusion that the existing rainwater sewer network cannot completely remove rainwater from the city, and therefore, it requires reconstruction.

CONCLUSIONS

The problem of environmental pollution is one of the most urgent in the modern society. This is especially true for the quality of surface waters, which are for the most part a source of fresh drinking water for the population, as well as satisfy a number of other needs, starting from the recreational ones and ending with melioration. Therefore, it is very important to maintain the proper quality of surface water ponds and watercourses. The surface runoff (rain and snowmelt) is the main factor that worsens the condition of surface waters.

In this article, it is determined the list of the most characteristic pollutants inherent in surface runoff; at the same time, it has been clarified the features of distribution of pollutant concentrations, the dependence of concentration on the duration and intensity of precipitation, the nature of underlying surface, including the fact how much the indicated territory has been subjected to anthropogenic and technogenic impacts. Due to the lack of possibility to conduct the direct instrumental and laboratory studies of volumes of surface runoff, a mathematical model has been developed. This model makes it possible to estimate with considerable accuracy the volumes of water entering water ponds and watercourses during precipitation and snow melting. The developed dependences are based on the isochrone theory. For a more accurate reflection of reality, a number of empirical coefficients have been introduced in the formula, such as the coefficient of accounting for the impact on lake runoff, the coefficient of indication of the level of groundwater, the coefficient of accounting for the state of cavernous porosity.

The presence of an adequate model that reflects all the features of formation of the surface runoff for a given drainage basin is of great importance, because it allows effectively predicting the volume of surface runoff entering the water ponds, as well as assuming to what extent and with what substances the runoff from a particular area will be polluted. This will allow developing the appropriate measures to reduce the pollution levels. The direction of further research may lie in the study of impacts that climate change can make on the formation of surface runoff.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Екологічні проблеми від дощового стоку води

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Анотація. Стан поверхневих водних об'єктів потребує постійної уваги, оскільки з одного боку вони є джерелами прісної води, а з іншої – приймачі стічних вод. На стан поверхневих вод впливає цілий комплекс факторів: кліматичні характеристики, гідрологія, особливості ґрунтів та якості води. Актуальність даної теми зумовлена складною соціально-екологічною ситуацією в басейнах річок України, адже впродовж десятиліть водні екосистеми розглядалися та використовувалися лише як економічний ресурс для промислового й сільськогосподарського виробництва та скидання забруднюючих речовин, що призвело до швидкого зниження екологічного потенціалу природних водних об'єктів. Метою дослідження є аналіз природних та антропогенних впливів на процес формування поверхневого стоку, визначення математичних залежностей для адекватного розрахунку обсягів поверхневого стоку з урахуванням антропогенних впливів, що змінює природні особливості гідрографів у водотоках та якості поверхневих вод. Наразі для визначення обсягів поверхневого стоку використовуються методи, які базуються як на безпосередніх інструментальних вимірюваннях, так і на побудові різноманітних цифрових моделей. В ході дослідження визначені основні фактори, які впливають на формування антропогенних паводків, а також найбільш характерні забруднюючі речовини, які наявні в поверхневому стоці з територій із житловою забудовою та штучним покриттям. В статті запропонована низка вдосконалень існуючих математичних залежностей, побудованих на теорії ізохрон, для більш точного відображення процесів, що формують поверхневий стік. Отримана математична модель може бути використана для прогнозування поверхневого стоку з різноманітних поверхонь, як природних, так і тих, які зазнали змін в результаті антропогенного впливу, що в подальшому може стати підставою для розробки природоохоронних заходів

Ключові слова: поверхневі стічні води; забруднюючі речовини; теорія ізохрон; водозбірний басейн; ґрунтові води

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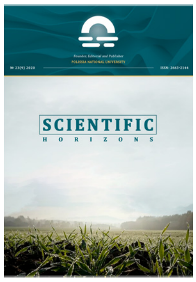

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Spread of rabies in the Kyiv Oblast during 2020-2022

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Abstract. In Ukraine, there is a prominent level of rabies circulation among domestic and wild carnivores. Consequently, the epizootic situation of rabies in Ukraine requires studying the spread of this infection using modern surveillance tools, which allow for territorial assessment and identification of risk zones during analysis. The purpose of this research was to describe the spatial characteristics of the rabies epizootic in the Kyiv Oblast during 2020-2022, focusing on both wild and domestic animals. Official reporting data were analysed to examine the total number of samples of pathological material (brain tissue) collected from various animal species with suspected rabies.

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Positive samples were georeferenced and visualized using software to form clusters of rabies cases based on years and types of animals, creating point layers and density mapping of cases. The analysis revealed that in the Kyiv Oblast, 1788 samples of pathological brain material from animals with suspected rabies were examined, of which 237 were positive. The largest number of samples belonged to wild animals (primarily foxes), acting as a reservoir of the infection. The proportion of wild animals accounted for 64.4% of the total examined, but the number of positive samples varied between 1.7% and 5.5%. Compared to domestic animals (cats and dogs), this figure reached up to 30.0% of the total number of samples examined. Other animal species accounted for 3.2% of positive cases among the total examined. Thus, the highest morbidity rate was observed in domestic animals, representing 72.1% of the total identified positive cases. The highest density of rabies cases in the Kyiv Oblast was observed in the southwest and centre. Persistent clusters of rabies cases were in the Bila Tserkva district and the western outskirts of Kyiv. In the western part of Kyiv, the cluster was formed by cases in wild animals, cats, and dogs. In the Bila Tserkva district, the cluster was formed by cases in wild animals, cats, dogs, and cattle. The highest density of rabies cases in wild animals was registered on the western outskirts of Kyiv

Keywords: *Rabies virus*; epizootic; mapping; density of cases; clusters of cases

INTRODUCTION

Rabies remains a relevant zoonotic disease in Ukraine, and despite all efforts to combat this infection, according to official veterinary reports, the number of registered cases during the first quarter of 2023 has nearly doubled both among wild and domestic animals. Therefore, epidemiological monitoring, surveillance, and analysis of the rabies situation are indispensable. The use of geographic information systems (GIS) provides the opportunity for comprehensive analysis of the epidemiological situation, allowing for the prediction of new cases, planning, and monitoring the situation.

GIS technologies are applied in various fields of rabiology, including routine monitoring, assessment of vaccination effectiveness, detection of new risk zones for animal infection with subsequent rabies spread, and identification of species-related patterns (Fayisa, 2020). In Ukraine, the initial steps have already been taken to determine the geographic coordinates for each rabies case, and a database using GIS technology has been established. Some authors have presented their research results on an endemic rabies outbreak in the Chernihiv Oblast using GIS (Polupan *et al.*, 2017). Subsequently, data related to rabies cases in the Volyn, Lviv, and Zakarpattia Oblasts were also presented. According to some authors, a national rabies database will become an effective information resource in the future (Makovska *et al.*, 2020). Determining spatial trends and identifying rabies clusters can be useful in making decisions about the effective allocation of efforts for disease control, facilitating the development and planning of anti-epizootic measures for rabies (Golik *et al.*, 2018).

Rabies stays a significant zoonotic disease affecting animals and poses a threat to human populations worldwide (Fisher *et al.*, 2018; Banyard *et al.*, 2018). Many researchers report that over 59,000 people die from rabies annually globally (Riccardi *et al.*, 2021; Scott *et al.*, 2021). According to Ukrainian scientists (Polupan *et al.*, 2019; Makovska *et al.*, 2020), approximately 1,600 cases of rabies among animals and sporadic cases in humans are recorded annually in Ukraine during the 21st century.

According to foreign authors (Vos *et al.*, 2017; Maki *et al.*, 2017; Mähl *et al.*, 2021), the most effective method of rabies control, targeting the infection reservoir directly, is oral vaccination of wild carnivores, primarily red foxes. These measures have been implemented in our country for a long time, but in an incomplete scope (Kornienko *et al.*, 2019), which is why Ukraine remains endemic for rabies (Flis, 2021). Another essential aspect of rabies control, especially its urban manifestation, is the vaccination of domestic carnivores (Moore *et al.*, 2018; Raynor *et al.*, 2021; Natesan *et al.*, 2023). The current "Instructions on measures to combat animal rabies" (1994) stipulate that all dogs and, in areas of permanent epizootic risk, at the discretion of state veterinary medicine authorities, cats must undergo mandatory rabies vaccination.

Unlike other countries in Eastern and Central Europe, Ukraine experiences a high circulation of rabies among domestic carnivores (including stray dogs and cats) and the same number of cases among wild carnivores (Mazur *et al.*, 2017). In Ukraine, over 3 million dogs and approximately 2 million cats are vaccinated annually, along with more than 300,000 heads of livestock. It should be noted that most companion animals are vaccinated against rabies by private veterinarians.

Issues with conducting parenteral antirabic vaccination of domestic animals include the lack of a proper identification system for animals, the absence of developed "Rules for keeping dogs, cats, and predatory animals in populated areas of Ukraine," and a program for humane control of stray animal population and vaccination. Therefore, despite significant efforts in combating rabies among dogs and cats, these animal species continue to be prominently featured in veterinary reports on infectious diseases and contribute to the tense epizootic situation of rabies in Ukraine (Golik *et al.*, 2018).

The ongoing direct and indirect impact on the rabies epizootic situation in Ukraine calls for studying the spread of this infection using modern surveillance tools, particularly programs and resources based on geographic information systems, which are promising for analysing the rabies epizootic situation (Bouslama *et al.*, 2020; Müller *et al.*, 2020).

Based on the above, the authors set out to describe the species and spatial characteristics of the rabies epizootic in the Kyiv Oblast over three years (2020-2022) among wild and domestic animals.

MATERIALS AND METHODS

The research material consisted of official data on rabies cases among animals in the Kyiv Oblast for the years 2020-2022. According to quarterly and annual reports from the Central State Testing Laboratory of the State Service of Ukraine for Food Safety and Consumer Protection in the Kyiv Oblast and the city of Kyiv (n.d.), as well as aggregated data from the State Scientific Research Institute of Laboratory Diagnostics and Veterinary Sanitary Expertise (2023), a total of 1788 samples of brain tissue suspected of rabies were examined from various animal species (foxes 64.42%, cats 18.51%, dogs 13.87%, raccoon dogs 0.17%, cattle 0.27%, roe deer 0.06%, hares 0.17%, weasels 0.22%, badgers 0.17%, hedgehogs 0.17%, squirrels 0.4%, muskrats 0.17%, martens 0.27%, moles 0.1%, hamsters 0.1%, rats 0.5%, mice 0.27%, bats 0.06%).

Positive samples underwent descriptive statistical analysis and were categorized by years, animal species, and administrative locations with geospatial coordinates (longitude and latitude). The overall dynamics of rabies cases, dynamics by animal species, and characteristics of the rabies epizootic process were also determined, including density and localization. In other words, the analysis focused only on confirmed positive cases of rabies without control of negative samples. The standard graphical components of MS Office were used for statistical processing.

The mapping of rabies cases was performed using QGIS 3.28.7 software (DIVA, 2023). To determine and visualize clusters of rabies cases by years and animal species, the Heatmap tool was utilized. This tool converts (smooths) the point layer into a continuous surface of point density. The main parameter of this tool is the search radius, which controls the degree of smoothing. The optimal search radius was calculated using the methodology proposed by Murray (2010). The pixel size of the output raster was set to 100 m. Other parameters were kept as default. The vector layers of Ukrainian administrative boundaries for regions and districts were obtained from the geoBoundaries: Global Database of Political Administrative Boundaries; QGIS provides information on borders of Ukrainian regions as of (2023).

RESULTS AND DISCUSSION

During the period from 2020 to 2022, a total of 1788 samples of pathological material (brain tissue) suspected of rabies were examined in the Kyiv Oblast, of which 237 (13.3%) tested positive. In 2020, there were 114 positive cases (19.0%) of rabies detected, 66 cases (6.7%) in 2021, and 57 cases (27.9%) in 2022 (Fig. 1).

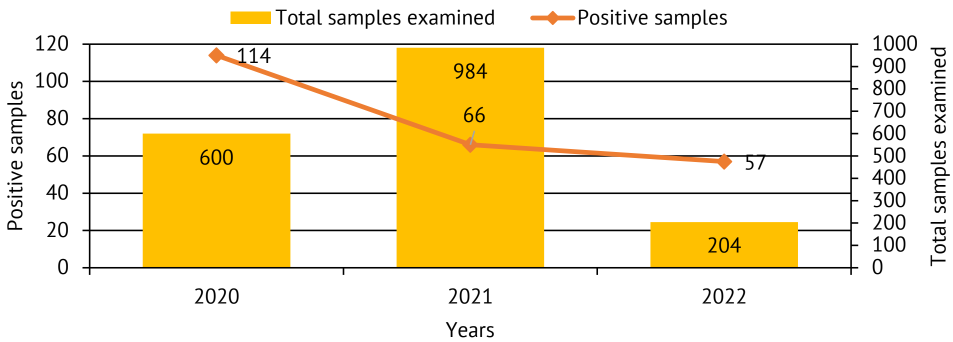

Figure 1. *Total number of examinations and detected positive cases of rabies (2020-2022)*
Source: *compiled based on the veterinary reports of the State Scientific Research Institute of Laboratory Diagnostics and Veterinary Sanitary Expertise (2023)*

It should be noted that during 2020-2021, the total number of examined brain samples from animals was significantly higher than in 2022, mainly due to a greater number of samples from foxes sent for evaluation of the effectiveness of the oral vaccination campaigns for rabies control. The percentage of these samples from the total number was 61.5% and 75.6%, respectively.

In 2022, only 204 samples with suspicion of rabies were examined, which is nearly five times lower than in the previous year (2021), due to the absence of oral vaccination for wild carnivores and, consequently, the absence of samples from shot foxes. The percentage of positive cases in 2022 was 27.9% of the total examined samples.

Most laboratory examinations were conducted on samples from wild animals, especially foxes, which serve as the reservoir and source of infection. During this period, the proportion of wild animals accounted for 64.4% of the total examined material. Although the percentage of positive results ranged from 1.7%

to 5.5%, it is significantly lower compared to domestic animals (dogs and cats) with positive rates ranging from 4.57% to 25.0% of the total number of examined samples. The reason for this is the presence of samples from healthy foxes as a result of active monitoring, and the average value of 3.0% represents a reliable prevalence rate of rabies within the fox population. On the other hand, the high percentage of positive samples among dogs and cats does not reflect the true prevalence rate, as all these samples were from animals with suspicion of rabies and had a history of clinical signs of the disease.

Comparing the percentage of positive samples from wild and domestic animals to the total number examined, it was found that the proportion of rabid dogs and cats is significantly higher than that of wild animals. The percentage of positive samples from domestic animals averages around 30.0% within each species (Fig. 2). In contrast, the percentage of positive samples from wild animals varies from 2.3% to 15.4%.

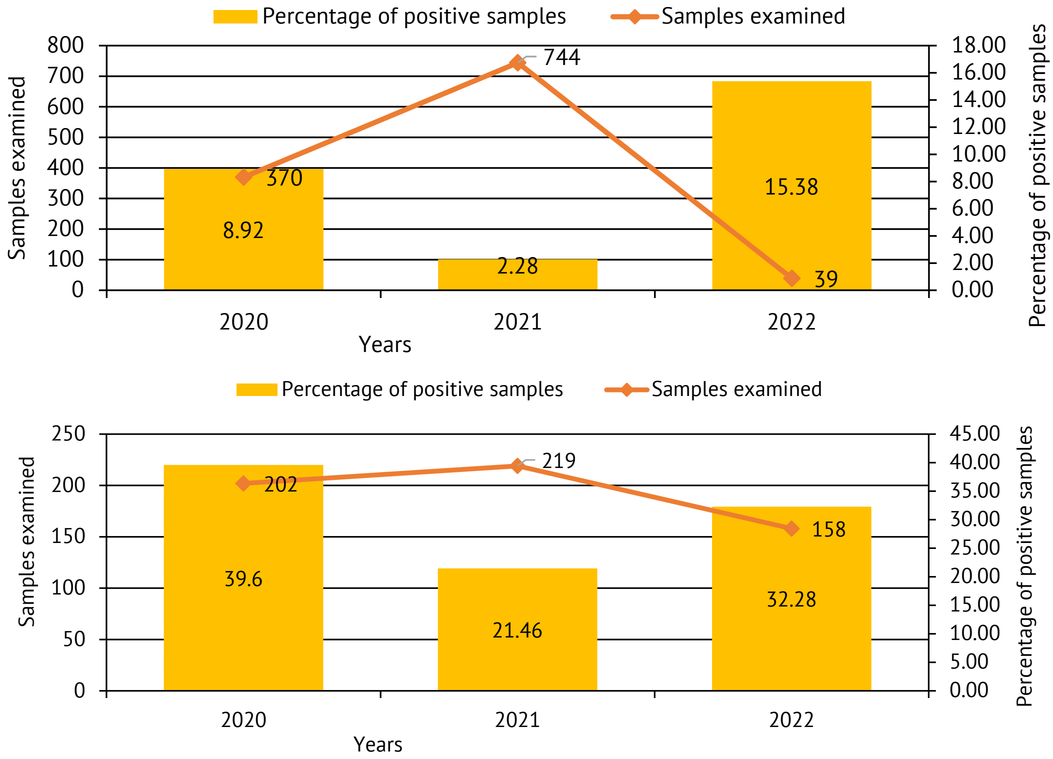

Figure 2. *Dynamics of positive cases as a percentage of the total number of examined samples from wild (A) and domestic animals (B) for rabies*

Source: *compiled based on the veterinary reports of the State Scientific Research Institute of Laboratory Diagnostics and Veterinary Sanitary Expertise (2023)*

The highest incidence rate of rabies is observed among cats, accounting for over 40.0% of the total number of positive cases. Among dogs during this period, the average percentage of positive cases was 32.1% (Fig. 3).

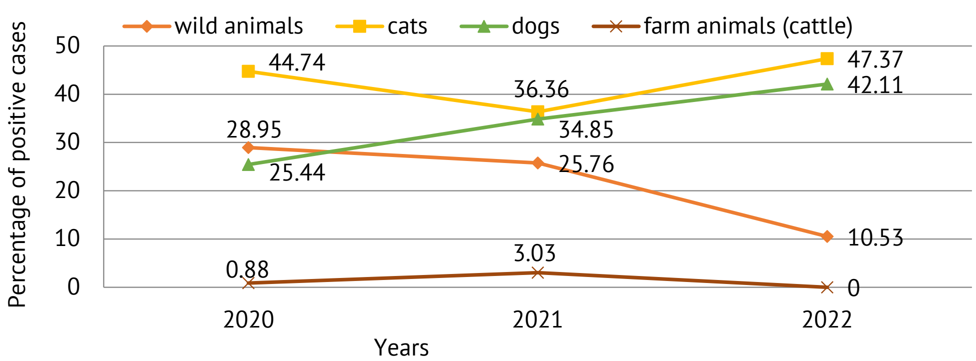

Figure 3. *Number of positive animals for rabies by species (2020-2022)*

Source: *compiled based on the veterinary reports of the State Scientific Research Institute of Laboratory Diagnostics and Veterinary Sanitary Expertise (2023)*

Notably, the percentage of positive cases among dogs increased each year, rising from 25.4% in 2020 to 42.1% in 2022. These indicators suggest the possible emergence of new endemic areas and an increase in the number of anthropurgic manifestations of rabies, due to the higher presence of stray animals. Only 3.2% of the total investigated samples were from other animals. Among them, there were three positive cases in cattle and one positive case each in a badger and a squirrel.

Analysing the seasonality of rabies cases in cats and dogs, it was observed that the highest number of cases occurred at the end of the autumn-winter and the beginning of the spring periods. The percentage of positive cases varied from 6.4% to 57.1% in relation to the number of samples investigated, according to quarterly reports. Among foxes, this indicator remained relatively stable during the quarters of 2020-2021, ranging from 62 to 150 samples, with the highest numbers observed in November and December. Outbreaks of rabies in other animals were predominantly registered during the summer and the autumn-winter periods. The results of the analysis of rabies distribution in the Kyiv Oblast during 2020-2022 indicate an annual persistence of a steady trend in stationary foci and areas with the highest density of rabies cases in western and central districts. Specifically, the highest number of rabies cases in the Kyiv Oblast was recorded in the south-western districts, which border Cherkasy and Vinnytsia Oblasts, where 362 and 415 positive cases were detected during 2020-2022, respectively. The western districts border the Zhytomyr Oblast, where 136 positive cases were registered during the same period. On the northeastern border, which is adjacent to Chernihiv Oblast, only six positive cases were recorded in 2020-2022, while in the Poltava direction, 68 cases were registered.

Analysing the data from neighbouring regions, a clear trend of decreasing rabies cases is observed, which is also reflected in the density of cases in the Kyiv Oblast over the years. The foci remain, but the density of cases is decreasing (Fig. 4).

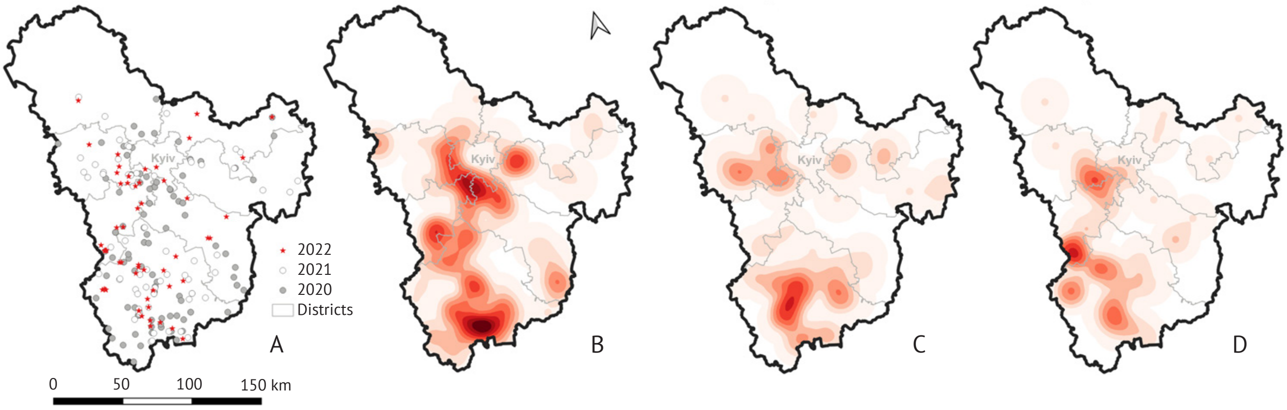

Figure 4. *Spatial distribution of rabies cases over the years (2020-2022). A – rabies cases; B – rabies case density for 2020; C – rabies case density for 2021; D – rabies case density for 2022*

Source: *compiled by the authors of this study*

Analysing the spatial distribution of rabies over the three years (Fig. 4), it was found that zones with the highest rabies case density were observed in the southwestern districts and the central region of the Kyiv Oblast (including Kyiv city). The lowest number of cases was registered in the northern region (exclusion zone and Polissia Reserve), and an average number of cases were recorded in the eastern and northern parts of the region. For example, in the analysis of 2021, it was observed that the zone with the highest density of rabies cases extended from the southern part of Bila Tserkva district to the northwestern border of Fastiv district, forming a dense cluster of cases near the western part of Kyiv, including Bucha, Obukhiv, and parts of Vyshhorod districts. A significant cluster was also present in the eastern part of Kyiv near the border with Boryspil district. In other districts, only isolated cases were registered. In 2021, the zone with the highest case density shifted towards the centre of Bila Tserkva district (up to 10 cases) and extended to the border of two adjacent districts. In the western part of Kyiv, the density of cases shifted to three clusters in Bucha district (up to 5 cases). In the northern region, isolated cases were registered in Vyshhorod and Brovary districts. In the eastern part, there were two clusters in Boryspil and one in Brovary district (up to 3 cases).

In 2022, the highest density of cases was observed in Bila Tserkva district, forming three clusters and isolated cases, which continued with positive cases in Fastiv and Bucha districts, forming a cluster near the western outskirts of Kyiv.

The considerable proportion of domestic animals (cats and dogs) in the etiological structure of rabies indicates a pronounced urban character of the epizootic. Rabies in cats is widespread in almost all districts of the Kyiv Oblast and constitutes the largest proportion of affected animals. In Bila Tserkva district, the cluster is formed by cases among cats and dogs, as well as three cases in cattle (Fig. 5, B, C, D). The etiological structure of rabies among cats forms the main clusters of density near the outskirts of Kyiv, covering all neighbouring districts. The highest density of cases is maintained in the centre and southwestern part of Bila Tserkva and the western part of Fastiv districts.

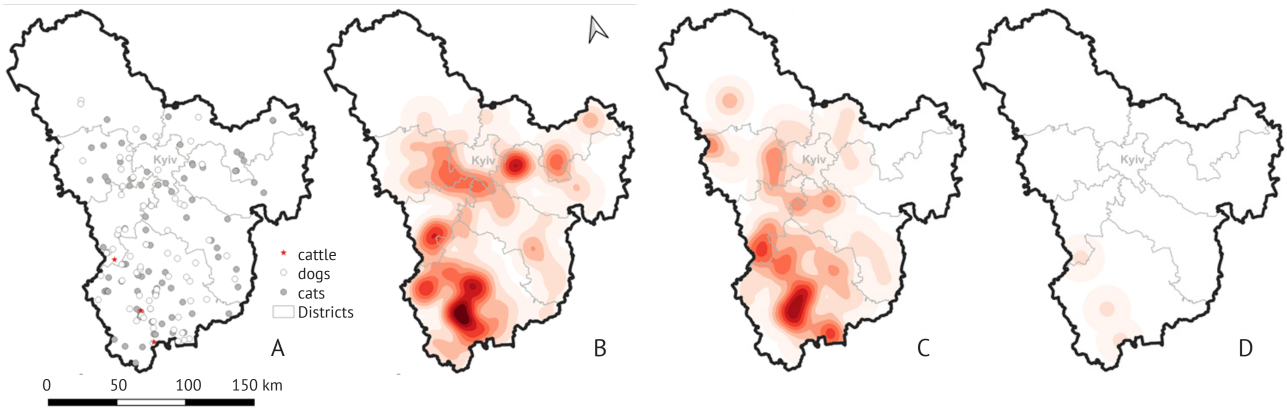

Figure 5. *Spatial distribution of rabies cases by types of domestic and farm animals. A – cases of rabies; B – density of rabies cases in cats; C – density of rabies cases in dogs; D – density of rabies cases in cattle*
Source: *compiled by the authors of this study*

The density of rabies cases among dogs was most frequently recorded in Bila Tserkva and Fastiv districts. Additionally, clusters of two to three cases were registered in all districts of Kyiv Oblast. It is noteworthy that the area of increased density of rabies cases in dogs near the outskirts of Kyiv is considerably distant from the city, unlike clusters of rabies cases in cats, which are located in close proximity to the city. It should be noted that the registered cases of rabies in cattle in Bila Tserkva district – two cases, and Fastiv district – one case, are associated with contact with wild animals (foxes).

Despite the predominant role of domestic animals over wild ones in the total number of rabies-infected animals, the main reservoir of the rabies virus in Kyiv Oblast is foxes. The highest density of rabies cases in wild animals is recorded on the western outskirts of Kyiv (Fig. 6).

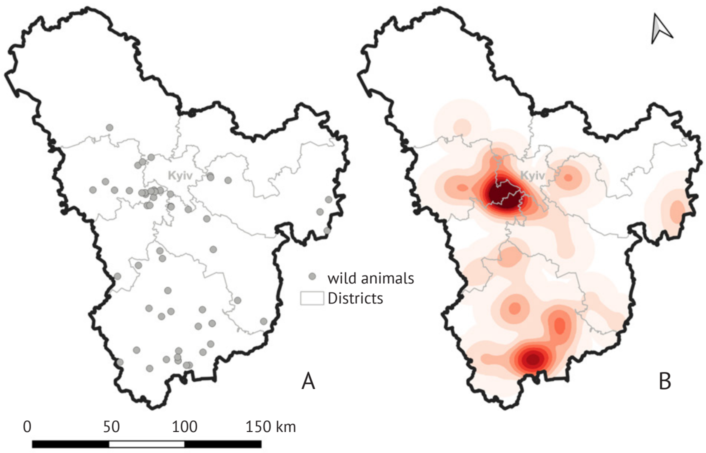

Figure 6. *Spatial distribution of rabies cases in wild animals. (A – rabies cases; B – density of rabies cases)*
Source: *compiled by the authors of this study*

The largest rabies cluster among wild animals is in the central part of Kyiv Oblast, specifically in Bucha and Fastiv districts. Additionally, over 20 cases have been registered in Bila Tserkva district, and up to 10 in Obukhiv and Boryspil districts. Overall, the highest density of rabies cases in Kyiv Oblast is observed in the southwestern and central regions. Persistent clusters of rabies cases are situated in Bila Tserkva district and on the western outskirts of Kyiv, formed by cases of the disease in wild animals.

Regarding the terrain characteristics, the territory of Kyiv Oblast can be divided into three parts: the northern part consists of lowland marshy plains of the Polissia Lowland; the southwestern and central parts lie on the Dnipro Upland (with elevations up to 273 meters); and the eastern, left-bank territory of the region is situated on the floodplain and terraces of the Dnipro within the Dnipro Lowland (Stetsiuk, 2010). The highest number of rabies cases is registered precisely on the Dnipro Upland of Kyiv Oblast, where predominantly black soil and grey forest soils are found. Through a comparative analysis of the geological features of Kyiv Oblast and the territorial distribution of animal rabies cases, it has been established that the geological characteristics of the region do not play a decisive role in the spread of rabies among animals, unlike the natural and anthropurgic foci of rabies that are located precisely in this part of the region.

It is worth noting that, according to anamnestic data, approximately half of the animals had owners, while the other part of the registered cases belonged to stray animals (up to 50% were cats, and up to 30% were dogs). Therefore, the main cause of rabies cases is inadequate coverage with preventive rabies vaccination and insufficient control over the keeping of domestic animals. The northern districts of the region turned out to be conditionally rabies-free due to the low population density and isolated incidents. Additionally, according to reports by Mazur *et al.* (2017), 80% of owned domestic carnivores were not vaccinated against rabies. Foreign authors (Brookes *et al.*, 2019) also emphasize the need for regulating the population of dogs and cats and ensuring an adequate number of planned vaccinations.

Overall, in recent years, Ukrainian researchers Polupan *et al.* (2019) and Makovska *et al.* (2020) have identified a trend of decreasing rabies cases in Ukraine (including Kyiv Oblast), where oral vaccination of wild carnivores against rabies was conducted. This trend continues and is confirmed by our research, as in the last three years, the number of positive cases in Kyiv Oblast decreased by 58.0% and 50.0% compared to 2020, which accounted for 114 cases, while in 2021, there were 66 cases, and in 2022, there were 57 cases.

The research has shown that rabies is most widespread among cats and dogs in Ukraine, which is confirmed by other researchers such as Mazur *et al.* (2017) and Makovska *et al.* (2020). Therefore, combating rabies among domestic animals is still an urgent issue and can only be addressed through joint efforts of administrative and management services, veterinary and human medicine specialists, aimed at improving the care of dogs and cats, timely animal vaccination, capturing, sterilization, and immunization of stray animals, and more. It has been proven that vaccinating the dog population can significantly and durably reduce human rabies deaths, but it requires informative monitoring of animal population demographics.

Geographical approaches using GIS analysis are highly essential tools for the epidemiology of rabies, helping to determine its localization, risk level, and control. These methods are widely used in EU countries (Tadesse & Reda, 2021). In Ukraine, the first attempts were made by Golik *et al.* (2018) on local territories. Makovska *et al.* (2020) made a significant contribution by conducting GIS analysis of rabies distribution in all Ukrainian regions for 2012-2018 and creating a database. These studies allowed establishing temporal patterns and distribution of rabies clusters among different animal species. While our research is specific to Kyiv Oblast, we have identified the highest density zones of rabies foci and the clustering patterns of cases, enabling more effective planning of preventive measures and rabies control in Kyiv Oblast.

Despite the COVID-19 pandemic, oral vaccination of wild carnivores against rabies was conducted in Ukraine in 2020 and 2021, following the "Plan of Anti-epizootic Measures for the Prevention of Main Infectious and Parasitic Animal Diseases in Ukraine (2020, 2021)", which undoubtedly had a positive impact on the tense epizootic situation with rabies. However, in 2022, due to military actions, oral vaccination of wild carnivores against rabies was not carried out. Consequently, the long-term strategy of combating rabies, which relied on extensive oral vaccination of wild carnivores, faces challenges, and may result in significant risks of virus spread among non-immune animals and the emergence of new endemic zones. There is also a possibility of increased cases of anthropurgic rabies due to the growing number of roaming domestic animals.

Given the challenges of today, the development of a novel approach strategy for the rabies control program in animals is necessary. Vaccination has been identified as the most effective means of combating rabies among all animal species. Measures to combat rabies in dogs and cats should include control, vaccination (annual campaigns targeting 70% of animals), and population density reduction through sterilization. As for wild animals, oral vaccination should be conducted twice a year, especially in endemic areas. It is crucial to separately determine the impact of population density on the spread of rabies, which is a complex process and may vary between species. Additionally, it is important to consider that rabies is a transboundary disease (Polupan *et al.*, 2019).

Therefore, conducting continuous monitoring with the study and analysis of spatial and temporal patterns of rabies spread, transmission routes, and mechanisms will allow predicting the disease occurrence in different geographical zones, understanding the epizootic situation, and implementing effective measures to combat rabies. An essential step in developing specific differentiated rabies control measures for each individual territory (oblast, district) is studying its territorial affiliation.

CONCLUSIONS

During the period of 2020-2022, the number of registered rabies cases in animals in Kyiv Oblast amounted to 237 cases out of 1788 examined brain samples. There is a trend towards a decrease in the intensity of the epizootic situation: 114 cases were registered in 2020, 66 in 2021, and 57 in 2022.

The highest incidence of rabies was observed among cats and averaged 42.8% (with slight fluctuations in the percentage of positive cases). In dogs, this rate varied from 25.4% to 42.1%. The highest number of rabies registrations occurred at the end of the autumn-winter and the beginning of the spring period, ranging from 6.4% to 57.1% of the total number of examined samples, according to quarterly reports.

During the analysed period, the highest number of pathological material samples was obtained from wild animals, accounting for 64.4% of the total samples investigated. The percentage of positive cases of rabies in wild animals ranged from 1.7% to 5.5%. The seasonality of rabies during 2020-2021 remained relatively stable and fluctuated within the range of 62-150 samples per quarter, with the highest number of positive cases registered in November and December. Three positive cases of rabies were identified in large ruminants, registered in the Bila Tserkva and Fastiv districts. These cases occurred during the summer and autumn-winter periods and were associated with contact with wild animals, particularly foxes.

The analysis of the results suggests that the spread of rabies in Kyiv Oblast shows an annual steady trend of maintaining stationary foci and areas with the highest density of rabies cases in the southwestern and central parts of the region. Among wild animals, the highest density of rabies foci is found in the central part of the region (in the Bucha and Fastiv districts) and on the western outskirts of Kyiv city. The highest density of rabies cases among cats is registered in the central and southwestern areas of the Bila Tserkva and the western part of the Fastiv districts, as well as in the outskirts of Kyiv city. It is worth noting that the area with an increased density of registered rabies cases in dogs near the outskirts of Kyiv city is significantly distant from the city, unlike the clusters of rabies cases in cats, which are in close proximity to the city.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Анотація. В Україні спостерігається високий рівень циркуляції сказу серед домашніх м'ясоїдних тварин та диких м'ясоїдних. Тому епізоотична ситуація зі сказу в Україні вимагає вивчення поширення цієї інфекції з використанням сучасних інструментів нагляду, що дозволить проводити оцінку територій та визначати зони ризику при аналізі. Метою дослідження було описати просторові характеристики епізоотії сказу в Київській області за 2020-2022 рр. серед диких і свійських тварин. За результатами офіційної звітності було проаналізована загальна кількість досліджених зразків патологічного матеріалу (головного мозку) від різних видів тварин з підозрою на сказ. Позитивні зразки були прив'язані до системи координат та візуалізовані програмним забезпеченням у кластерні випадки сказу по роках і видах тварин з формуванням точкового шару й щільності випадків. За результатами аналізу в Київській області було досліджено 1788 зразків патологічного матеріалу головного мозку від тварин з підозрою на сказ, з яких 237 були позитивними. Найбільша кількість зразків припадає на диких тварин (переважно лисиць), як резервуар інфекції. Частка диких тварин становила 64,4 % від загальної кількості досліджень, але кількість позитивних зразків варіює у межах від 1,7 % до 5,5 %. Порівнюючи з домашніми тваринами (коти та собаки), цей показник сягав до 30,0 % від загальної кількості досліджених зразків. На інші види тварин припадає 3,2 % позитивних випадків від загальної кількості досліджень. Тобто найбільший показник захворюваності спостерігали у домашніх тварин, що становило 72,1 % від загальної кількості встановлених позитивних випадків. Найвища щільність випадків сказу в Київській області спостерігається на південному заході та в центрі. Персистентні кластери випадків сказу розміщувались в Білоцерківському районі та на західній околиці Києва. На заході Києва кластер сформований випадками у диких тварин, котів і собак. В Білоцерківському районі кластер сформований випадками у диких тварин, котів, собак і великої рогатої худоби. Найвища щільність випадків сказу у диких тварин реєструється на західній околиці Києва

Ключові слова: *Rabies virus*; епізоотія; картографування; щільність випадків; кластери випадків

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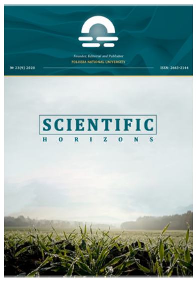

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Financing of Ukrainian agricultural enterprises: Correlation-regression analysis

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Abstract. The relevance of this study is determined by the fact that financing is a key element of the effective economic activity of agricultural enterprises and the industry as a whole, its food security and the restoration of the work of agricultural enterprises, especially amidst a full-scale war and in the post-war period. The purpose of this study was to investigate the relationship between the obtained net profit (loss) and the sources of financing of agricultural enterprises of Ukraine for 2014-the first half of 2023. The study used general scientific methods (analysis of the dynamics of the volume of financing sources (equity, loans, capital investments, state aid, and deposits), analysis of the net profit of agricultural enterprises, formation of the structure of financing

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sources, determination of growth rates of indicators), and specific research methods (correlation analysis and multivariate regression method). The authors of the study suggested using the method of correlation-regression analysis with further forecasting of indicators using Chaddock's tables, Fisher's and Student's tests. The correlation-regression analysis established that a decisive share in financial support is own capital, while the smallest share is state aid. But in connection with the full-scale war in the country and limited own resources, the authors of the study proposed to involve bank loans and state aid more widely in their own economic activities. A correlation-regression analysis was developed to identify the dependence of the financial results of agricultural enterprises (net profit (loss)) and their sources of financing for 2014-2021, a regression equation was developed, and a forecast of the possible net profit (loss) of agricultural enterprises for the future period of 2023-2027 was made. The practical value of the findings is that these results can be used by the host activities of the agricultural enterprise of Ukraine and during the development by state bodies of the Strategy for the Development of the Agricultural Sector and their support programs

Keywords: net profit (loss); sources of financing; agricultural enterprise; agriculture; influencing factors; correlation; own funds; credit; state aid

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INTRODUCTION

With the onset of a full-scale war in Ukraine, many countries to which Ukrainian agricultural products were exported are suffering from food shortages, and their prices have risen sharply. During the war, the financing of Ukrainian agricultural enterprises is a particularly relevant and difficult task because many agricultural producers have suffered destruction and damage to the infrastructure, lost agricultural machinery and equipment, many agricultural lands are still mined, access to financial resources has been limited due to the growth of risks affecting the solvency of agricultural enterprises, the prices of fuel and lubricants, fertilizers and seed material have increased, the processes of selling grown products, logistics routes and the number of fraudsters has increased. To the above-listed challenges faced by Ukrainian agricultural producers, it is worth adding the premeditated destruction of the Kakhovka HPP by Russia and the flooding of more than 10,000 sown agricultural lands in the right-bank territory of the Kherson region (much more in the left-bank part of the region) and the damage caused to agriculture in the amount of more than UAH 10 million. Therefore, Ukrainian agrarians face the important question of finding sources of financing their economic activity that will help restore the lost production potential of the enterprise and stabilize its financial security. The relevance of this study is enhanced by the fact that more than a third of agricultural enterprises do not have the possibility of self-financing, and therefore causes a steady increase in the importance of theoretical and practical consideration of approaches to the formation of sources of financing in the wartime.

Many scientific achievements are devoted to the issue of financial support of agricultural enterprises. However, this issue stays relevant. Thus, Ongena *et al.* (2013) define the term "financing" and claim that it is the process of providing monetary resources for the implementation of certain economic activities or projects, and this study focuses on financial decisions in the conditions of risky entrepreneurship and reflects the relationship between financial decisions, risk, and enterprise management.

Tatarinov *et al.* (2021) note that financing, in other words, is a resource-balanced coverage of the needs of expanded reproduction of enterprises, organizations, institutions at the expense of own and/or borrowed funds, which is achieved through economically sound financial planning.

There are also other interpretations of scientists regarding financial support, which is one of the principal factors in the effectiveness of the state's implementation of its functions in terms of commodity-money relations (Karnaushenko *et al.,* 2020; Kozyuk *et al.,* 2023). Furthermore, there is a slightly different opinion held by Leo *et al.* (2019). Ben *et al.* (2020), who claim that financing from banking institutions of other enterprises is a risky activity for banks, and also claim that the issue of shares by an enterprise is one of the main ways of attracting financial resources to economic activity.

Sirenko *et al.* (2020) believe that "institutions are a synergistic combination of opportunities and limitations of the development of the agricultural sector, the structuring of its connections, a combination of the system of factors, organizational components, processes, and results of their activities". Shushkova & Kulchytskyi (2022) analysed the sources of formation of agricultural enterprises of Ukraine in 2016-2020 and noted that the financial resources of the enterprise are one of the key ones. Without them, it is impossible to meticulously organize the processes of creation, operation, and development of each business entity.

Shahini *et al.* (2023) analysed the profitability of agricultural production, influencing factors and determining areas for its improvement. Financial results and their sources of financing are directly one of the factors that affect the profitability of an agricultural enterprise.

Considering the importance of various sources of financing of agricultural enterprises, it is worth noting the research of Malii & Syzykova (2023), who note that the normal functioning of agriculture without credit resources is practically impossible, and "the main areas of stabilization of the lending mechanism should be the development of a set of measures by the state and the banking system, aimed at developing a system of interaction with the agricultural sector of the economy: increasing budget allocations, rational use of budget funds, lowering interest rates for the agricultural sector".

Chumak & Brazhnyk (2022) claim that "the profit of an agricultural enterprise is the main financial source of its scientific and technical development, capital and financial investments, improvement of the commodity and material base and other forms of investment". Pomaz & Sarana (2022) examine the issue of financing agricultural enterprises, analysing various sources of financing and their impact on the sustainability and efficiency of agricultural enterprises. The classification of sources of financing of an agricultural enterprise is given on a real example.

Voloshchuk *et al.* (2023) note that the coordination and combination of efforts of business structures, state authorities and local governments are highly effective in improving the financial situation of agricultural enterprises, and investigate the problems of financing the agricultural sector in Ukraine, consider the issue of access to loans for agricultural enterprises and the role of national support in the development of agriculture.

The purpose of this study was to investigate the specific features of financing Ukrainian agricultural enterprises during the period of financial instability, to identify the relationship between the obtained financial result and various sources of financing of agricultural enterprises of Ukraine for the periods of 2014-1st half of 2023, and the possibility of forecasting profits or losses based on correlation-regression analysis.

MATERIALS AND METHODS

The basis of the methodological approach in the study is the general scientific methods used: 1) analysis of open data, namely: during the analysis of the dynamics of the volume of financing sources (equity, loans, capital investments, state aid, and deposits), analysis of the net profit of agricultural enterprises, formation of the structure of financing sources, determination of growth rates of indicators; 2) graphic method, when constructing a diagram of the structure of sources of financial support of agricultural enterprises of Ukraine for 2014-2022 (1st half of 2023) and displaying forecast values of the dependence of indicators of net profit and sources of financing of agricultural enterprises; 3) method of generalization, when summarizing and forming research conclusions. The research used specific research methods, namely: 1) correlation analysis – to determine the direct or inverse relationship between indicators, i.e., to investigate how the amount of net profit (loss) of the enterprise's activity changes with an increase or decrease in the use of financing sources); 2) the multifactor regression method – to determine the influence of factors on the performance indicator based on the regression equation, i.e., to identify the relationship between the sources of financial support and the financial result of the enterprise for 2014-2022 (1st half of 2023)

The study used open statistical data from the official websites of the State Statistics Service (2022), the Ministry of Agrarian Policy and Food of Ukraine (2023), the Ministry of Economy of Ukraine (2023), the National Bank of Ukraine (2023) regarding the financial activity of agricultural enterprises of Ukraine, their lending, national and international support, capital investments.

The application of the statistical analysis method helped identify the dynamics of the net profit (loss) of the activities of agricultural enterprises of Ukraine, the volume of sources of financial support for agricultural enterprises of Ukraine, analyse the structure of the sources of financial support for agricultural enterprises of Ukraine, as well as make a correlation-regression analysis of the dependence of net profit (loss) on the sources of financing of agricultural enterprises of Ukraine.

Correlation-regression analysis helped establish how strongly one variable depends on another, whether there is a statistically significant relationship between them, and to predict the value of one variable based on another. The principal indicator of correlation analysis is the correlation coefficient, which indicates the degree of linear relationship between variables.

Regression analysis was used to build a mathematical model that describes the relationship between the dependent variable (the variable to be predicted) and one or more independent variables (factors). Regression analysis can be used to determine which variables have the greatest effect on the dependent variable and how. In addition, regression analysis allows predicting the value of the dependent variable based on the values of the independent variables.

In regression analysis, the method of least squares is used to construct the regression equation. This method allows finding the best linear approximation of the dependent variable (in this case, the net profit) from the independent variables (in this case, the volume of financial support from various sources), and therefore it is worth applying the following formula to form the regression equation:

$$y = a - b\bar{x} \quad (1)$$

where: y is the dependent variable (in our case, net profit); x is the independent variable (amount of financial support); a is the intercept (the coefficient responsible for the value of Y at X=0); b is the regression coefficient (indicates the change in Y when X changes by one unit).

Formulas can be used to obtain the values of coefficients a and b:

$$b = \sum \frac{(x-\bar{x})(y-\bar{y})}{(x-\bar{x})^2} \quad (2)$$

$$a = \bar{y} - bx \quad (3)$$

where: Σ is the sum; x is the mean value of the independent variable, y is the average value of the dependent variable.

After calculating the values of the coefficients a and b, the obtained regression equation can be used to predict the values of the dependent variable (net profit) based on the known values of the independent variable (the amount of financial support).

The quality of the econometric model is determined by indicators such as the coefficient of determination, Fisher's and Student's criteria. Fisher's test (F-statistic) is used to test the statistical significance of the relationship between independent and dependent variables in a regression model. Student's criterion (t-test) is used to assess the statistical significance of individual regression coefficients. Therefore, the quality of the model should be checked according to the following formulas:

$$\sigma(y)^2 = \bar{y}^2 - (\bar{y})^2 \quad (4)$$

$$\sigma(x)^2 = \bar{x}^2 - (x)^2 \quad (5)$$

The correlation coefficient (r) measures the degree of linear relationship between two variables. This coefficient takes values in the range of -1 to 1. A value of 1 indicates a full positive linear relationship, -1 indicates a full negative linear relationship, while a value of 0 indicates no linear relationship. To determine the tightness of the linear connection, the correlation coefficient is determined according to the following formula:

$$r_{xy} = b\frac{\sigma(x)}{\sigma(y)} \quad (6)$$

The value of the correlation coefficient can be interpreted as follows:

If $r>0$, there is a positive linear relationship between the variables. If $r<0$, there is a negative linear relationship between the variables. If $r=0$, there is no linear relationship between the variables.

The coefficient of determination (r^2) is used to measure the variation in the dependent variable that can be explained by the independent variable (or variables) in a linear regression model. r^2 indicates how much of the variance of the dependent variable can be explained by the independent variables used.

The coefficient of determination takes a value between 0 and 1. A value of 0 means that the independent variables do not explain any of the variation in the dependent variable, while a value of 1 means that all the variation in the dependent variable can be explained by the independent variables. The coefficient of determination is calculated by squaring the correlation coefficient (r^2x).

The value of the coefficient of determination can be interpreted as follows:

The closer the value of r^2 is to 1, the better the model explains the variation in the dependent variable.The closer the value of r^2 is to 0, the less the ability of the model to explain the variation of the dependent variable.

RESULTS AND DISCUSSION

The agricultural sector is the main component of the economy of Ukraine, which has positive trends towards development and expansion. This is confirmed by the analysis of statistical data on the dynamics of profits of agricultural enterprises for 2014-2021 and partially displayed data for January-September 2022 (Table 1).

Table 1. *Dynamics of net profit (loss) of agricultural enterprises of Ukraine for 2014-2021, UAH million*

Years	Net income from product sales and net earned insurance premiums	other operating income	other income	Total
2014	214,972.50	41,820.50	5,414.50	262,207.80
2015	366,966.40	68,659.20	15,378.10	451,008.40
2016	402,597.40	47,501.80	6,811.20	456,910.90
2017	452,760.10	40,368.20	6,846.60	499,974.90
2018	528,657.80	49,067.20	10,282.40	588,554.00
2019	560,598.70	94,702.70	16,315.40	671,617.70
2020	602,684.40	67,388.00	11,223.30	681,306.20
2021	770,262.80	110,758.20	14,270.90	895,298.70
9 months of 2022	-392.20	…	…	-392.20
R_{gr}, 2021 in % to 2014	358.31	26484	263.57	341.45

Note*: … – no data*

Source: *compiled based on the data from the State Statistics Service of Ukraine (2023)*

Having examined the data in Table 1, the dynamics of the net profit of agricultural enterprises of Ukraine has a positive value during 2014-2020. The growth rate (R_{gr}) of this indicator increased by 341.45% (or +633,090.90 million UAH). In connection with the full-scale war in Ukraine, for January-September 2022, agricultural enterprises received losses in the amount of UAH 392.2 million.

The percentage ratio of the total number of enterprises to the enterprises that received losses is 56%, i.e., every second agricultural enterprise received losses in 9 months of 2022.

Table 2. *Dynamics of the volume of sources of financial support of agricultural enterprises of Ukraine for 2014-2021 and not in full for 2022-1st half of 2023, UAH million*

Year	Equity	Loans	Capital investments	State aid	Deposits	Total
2014	163,931.68	55,335.00	18,388.10	4,624.44	27,849.00	270,128.22
2015	275,303.78	48,425.00	29,309.70	3,472.60	17,111.00	373,622.08
2016	369,370.89	55,374.00	49,660.00	3,062.90	20,293.00	497,760.79
2017	436,337.64	59,706.00	63,400.70	4,326.50	21,126.00	584,896.84
2018	482,978.74	67,675.00	65,059.40	7,737.80	22,564.00	646,014.94
2019	522,778.66	61,600.00	58,555.40	3,090.57	24,260.00	670,284.63
2020	612,250.89	61,486.00	50,189.40	4,664.97	41,063.00	769,654.26
2021	796,549.72	82,600.00	49,127.38	4,665.00	50,058.00	983,000.10
2022	…	55,108.00	…	1,647.50	…	56,755.50
January-June 2023	…	35,900.00	…	1,560.00	…	36,107.00
R_{gr}, 2021 in % to 2014	485.90	149.27	267.17	100.88	179.75	363.90

Note*: … – no data*

Source: *State Statistics Service of Ukraine (2023); Ministry of Agrarian Policy and Food of Ukraine (2023); Ministry of Economy of Ukraine (2023); National Bank of Ukraine (2023); Verkhovna Rada of Ukraine (2023)*

Equity is formed at the expense of internal cash flow in the form of net income and depreciation deductions, while external – contributions from founders (shareholders), free financial support. The size of the net income does not change the size of the company's equity essentially, as it reproduces it in the part of the replacement fund and multiplies it in the part of the net profit. Therefore, the dynamics of the amount of equity capital for 2014-2021 has a positive tendency to increase, the growth rate is 4.86 times (or +632,618.04 million UAH).

The formation and conduct of effective entrepreneurial activity by agricultural enterprises requires the involvement of credit resources. It is credit, as one of the tools of influence on the production process, which is a solution to the problems of financial support of subjects of entrepreneurial activity in the agrarian sphere. Synenko & Kovalova (2020) claim that the availability of credit resources considerably impacts the expansion of financial opportunities, the effective use of material resources and cash receipts, the acceleration of the turnover of the means of production and the increase of the level of competitiveness of the enterprise. Therefore, the attraction of loans has positive dynamics, the growth rate is 49.27% (or +27,265.0 million UAH).

The volume of capital investments mastered by agricultural enterprises from 2014 to 2018 inclusive has a positive tendency to increase. Thus, the growth rate of this source of financing is 353.81% (or by +46,671.3 million UAH). During 2019-2021, there was a decrease in the volume of capital investments by 16.11% (or by -9,428.02 million UAH).

State financial support for the agriculture of Ukraine in 2021 was implemented through the financing of the following programs: partial compensation for the cost of agricultural machinery and production equipment (according to the plan, UAH 1 million); cheaper loans (according to the plan, UAH 1.2 million); financial support for the development of farms (according to the plan, UAH 0.5 million); financial support for the development of horticulture, viticulture, and hops (according to the plan, UAH 0.3 million); provision of additional financial support to family farms through the mechanism of added payment for the benefit of insured persons – members/heads of family farms of a single contribution to mandatory state social insurance (according to the plan, UAH 0.2 million) (Ministry of Agrarian Policy and Food of Ukraine, 2023). However, the volume of this type of financing is insufficient. This is confirmed by the growth rate, which is 0.88% (or +30.56 million UAH), comparing 2021 to 2014.

Deposits, as one of the sources of financial security of the enterprise, appear in the form of financial savings in bank accounts. The growth rate of this indicator is 79.75% (or + UAH 22,209.0 million) for the analysed period. Notably, the data for 2022 and the 1st half of 2023 are not available on the official websites of state bodies (the State Statistics Service of Ukraine, the Ministry of Agrarian Policy and Food of Ukraine, the Ministry of Economy of Ukraine, and the National Bank of Ukraine) for such indicators as equity capital, capital investments, and deposits.

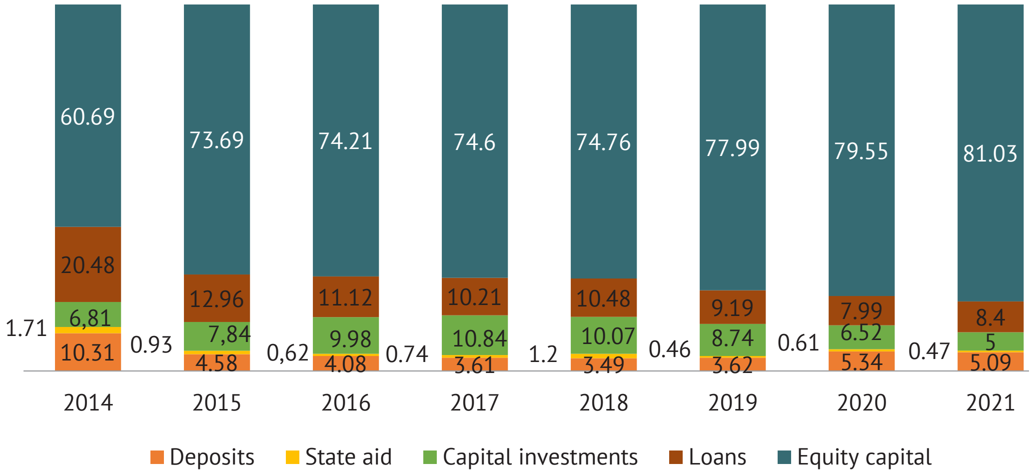

Figure 1. *Structure of sources of financial support of agricultural enterprises of Ukraine for 2014-2021, %*
Source: *State Statistics Service of Ukraine (2023); Ministry of Agrarian Policy and Food of Ukraine (2023); Ministry of Economy of Ukraine (2023); National Bank of Ukraine (2023); Verkhovna Rada of Ukraine (2023)*

Considering the obtained data, the share of equity capital in the structure of sources of financial support for 2014-2021 is 60.69% in 2014 and 81.03% in 2021. The smallest component in the structure of financial support is the share of state funding, the value of which is 1.71% in 2014 and 0.47% in 2021. Lending takes the leading place among the sources of financing, namely obtaining loans from banking structures through the issuance of bond loans and financial leasing. Therefore, the attraction of loans has the largest share in the structure of financing sources in 2014 – 20.48%, and the smallest in 2020 – 8.40%. Capital investments for the financing of agricultural enterprises in the overall structure of financing sources account for the smallest value in 2021 – 5%, and the largest in 2017 – 10.84%. The share of the volume of deposits in 2014 is 10.31%, and in 2021 – 5.09% as part of sources of financing.

To determine the dependence of the net profit (loss) of agricultural enterprises on the volume of financing sources, a correlation-regression analysis was conducted. Given that some data are not available for 2022 and the 1st half of 2023, the starting data for the correlation-regression analysis will be data from 2014 to 2021, because starting from February 2022 and until the end of the war cannot be considered standard and usual periods of operation of agricultural enterprises, since during this period agricultural enterprises are on the verge of survival, not further development (Table 3).

Table 3. *Output data of the correlation-regression analysis of the dependence of net profit (loss) on the sources of financing of agricultural enterprises of Ukraine, UAH million*

Year	Net profit (loss) (y)	Sources of funding, UAH million				
		Equity (x_1)	Loans (x_2)	Capital investments (x_3)	State aid (x_4)	Deposits (x_5)
2014	262,207.80	163,931.68	55,335.00	18,388.10	4,624.44	27,849.00
2015	451,008.40	275,303.78	48,425.00	29,309.70	3,472.60	17,111.00
2016	456,910.90	369,370.89	55,374.00	49,660.00	3,062.90	20,293.00
2017	499,974.90	436,337.64	59,706.00	63,400.70	4,326.50	21,126.00
2018	588,554.00	482,978.74	67,675.00	65,059.40	7,737.80	22,564.00
2019	671,617.70	522,778.66	61,600.00	58,555.40	3,090.57	24,260.00
2020	681,306.20	612,250.89	61,486.00	50,189.40	4,664.97	41,063.00
2021	895,298.70	796,549.72	82,600.00	49,127.38	4,665.00	50,058.00

Source: *State Statistics Service of Ukraine (2023); Ministry of Agrarian Policy and Food of Ukraine (2023); Ministry of Economy of Ukraine (2023); National Bank of Ukraine (2023); Verkhovna Rada of Ukraine (2023)*

Let us build a correlation matrix that allows determining the relationship between net profit and selected sources of financing of agricultural enterprises of Ukraine (Table 4).

Table 4. *Correlation matrix of the dependence of the net profit (loss) of enterprise activity on sources of financing*

Factor name	Net profit (loss)	Equity capital	Loans	Capital investments	State aid	Deposits
Net profit (loss)	1					
Equity capital	0.980895	1				
Credits	0.823391	0.85682	1			
Capital investments	0.551913	0.597216	0.442987	1		
State aid	0.122592	0.171105	0.420934	0.299565	1	
Deposits	0.705662	0.755108	0.769698	0.008046	0.140414	1

Source: *calculated by the authors of the study based on the following sources: State Statistics Service of Ukraine (2023); Ministry of Agrarian Policy and Food of Ukraine (2023); Ministry of Economy of Ukraine (2023); National Bank of Ukraine (2023); Verkhovna Rada of Ukraine (2023) using the statistical function "CORREL" in Microsoft Office Excel*

According to the Chaddock scale, the net profit of agricultural enterprises and sources of financing such as equity are directly dependent on each other, the correlation is too high (correlation coefficient is 0.963), loans – the correlation is high (correlation coefficient 0.747), capital investments – the correlation is significant (correlation coefficient 0.605), state aid – the correlation is weak (correlation coefficient 0.116), deposits – the correlation is moderate (correlation coefficient 0.360). This analysis confirms that the most important source of financing according to the given matrix is equity capital. Considering the fact that, as of May 5, 2023, the regions of Ukraine most affected by the war with the Russian Federation are Donetsk, Luhansk, Kherson, and Zaporizhzhia regions (the Cabinet of Ministers highlighted the most…, 2023), the results of the correlation-regression analysis for agricultural enterprises in these regions may not be reliable, since most agricultural enterprises in these territories are not operational, or have been destroyed or completely looted by the occupiers. The total number of agricultural enterprises registered in these regions is 11,542 farms. For such agricultural enterprises, there are many state and international support programs that can replace equity in financing the economic activity of the enterprise (Table 5). Table 6 shows the results of calculating the relationship between net profit and the amount of financial support of agricultural enterprises of Ukraine.

Table 5. *Support of Ukrainian agricultural enterprises under martial law*

Seq. No.	Organization	Program name	Period	Total cost	Notes
1.	USAID	Agricultural and Rural Development Program (AGRO)	for 5 years (until 2024)	USD 35 million	To agricultural producers who suffered the most from the war
		Project "Credit resources for agricultural producers"	for 7 years (until 2023)	USD 8.9 million	To credit unions, which subsequently provide loans to micro and small agricultural producers
		"Agricultural Sustainability Initiative in Ukraine"	–	USD 100 million	Aimed at the export of Ukrainian agricultural products
2.	FAO together with the Ukrainian government	Humanitarian aid from FAO – temporary facilities for grain storage	until 03.11.2022	30,000 pieces of sleeves for grain storage	Agricultural producers are given polymer sleeves for grain storage
3.	Ukrainian government	Law No. 2445-IX dated July 27, 2022	–	–	Agricultural producers who purchase goods used to ensure the storage of grain and/or oil crops are exempt from import duty taxation
		Resolution of the Cabinet of Ministers of Ukraine No. 694 dated July 8, 2009 as amended on April 12, 2022 No. 434)	–	–	Simplified procedure for registration of agricultural machinery

Table 5, Continued

Seq. No.	Organization	Program name	Period	Total cost	Notes
3.	Ukrainian government	State program "Affordable loans 5-7-9%"	–	up to UAH 60 million per agricultural producer	Agricultural producers who have movable and immovable property and need financial resources
4		"eRobota" program	12 months for project implementation	No more than UAH 7 million per project	Grant applications for the construction of one modular greenhouse with an approximate area of 2 hectares (from 1.6 to 2.4 ha) according to a standard project, or for planting gardens (up to UAH 400,000 per ha)
5	The EU together with the Ukrainian government	support programs financed by the EU	until 15.11.2022, but due to numerous applications, the program was suspended on 16.08.2022	UAH 1 billion	Micro and small agricultural producers were able to receive funds per unit of cultivated land or cattle
6	EU	subsidy program for small farmers	2023	USD 80 million	for small farmers who keep up to 100 cows or cultivate from 1 to 120 ha

Source: *Support of the agricultural sector... (2022); State support for agriculture... (2022); Support for agriculture in 2023...(2023)*

Table 6. *The results of calculating the relationship between net profit and the amount of financial support of agricultural enterprises of Ukraine*

No.	x	y	x×y	x²	y²	ỹ	$y-\tilde{y}_x$	$\frac{\lvert y-y_x \rvert}{y}$	$(y-\tilde{y}_x)^2$
1	270.13	262.21	70,830.79	72,970.22	68,754.08	-35.74	297.95	0.12	88,774.20
2	373.62	451.01	168,506.36	139,591.90	203,410.02	9.41	441.60	0.02	195,010.56
3	497.76	456.91	227,431.52	247,765.02	208,766.75	10.63	446.28	0.02	199,165.84
4	584.90	499.97	292,432.45	342,108.01	249,970.00	19.49	480.48	0.04	230,861.03
5	646.01	588.54	380,202.73	417,328.92	346,379.33	40.17	548.37	0.07	300,709.66
6	670.28	671.62	450,173.45	449,275.28	451,073.42	57.62	614.00	0.09	376,996.00
7	769.65	681.31	524,370.24	592,361.12	464,183.32	56.86	624.45	0.09	389,937.80
8	983.00	895.30	880,079.90	966,289.00	801,562.09	57.32	837.98	0.09	609,430.03
Result	4,795.35	4,506.87	2,994,027.4	3,227,689.5	2,794,099	–	–	0.54	2,390,885.12
Average value	599.42	563.36	374,253.43	403,461.18	349,262.38	–	–	–	–
	122.27	178.57	–	–	–	–	–	–	–

Source: *calculated by the authors of the study based on the following sources: State Statistics Service of Ukraine (2023); Ministry of Agrarian Policy and Food of Ukraine (2023); Ministry of Economy of Ukraine (2023); National Bank of Ukraine (2023); Verkhovna Rada of Ukraine (2023) using the statistical function "CORREL" in Microsoft Office Excel*

The parameters of the regression equation are calculated as follows:

$$b = \frac{374{,}253.43 - 599.42 \times 563.36}{403{,}461.18 - (599.42)^2} = 0.83\,;$$

$$a = \bar{y} - b\bar{x} = 563.36 - 0.83 \times 599.42 = 65.84\,.$$

The empirical equation of a simple linear regression is defined as follows:

Net profit volume $Y = a + bx = 65.84 + 0.83x$.

The quality of the econometric model is determined by indicators such as the coefficient of determination, Fisher's and Student's criteria. The quality of this model is determined as follows:

$$\sigma(y)^2 = 349{,}262.38 - 563.36^2 = 31{,}887.89;$$

$$\sigma(y) = 178.57$$

$$\sigma(x)^2 = 403{,}461.18 - 599.42^2 = 44{,}156.84;$$

$$\sigma(x) = 210.13.$$

To determine the tightness of the linear relationship, the correlation coefficient is determined as follows:

$$r_{xy} = 0.83\frac{210.13}{178.57} = 0.98;$$

Coefficient of determination:

$$r^2{}_{\mathrm{xy}} = 0.98^2 = 0.96.$$

The obtained indicators are evidence that the net profit (y) is explained by the variation of factor x – the amount of financial support by 98.0%, and by other factors by 2.0%. Ponedilchuk et al. (2021) states that "the financial security of agricultural production is based on the assessment of the financial results of business entities, which are determined by a set of financial and economic indicators. National financial policy should direct the participants of financial relations to the implementation of political, social, and economic goals, determining the aims and ways of their achievement. The state should play a key role in the innovation process and consider its impact on the financial support of research and development and act as a large and sometimes the main investor in new knowledge and technologies. This situation is explained by the fact that the branch of agriculture is specific, namely, natural conditions exert the greatest influence on obtaining a net profit. State regulation of prices, tariffs, tax rates and benefits, the demographic situation, the prices of production resources, competition, and inflation are also among the factors affecting profit. The authors of the study agree with the opinion of Byba & Kovalets (2016) that the main factor in the growth of the profit of an agricultural enterprise is the reduction of the cost of production. Therefore, it is possible to propose factors affecting the reduction of the cost of production of agricultural enterprises: increasing the technological level of production (improvement of equipment, technology, mechanization, automation of production processes, use of new, more productive varieties of agricultural crops and animal breeds); improvement of production and labour organization (development of production specialization, improvement of labour organization); change in the structure and volume of production (relative reduction in contingent costs, change in the structure of production); improving the use of natural resources, using cheaper materials, waste-free production technologies; industry and other factors.

Such a group of factors as indicators of the use and movement of fixed assets, namely agricultural machines and equipment used in the production process, considerably affects the profit of an agricultural enterprise. In the conditions of technological advance, agricultural machinery is constantly updated and modernized, technologies are created that are more productive and less energy-consuming. That is why, by investing in the modernization of fixed assets, the owners of agricultural enterprises reduce the cost of production due to more productive technologies. The uniqueness of agriculture also lies in the fact that it is dependent on such a factor as soil fertility. Although in Ukraine, 67% of land that is suitable for agriculture is covered with fertile chernozem, over the years land resources are depleted and become less productive. Hmyria *et al.* (2019) call the reasons for the loss of soil quality its improper use, environmental pollution, and depletion by certain crops, and therefore there is a need to increase soil fertility. Furthermore, in the territories that were under occupation and are still under occupation, there is a prominently dangerous level of land mining, and with the detonation of the Kakhovka HPP – the flooding of fertile lands and the loss of their quality indicators.

Therefore, the determined value of the coefficient of determination indicates the identification of one of the many influencing factors on the volume of the obtained net profit.

Average error of approximation:

$$A = \frac{i}{n}\sum_{i=1}^{n}\left|\frac{y_i - Y_x(x_i)}{y_i}\right| \times 100\% = (0.54/8) \times 100\% = 6.75\%$$

The significance of the regression equation was assessed using Fisher's F-test:

$$F = \frac{r_{\mathrm{xy}}{}^2}{1\text{-}\mathrm{r}^2{}_{xy}}(n-2) = \frac{0.96}{1-0.96} \times 6 = 144.$$

The tabular value of the criterion for degrees k=1 and k=5 is F_{tab}=6.61. Since F_{fact}=144⟩F_{tab}=6.61, the regression equation is determined to be statistically significant, and the constructed model is adequate.

Evaluation of the statistical significance of the regression parameters using the Student's t-test: the tabular value of the t-criterion for the number of degrees of freedom *df=n-2=16-2=14* i α=0.05 is t_{tab}=2.57.

Random errors of regression parameters and correlation coefficient:

$$S_{\mathrm{dep}} = \sqrt{\frac{\sum_{i=1}^{n}(Y(x_i) - Y_i(x_i))^2}{n-2}} = \sqrt{\frac{2{,}390{,}885.12}{6}} = 19.96\,.$$

The standard error of the regression coefficient *m(a)*:

$$m(a) = S_{\mathrm{gen}}\frac{(\sum x^2)^{\frac{1}{2}}}{\sigma_y n} = 631.25\frac{3{,}227{,}689.5}{162.618\times 7} = 9.91\,.$$

Standard error of parameter *b*:

$$m(b) = \frac{S_{gen}}{\sigma(x)\sqrt{n}} = \frac{9.91}{210.13\times 2.83} = 0.02\,.$$

The error of the Pearson correlation coefficient *m(r)*:

$$m(r) = \sqrt{\frac{1-r^2}{n-2}} = \sqrt{\frac{1-0.96}{6}} = 0.08\ .$$

Indicators of the factual values of the coefficients t_a, t_b, t_r:

$$t_a = a/m(a) = 65.84/19.96 = 3.29\ ;$$

$$t_b = b/m(b) = 0.83/0.02 = 0.1;$$

$$t_r = r/m(r) = 0.98/0.08 = 12.25;$$

$$t(0.05{,}5) = 2.57\,.$$

Confidence intervals for regression parameters *a*, *b*:

$$a \pm t_{tab}m(a) = 65.84 \pm 2.57 \times 9.91 = 65.84 \pm 25.46;\ \mathrm{a}\ \in\ [40.38;\ 91.3];$$

$$b \pm t_{tab}m(b) = 0.83 \pm 2.57 \times 0.1 = 0.83 \pm 0.26;\ b\ \in\ [0.57;\ 1.09]\,.$$

Parameters a, b are within the specified limits, do not take zero values, and therefore are statistically significant.

Since the model is adequate and its parameters are significant, it is possible to build a forecast of data for 2023, if it is planned to increase the volume of financial support by 20% compared to 2021 and starting from 2024 to increase this indicator by 10% in each subsequent year. Therefore, an increase in the volume of funding sources by 20% is:

$$x_p = 1.20 \times 983 = 1{,}179.6 \text{ UAH billion}$$

Therewith, the forecast value of net profit will be as follows:

$$Y_x(x_p) = Y_x(1{,}179.6) = 65.84 + 0.83 \times 1{,}179.6 = 1{,}044.91 \text{ UAH billion}$$

Since statistical data for 2023 are missing due to the lack of reports in the databases (the reporting deadline has not yet arrived), the authors of the study made a forecast for 2023. The forecast of the net profit of agricultural enterprises for 2023 with a probability of 0.96 is in the range from UAH 963.41 billion to UAH 1,081.41 billion (Fig. 1).

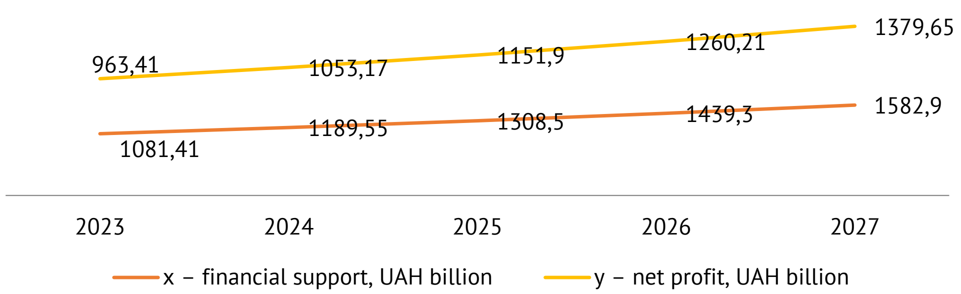

Figure 2. *Forecast value of dependence of net profit indicators and sources of financing of agrarian enterprises, UAH billion*
Source: *calculated by the authors of the study based on the following sources: State Statistics Service of Ukraine (2023); Ministry of Agrarian Policy and Food of Ukraine (2023); Ministry of Economy of Ukraine (2023); National Bank of Ukraine (2023); Verkhovna Rada of Ukraine (2023) using the statistical function "CORREL" in Microsoft Office Excel*

Determination of the accuracy of the forecast factoring in the error and the confidence interval:

$$Y_x(x_p) \pm \Delta_p$$

$$\Delta_p = t_{tab} \times m(x_p) = 2.57 \times m(x_p)$$

$$m(x_p) = S_{gen}\left(1 + 1/n + \frac{(x_p-\bar{x})^2}{n\sigma^2}\right)^{\frac{1}{2}} = 19{,}96 \times \sqrt{1+\frac{1}{8}+\frac{(1{,}179.6-599.42)^2}{8\times 44{,}154.62}} = 28.77\,;$$

$$\Delta p = 2.57 \times 28.77 = 73.9.$$

Confidence interval of the forecast:

$$Yx(xp) \pm \Delta p = 1{,}044.91 \pm 73.9\,.$$

According to the obtained results, the research of the results of other scientists becomes increasingly necessary. Thus, Adewale *et al.* (2022) conducted research on the impact of bank lending on the volume of agricultural products grown by agricultural producers in Nigeria. As a result, the researchers found that agricultural bank credit (β=0.667173, t=5.961095 & P<0.05) has a significant positive effect on agricultural production and bank lending has a significant positive effect on agricultural productivity in Nigeria. Which, in turn, is confirmed by the results obtained in the present study, namely: a high correlation between the net profit of agricultural enterprises and loans. A study by Magazzino & Santeramo (2023) also confirms the results obtained, as the effect of the credit-volume-productivity relationship (as highlighted by the statistical significance of the relationships between the variables) is stronger for developing countries and OECD countries, and weaker for less developed countries and NFID countries.

Furthermore, it is possible to partially agree with the results of Zakaria *et al.* (2019), who found a non-linear

U-shaped relationship between financial development and productivity in the agricultural sector in five Asian countries. The authors of the study do not fully agree with the opinion of Olowu *et al.* (2019), as their study states that "financial development and agricultural value added reduce employment in 11 African countries", while the study by Farooq *et al.* (2021) emphasizes the unidirectional causality between access to credit and the decline in agricultural production. Therefore, during the war, Ukrainian agricultural producers should pay more attention to bank lending programs, state aid, and international grant programs, rather than relying on equity capital.

CONCLUSIONS

Based on the conducted correlation-regression analysis, it was proved that equity, loans, capital investments, state aid, and deposits have a sufficient influence on the volume of financial support. Equity capital is the main source of financing the activities of enterprises, but its volume is insufficient to fully ensure the financing of entrepreneurial activities. Therefore, the authors of this study used other types of financing for the analysis. A correlation matrix of the dependence of net income on sources of financial support was also formed, which shows the correlation coefficient of equity – 0.981 (the correlation is too high), the correlation coefficient of loans – 0.823 (the correlation is high), the correlation coefficient of capital investments – 0.552 (the correlation is noticeable), the correlation coefficient of state aid – 0.122 (the correlation is weak), the correlation coefficient of deposits – 0.705 (the correlation is moderate). During the war, agricultural producers should pay attention to bank loans, as the Ukrainian government has developed and implemented particularly good lending programs for agricultural enterprises; furthermore, one can also take advantage of international aid from various international organizations.

The correlation coefficient between the amount of net profit received and the amount of financial support for agricultural enterprises is 0.94, which is evidence of a close connection between the selected data. The initial statistical sample is represented by annual data for 2014-2021. As a result of data processing, an empirical simple linear regression equation was constructed. Having carried out some calculations regarding the significance of all parameters of the model, it was proved that the built model is adequate, and a forecast can be made based on this model.

In the perspective of further research, it is necessary to substantiate the legal conditions for attracting the main sources of financing, to identify their advantages and disadvantages for entrepreneurial activity. Since the issue of financial support needs a detailed solution, the research of the main sources of financing should be expanded, distinguishing them from each other in more detail. Furthermore, it is necessary to focus on the following understanding, for various sources of financing to work effectively in a difficult time for the entire country, it is necessary to develop an effective integrated model of financing agricultural enterprises that would factor in the specifics of each region (especially during a full-scale war in the country, when the territories are still occupied, or those that were recently de-occupied) and an individual business entity (determining its needs).

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Фінансування українських сільськогосподарських підприємств: кореляційно-регресійний аналіз

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Анотація. Актуальність даного дослідження зумовлена тим, що фінансування є ключовим елементом ефективної господарської діяльності аграрних підприємств та галузі в цілому, її продовольчої безпеки та відновлення роботи сільськогосподарських підприємств особливо у період повномасштабної війни та в після воєнний період. Метою статті було дослідження взаємозв'язку між отриманим чистим прибутком (збитком) та джерелами фінансування підприємств сільського господарства України за період 2014- І півріччя 2023.У дослідженні використано: загальнонаукові методи (аналіз динаміки обсягів джерел фінансування (власний капітал, кредити, капітальні інвестиції, державна допомога та депозити), аналіз чистого прибутку діяльності сільськогосподарських підприємств, формування структури джерел фінансування, визначення темпів приросту показників) та специфічні методи дослідження (кореляційний аналіз та метод багатофакторної регресії). Автори дослідження запропонували використання методу кореляційно-регресійного аналізу з подальшим прогнозуванням показників, використовуючи таблиці Чеддока, критерії Фішера та Ст'юдента. При проведенні кореляційно-регресійного аналізу встановлено, що визначну частку в процесі фінансового забезпечення становить власний капітал, а найменшу частку становить державна допомога. Але в зв'язку з повномасштабною війною в країні та обмеженими власними ресурсами, автори дослідження запропонували більш ширше залучати банківські кредити та державну допомогу у власну господарську діяльність. Набули подальшого розвитку проведення кореляційно-регресійного аналізу виявлення залежності фінансового результату діяльності аграрних підприємств (чистого прибутку (збитку)) та їх джерел фінансування за 2014-2021 рр., розроблено рівняння регресії, здійснено прогнозу можливого чистого прибутку (збитку) діяльності аграрних підприємств на майбутній період 2023-2027 рр. Практична цінність отриманих результатів проведеного дослідження полягає в тому, що дані результати можуть бути використані у господарській діяльності аграрного підприємства України та під час розробки державними органами Стратегії розвитку аграрного сектору та їх програм підтримки

Ключові слова: чистий прибуток (збиток); джерела фінансування; аграрне підприємство; сільське господарство; фактори впливу; кореляція; власні кошти; кредит; державна підтримка

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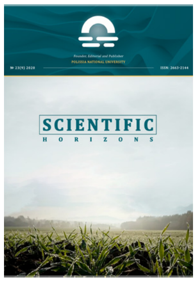

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Ecological and economic determinants of energy efficiency in European countries

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Abstract. Since economic development is often associated with an increase in greenhouse gas emissions, it is especially important to answer the question of whether it is possible to achieve sustainable economic development and improve energy efficiency at the same time, which implies a reduction in greenhouse gas emissions. The purpose of this study was to build models that can help find the environmental and economic determinants of energy efficiency in European countries. An ecological and economic determinants of energy efficiency indicators of 38 European countries were found based on panel regression models. The models were built based on statistical data characterizing the level of their economic development and consumption of diverse types of energy for 1995-2021. To obtain the necessary approximations of energy efficiency indicators, one of three types of models was used: the random effects method, the fixed effects method, or the pooled model. For this, appropriate statistical

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tests were used. As a result, it was found that the factors that have a statistically significant impact on the energy intensity of GDP in European countries include the intensity of carbon dioxide emissions, unemployment rate, primary energy consumption per capita, and gross electricity production per capita. The findings showed that determinants of primary energy consumption were domestic consumption of solid fossil fuels per capita, domestic natural gas consumption per capita, and primary energy consumption per capita. The study results generally confirm the modern-day thesis that economic development can be achieved while reducing greenhouse gas emissions. The monitoring of factors that have a statistically significant impact on the indicators under consideration can become an essential element of the modern energy efficiency management system of the national economies of European countries

Keywords: Energy intensity; economic growth; fossil fuel; primary energy consumption; GDP; electricity consumption; gas consumption; CO_2 emission

INTRODUCTION

The world is facing a growing risk of climate change caused by increased greenhouse gas emissions, which poses new challenges for governments of all countries. Economic development is usually associated with an increase in greenhouse gas emissions. Therefore, the question arises whether it is possible to achieve sustainable economic development and reduce greenhouse gas emissions at the same time. Besides, the EU's planned reduction of greenhouse gas emissions by at least 55% by 2030 will require significant additional investments, decarbonization of electricity generation, industry and transport, and energy efficiency in buildings. The identification of macroeconomic factors that significantly affect the energy efficiency of the European economies will allow national governments and regulators to develop effective mechanisms to achieve these goals.

Many scientific papers have covered this issue. Thus, Zioło *et al.* (2020) analysed the factors affecting the energy efficiency of the countries of the Organization for Economic Cooperation and Development (OECD). The results suggest a slight upward trend in the overall TFEE in OECD countries over the period under study, but developed OECD countries have higher levels than other OECD countries. Access to credit and the inflow of foreign direct investment that new energy-saving technologies bring can improve energy efficiency. The analysis showed that urbanization is not statistically significant for TFEE. Furthermore, the results show that increased energy efficiency leads to a reduction in carbon dioxide emissions.

The research of Klyvienė *et al.* (2020) is devoted to establishing the relationship between indicators that affect the green economic growth of the Eurozone countries, investigating the possible impact of environmental policy on macroeconomic variables such as GDP, investment, employment, and trade. Klyvienė *et al.* (2020) used the PVAR econometric model to estimate an influence of energy consumption, CO_2 emissions, and some another macroeconomic indicators on GDP growth in 19 Eurozone countries for 2000-2016. A short-term adverse impact of ecology-oriented economic policies on business activity was indicated. This is consistent with the traditional view that green economic policies can create added costs at all levels of the economic system. However, in the long term, the consequences of the implementation of environmental policy become positive.

Pimonenko *et al.* (2021) analysed 1,335 studies on economic stability and 1,811 studies on environmental protection. The results obtained showed a close correlation between the factors of energy efficiency and business efficiency, economic and macroeconomic stability. Considering this, the authors made a forecast for the development of energy efficiency. In this study, primary energy consumption was singled out as the basis for the energy efficiency forecast. The study used data from European countries (EU27) for 1991-2018.

Nobel Prize Winner S. Kuznets (1955) managed to prove the existence of a relationship between the level of human well-being and the state of the environment in the form of an inverse U-curve. The country's economic growth entails an increase in pollutant emissions, but after reaching a certain level of its development or the so-called extreme, the state of the environment gradually begins to improve. Such a dependence in the economic literature is called the ecological-economic Kuznets curve. Cherkashina (2020), using correlation-regression analysis, investigated the features of the ecological-economic Kuznets curve in the countries of the Visegrad group. The analysis showed that the ecological-economic Kuznets curve for the countries of the Visegrad group has the form of an N-shaped curve. This means that an increase in GDP per capita contributes to a decrease in CO_2 emissions, but not in the proportion in which people's well-being increases. The IMF, using statistics of 127 countries for two centuries, found evidence for an environmental-economic Kuznets curve, with an initial decline in energy demand due to low per capita income, followed by acceleration and then high-income saturation phases. It was confirmed that there is a downward trend in energy demand globally by about 1.2% per year, thus helping to stabilize energy demand in high-income countries.

Cibinskiene *et al.* (2020) and Laurens *et al.* (2017) investigated the issue of determining the key determinants of energy efficiency at different levels (not only the macro level). Zubeltzu-Jaka *et al.* (2018) and Pacheco *et al.* (2017) analysed the cause-and-effect relationships between indicators of economic development of countries and energy efficiency.

Thus, considering the above, the purpose of this study was to investigate the correlation between economic development and energy efficiency indicators in European countries based on the search for factors that significantly affect energy efficiency.

LITERATURE REVIEW

The correlation between energy efficiency and the level of economic development of the country is the subject of constant debate, and there is no consensus on this issue yet. Özcan & Özkan (2018) explored causal relationships between energy consumption, economic performance, and energy intensity in the G20 countries. The analysis suggested that these three variables tend to change in the same way in the long run. Furthermore, Granger causality tests show that there is a unidirectional causality that goes from energy intensity to economic performance, but not the other way around.

G. Bersalli *et al.* (2020) investigated the efficiency of the government policy in the field of renewable energy sources based on panel data from 20 Latin American and 30 European countries over 20 years. They confirm the effectiveness of such policies: the findings proved a positive and statistically significant impact on investment in renewable energy, being the main factors in all regions. It was also shown that tax incentives alone are insufficient to ensure the continued deployment of renewable energy technologies.

Kvach *et al.* (2021) pointed out the extremely high energy intensity of the Ukrainian economy and noted the need for "transformation of the electricity market by introducing market pricing principles that are uniform for all consumers of energy resources, energy efficient and energy-saving use and consumption of energy resources based on modern innovative technologies".

Segarra-Blasco & Jové-Llopis (2019) analysed the factors contributing to energy efficiency (EE) and the use of renewable energy (RE) sources by small and medium-sized enterprises in European countries. It was suggested that there is a corresponding complementarity between EE and RE practices and other methods of efficient use of resources. Furthermore, EE strategies mainly focus on cost savings and regulation, while RE strategies rely more on public support and environmental knowledge. Šumakaris *et al.* (2021) performed a systematic review of the literature devoted to the innovations in the identification of the efficiency determinants in the field of energy saving. According to the received data, the following determinants of energy-efficient innovations were identified at the micro level: cost savings; previous experience; technological capabilities; green tariffs; innovative opportunities; organizational innovations; financial resources; investments in tangible assets. Therewith, such determinants as the competitive environment, pressure from customers and suppliers, external cooperation in the field of knowledge, social pressure, and voluntary agreements are highlighted at the meso level. At the macro level, the determinants included state subsidies, current or future regulation. Ari *et al.* (2022), Sterlacchini (2020) and Costa-Campi *et al.* (2015) analysed the ways in which innovative technologies are introduced into the energy sector and their impact on energy efficiency factors.

MATERIALS AND METHODS

To find the ecological and economic determinants of energy efficiency in the article, the authors of this study used panel regression models, which were built using indicators of 38 European countries describing energy efficiency and macroeconomic indicators for 1995-2021. For this, statistical resources such as ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook 2022 were used. To determine the level of energy efficiency of the national economies of European countries, authors used the values of primary energy intensity EI, carbon dioxide emission intensity CO_2_GDP, gross electricity production per capita EL_CAP, electricity available for final consumption per capita ELSUP_CAP, domestic consumption of natural gas, domestic consumption of solid fossil fuel (per capita) SOLID_CAP, primary energy consumption CON_ENER_EU, primary energy consumption per capita CON_ENER_EU_PC and gross available energy per capita CON_ENER_TOTAL_PC.

The level of development of the national economies of European countries was determined based on the following indicators: the ratio of exports of goods and services to GDP EXP_GDP, the unemployment rate UNEMP, GDP per capita GDPCAP, the ratio of direct foreign investments (net inflows) to GDP FDGDP, annual growth rates of GDP GDP_GROW, annual percentage growth rate of GDP per capita GDP_GROW_PC (Table 1).

Table 1. *Variables of the models*

EI	Energy intensity level of primary energy (MJ/$2017 PPP GDP)
CO2_GDP	Intensity of CO_2 emissions (kg per PPP $ of GDP)

Table 1, Continued

EXP_GDP	Exports of goods and services (% of GDP)
EL_CAP	Gross electricity production per capita (Thousand tonnes of oil equivalent)
UNEMP	Unemployment, total (% of total labour force) (modelled ILO estimate)
GDPCAP	GDP per capita (dollars USA)
CON_ENER_EU	Consumption of primary energy (Europe 2020-2030) (Million tonnes of oil equivalent)
CON_ENER_EU_PC	Consumption of primary energy (Europe 2020-2030) per capita (Million tonnes of oil equivalent)
CON_ENER_TOTAL_PC	Gross available energy per capita (kgoe)
ELSUP_CAP	Electricity, available for final consumption (Gigawatt-hour per capita)
FDGDP	Foreign direct investment, net inflows (% of GDP)
GASCAP	Inland consumption of gas – calculated (Terajoule per capita)
GDP_GROW	GDP growth (annual %)
GDP_GROW_PC	Annual percentage growth rate of GDP per capita based on constant local currency.
SOLID_CAP	Solid fossil fuels inland consumption (thousand tonnes per capita)

Source: *compiled by the authors of this study*

An identification of energy efficiency determinants in European countries will then be based on the one of three models: a pooled data model, a panel regression model with fixed or variable effects. A panel regression model that factors in the fixed effects method can be represented as follows:

$$Y_{it} = \alpha_i + \beta_k X_{k,it} + \varepsilon_{it}\,, \quad (1)$$

where i is the country, t is the time ($2000 \leqslant t \leqslant 2021$); α_i (i=1...38) is the unknown constant of the panel regression model; Y_{it} is the dependent variables; $X_{k,it}$ is the independent variables; β_k is the panel regression model parameters; ε_{it} is the error.

The model that factors in the random effects will look as follows:

$$Y_{it} = \alpha + \beta_k X_{k,it} + u_{it} + \varepsilon_{it}\,, \quad (2)$$

where α is the unknown constant of the panel regression model; u_{it} is the individual influence of the i^{th} country, which is called a random effect, similar to random errors, and is assumed to have a zero mean.

The pooled model of panel data or cross-sectional regression (pooled model) will look as follows:

$$Y = \alpha + \beta_k X_k + \varepsilon\,. \quad (3)$$

To create econometric models and conduct respective statistical tests, the authors of this study used the Eviews program. To select the variables of the regression model, authors used a stepwise regression method, in which factors are included in the model one by one until it becomes satisfactory. The order of inclusion of the factor was determined based on the correlation coefficient of the independent and dependent variables.

Having obtained the respective models with random effects, the Hausman test was implemented to determine the most appropriate method for constructing panel regression models – based on random effect (RE) or fixed effect (FE). To determine the priority between the panel model with fixed effects and the pool model with a common constant, the Wald test was used, which checks the non-zero regression coefficients.

RESULTS AND DISCUSSION

At the turn of the 20th century, the demand for energy increased sharply, caused by an increase in the rate of economic growth. From 1900 to 1950, with the spread of electric lighting and the development of all modes of transport, the demand for primary energy almost doubled. Economic growth also picked up sharply, prompting a shift from biomass to fossil fuels as the main source of primary energy. For example, in the United States, GDP per capita in 1950 was more than double what it was in 1900. The use of oil (in addition to coal) in the 20th century dramatically increased production and consumption. Fossil fuels lose from 40% to 70% of their energy when converted into electrical or mechanical energy, which is a lot, but not compared to almost complete losses when burning wood or other biomass. Although modern economies need increased energy resources, McKinsey & Company experts predict that the demand for primary energy by 2030 will slow down primarily due to the rapid spread of renewable energy sources (Fig. 1).

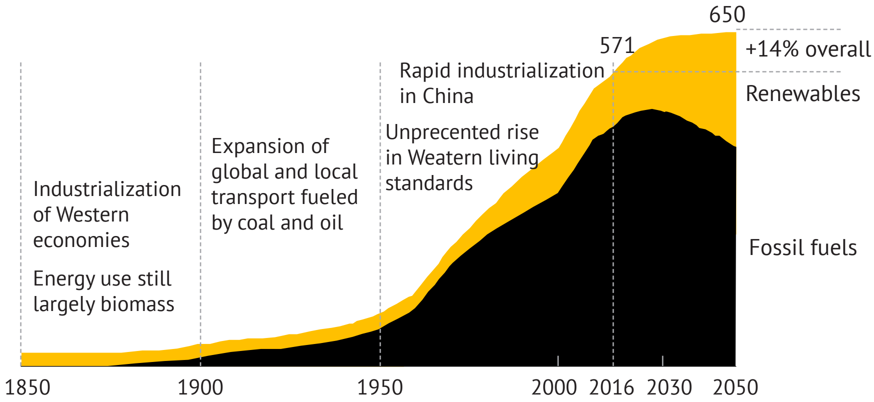

Figure 1. *Global primary energy demand, millions terajoules*

***Source**: (Sharma et al., 2019)*

Increasing the level of energy efficiency is a necessary condition for the complete decarbonization of EU economy and achieving independence from Russian fossil fuels. The close relationship between macroeconomic stability and energy efficiency has been more clearly seen recently at the international level, especially after the beginning of Russia's full-scale aggression against Ukraine. Fossil fuel prices caused the biggest inflationary shock in Europe since Second World War, outpacing the oil crisis of the 1970s. In September 2022, the price of energy was 40.8% higher than a year earlier (Fig. 2).

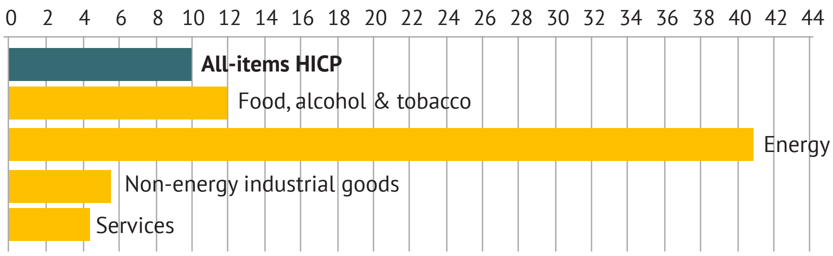

Figure 2. *Euro area annual inflation, September 2022, %*

***Source**: (Eurostat, 2022)*

Authors first estimate the level of primary energy intensity, which is the ratio between primary energy input and gross domestic product measured at purchasing power parity. Overall, total energy consumption per unit of GDP in the world declined much less in 2021 than in the previous few years (averaging -1.5% per year from 2000 to 2020). All this significantly complicates the task of increasing the average temperature by no more than 2°C. To achieve these indicators, a reduction of 3.5% per year should be observed. Experts note that such a slowdown is mainly due to an increase in energy consumption in 2021 (Enerdata, 2022).

As a result, a panel regression model was obtained to assess the energy intensity of EI (see Table 3). It is based on the random effect, since the results of the Houseman test showed that there is no reason to reject the hypothesis about the advisability of using a random effect (Table 2).

Table 2. *Results of the Hausman test for the EI model*

Test Summary	Chi-Sq. statistic	Prob.
Cross-section random	9.356953	0.0528

Source: *compiled by the authors of this study using Eviews based on data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

Table 3. *Model for estimating of the energy intensity EI*

Dependent Variable: EI				
Sample: 1995-2021		**Periods included: 27**		
Cross-sections included: 38		**Total panel (unbalanced) observations: 1026**		
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	0.670808	0.175068	3.831692	0.0001

Table 3, Continued

Dependent Variable: EI				
Sample: 1995-2021		Periods included: 27		
Cross-sections included: 38		Total panel (unbalanced) observations: 1026		
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
CO2_GDP	5.128102	0.114631	44.73559	0.0000
UNEMP	0.044043	0.003949	11.15197	0.0000
CON_ENER_TOTAL_PC	0.000410	4.12E-05	9.949097	0.0000
EL_CAP	584.2782	133.0672	4.390851	0.0000
R-squared	0.840511	F-statistic		998.6714
Adjusted R-squared	0.839670	Prob(F-statistic)		0.000000

Source: *compiled by the authors of this study using Eviews based on data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

Of all macroeconomic indicators, only the unemployment rate has a statistically significant impact on the energy intensity of GDP, and its growth entails an increase in energy intensity. This can be explained by the fact that more developed economies naturally have lower unemployment rates and higher levels of energy efficiency. Carbon dioxide emissions CO2_GDP, gross available energy per capita CON_ENER_TOTAL_PC and gross electricity production per capita EL_CAP have a positive effect on the energy intensity of GDP in European countries.

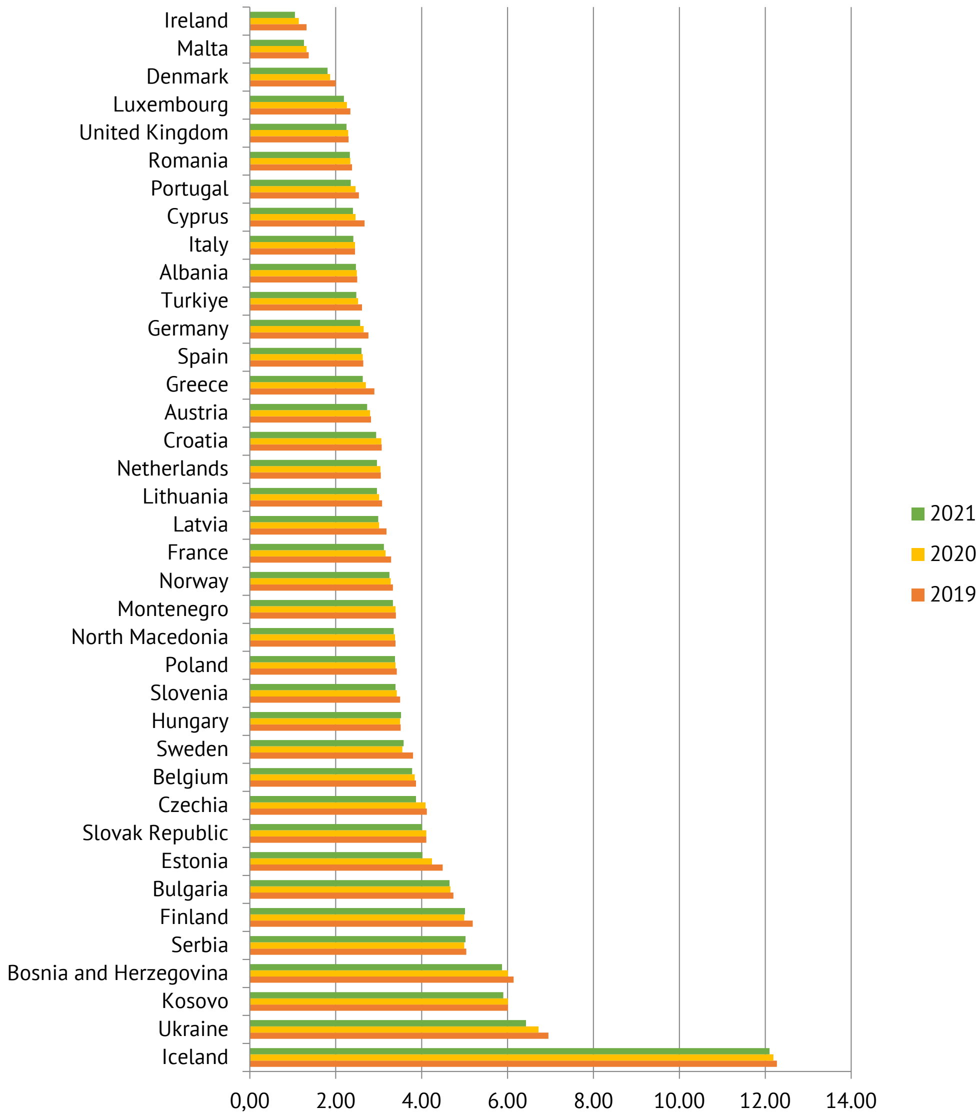

Figure 3. *Energy intensity of the GDP of European countries (MJ/$2017 PPP GDP)*
Source: *compiled by the authors of this study based on World Bank statistics (n.d.)*

According to the results of the Hausman test (Table 4), the use of panel regression with fixed effects is better for estimating carbon dioxide emissions CO2_GDP. Carbon dioxide emissions CO2_GDP are associated with the combustion of fossil fuels and the production of cement. These include carbon dioxide generated during the consumption of solid, liquid, and gaseous fuels and the combustion of associated gas.

Table 4. *Results of the Hausman test for the CO2_GDP model*

Test Summary	Chi-Sq. Statistic	Prob.
Cross-section random	95.595207	0.0000

Source: *compiled by the authors of this study using Eviews based on data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

As a result, model was obtained with EI, GDPCAP, ELSUP_CAP and EXP_GDP as explanatory variables (Table 5). Interestingly, as the share of electricity available for final consumption per capita increases, carbon dioxide emissions per capita will decrease. Considering the current trends in electricity generation in Western Europe, which consist in the almost complete abandonment of the use of coal in the energy sector, primarily for environmental reasons, such a correlation between carbon dioxide emissions and electricity supply is expected.

Table 5. *Model for estimating of CO2_GDP*

Dependent Variable: CO2_GDP				
Sample: 1995-2021			Periods included: 27	
Cross-sections included: 38			Total panel (unbalanced) observations: 1026	
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	-0.445314	0.027107	-16.42829	0.0000
EI	0.106754	0.003222	33.12883	0.0000
GDPCAP	-1.31E-06	2.53E-07	-5.178391	0.0000
ELSUP_CAP	-17.47378	1.055253	-16.55886	0.0000
EXP_GDP	-0.001883	0.000258	-7.308944	0.0000
Dummy variables				
Belgium	0.540954		Austria	0.584837
Bulgaria	0.397835		Poland	0.530677
Czech Republic	0.523956		Portugal	0.499157
Denmark	0.641431		Romania	0.470945
Germany	0.563469		Slovenia	0.507424
Estonia	0.634958		Slovak Republic	0.387735
Ireland	0.778473		Finland	0.483719
Greece	0.557533		Sweden	0.459980
Spain	0.500420		Iceland	0.163991
France	0.403355		Norway	0.750855
Croatia	0.445059		Great Britain	0.520356
Italy	0.528905		Montenegro	0.434695
Cyprus	0.619616		North Macedonia	0.535257
Latvia	0.396583		Albania	0.379178
Lithuania	0.357618		Serbia	0.463215
Luxembourg	1.029918		Turkey	0.479732
Hungary	0.455413		Bosnia and Herzegovina	0.369065
Malta	0.764837		Kosovo	0.473817
Netherlands	0.582753		Ukraine	base
R-squared	0.902638		Prob(F-statistic)	0.000000
Adj. R-squared	0.897403			

Source: *compiled by the authors of this study using Eviews based on data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

Renewable energy technologies for electricity generation are the main tool for the decarbonization of the energy sector around the world. Government policies to promote their spread have been carried out in developed countries since 1980, and since the 2000s, increasingly more developing countries have begun to implement an analogous strategy in the energy sector. European countries are building their energy policies to completely phase out coal in electricity generation within this decade. Furthermore, as Figures 4 and 5 suggest, there is a clear upward trend in the share of electricity in total final energy consumption in Europe and in the world as a whole, and an increase in the share of wind and solar power plants in electricity generation. Because of this, an increase in the share of electricity available for final consumption naturally leads to a decrease in carbon dioxide emissions, which is consistent with the resulting model.

By 2030, the European Parliament has planned to increase the use of renewable energy sources and dramatically reduce energy consumption. By 2030, the Renewable Energy Directive (RED) aims to increase the share of renewable energy sources in total energy consumption in the EU to 45%. An analogous goal is also planned by the European Commission in a special RepowerEU package. The Fit for 55 package also includes a revision of the Energy Efficiency Directive (EED) to achieve a 55% greenhouse gas emission target. Today, the EED directive sets the level of EU energy saving that the EU must achieve by 2030 to reach the goal of 32.5% energy efficiency improvement (Parliament backs boost..., 2022).

The results of the Wald test for zero coefficients of dummy variables for the resulting model showed the feasibility of using a fixed effects model as opposed to a model based on a pool of data (Fig. 4, 5).

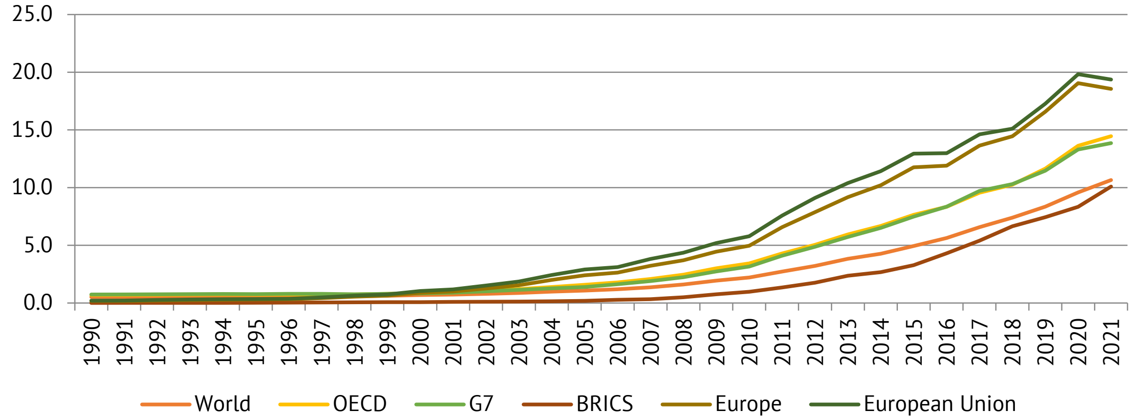

Figure 4. *Share of wind and solar power plants in electricity generation (%)*
Source*: compiled by the authors of this study based on World Energy & Climate Statistics – Yearbook (2022)*

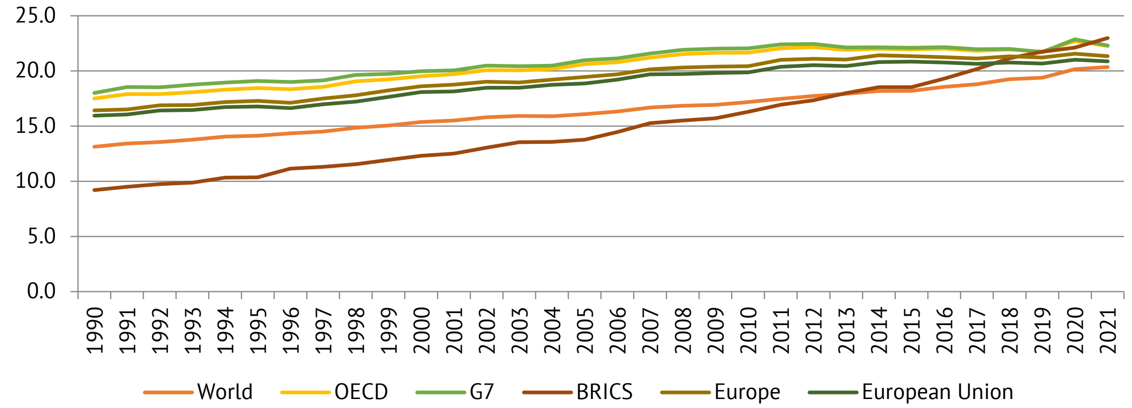

Figure 5. *The share of electricity in the total final energy consumption (%)*
Source*: compiled by the authors of this study based on World Energy & Climate Statistics – Yearbook (2022)*

Thus, according to the constructed panel regression model, the macroeconomic determinants of the carbon dioxide emissions intensity are GDP per capita and the share of exports in GDP. The greater the value of both these factors, the higher the level of economic development of the country, and, consequently, the higher energy efficiency, which is a characteristic feature of the modern eco-oriented economy of European countries. This is consistent with the fact that GDP per capita and the share of exports in GDP negatively affect the intensity of carbon dioxide emissions. Figures 6, 7 show the evolution of these indicators in the EU in 2021. Of the 38 European countries analysed in this study, Luxembourg had the highest level of GDP per capita in 2021 – $133,590.16, while Ukraine had the lowest value – $4,568.91.

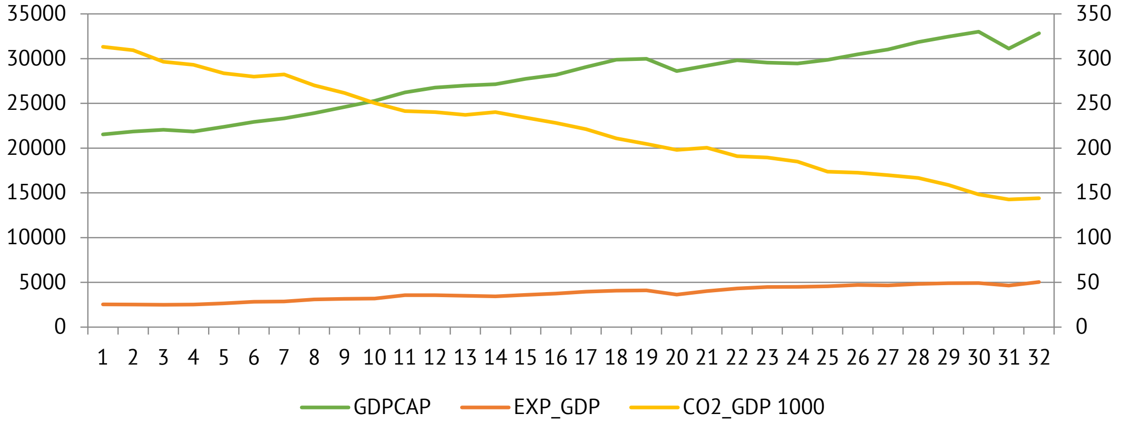

Figure 6. *Dynamics of changes in GDP per capita, the share of exports in GDP and an intensity of carbon dioxide emissions in the EU in 2021*

Source*: compiled by the authors of this study based on World Energy & Climate Statistics – Yearbook (2022)*

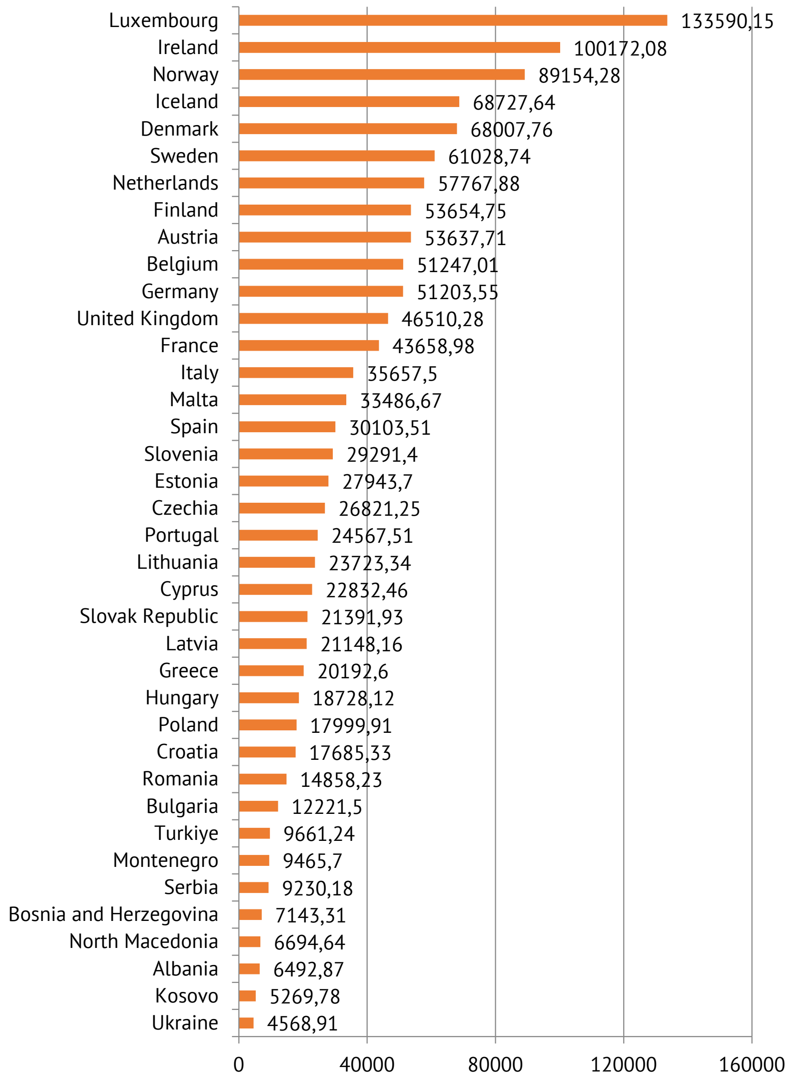

Figure 7. *GDP per capita in 2021 (USD)*

Source*: compiled by the authors of this study*

As is known, the European Union has pledged to reduce energy consumption by 20% by 2020 compared to the baseline forecasts. In other words, the EU plans to consume just over 1,483 million tonnes of oil equivalent in primary energy and just over 1,086 million tonnes in final energy in 2020. By 2030, a reduction of at least 32.5% is planned (Saheb *et al.*, 2018).

The maximum consumption of primary energy in the EU occurred in 2006. In 2021, consumption was 18.1% below the peak value. The distance from the actual level of primary energy consumption and the target level for 2030 was 34% in 2006. In 2020, the distance decreased to 9.5% and increased to 16.0% in 2021 (Fig. 8).

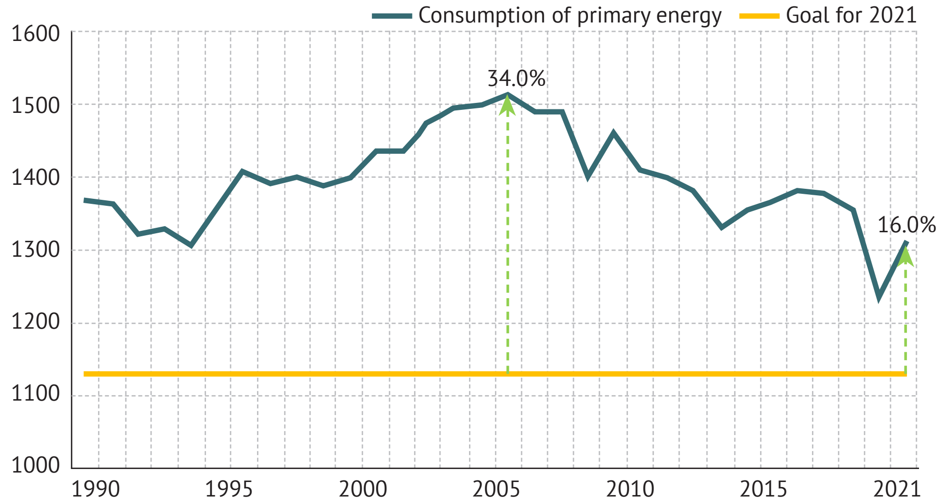

Figure 8. *Primary energy consumption in the EU (distance to 2030), million toe*
Source*: compiled by the authors of this study based on ESMS Indicator Profile*

The CON_ENER_EU primary energy consumption estimation model was obtained using the fixed effects method, since the results of the Hausman and Wald tests showed the advantage of FEM models over random effects and data pool models (Table 6). Domestic consumption of solid fossil fuels per capita, domestic consumption of natural gas per capita and available gross energy per capita were statistically significant (Table 7). Moreover, all variables have a positive effect on the resulting indicator. Macroeconomic characteristics were not statistically significant when assessing CON_ENER_EU.

Table 6. *Results of the Hausman test for CON_ENER_EU model*

Test Summary	Chi-Sq. Statistic	Prob.
Cross-section random	98.785112	0.0000

Source: *compiled by the authors of this study using Eviews based on data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

Table 7. *Model for estimating of CON_ENER_EU*

Dependent Variable: CON_ENER_EU				
Sample: 1995-2021		Periods included: 27		
Cross-sections included: 38		Total panel (unbalanced) observations: 1026		
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	31.00476	1.738194	17.83734	0.0000
SOLID_CAP	3611.730	612.7344	5.894446	0.0000
GASCAP	217.7291	40.91441	5.321575	0.0000
CON_ENER_EU_PC	0.001715	0.000454	3.779405	0.0002
Dummy variables				
Belgium	38.45966		Austria	28.35773
Bulgaria	9.371768		Poland	86.95388
Czech Republic	23.31707		Portugal	28.49187

Table 7, Continued

Dependent Variable: CON_ENER_EU				
Sample: 1995-2021		**Periods included: 27**		
Cross-sections included: 38		**Total panel (unbalanced) observations: 1026**		
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
Denmark	17.64596	Romania		35.06615
Germany	293.8608	Slovenia		4.204755
Estonia	9.026506	Slovak Republic		11.11043
Ireland	13.19174	Finland		27.23074
Greece	16.26054	Sweden		50.23856
Spain	124.7226	Iceland		-8.230735
France	246.4671	Norway		20.34210
Croatia	13.68862	Great Britain		196.7502
Italy	158.7604	Montenegro		4.597591
Cyprus	11.97060	North Macedonia		3.120500
Latvia	9.924953	Albania		16.02440
Lithuania	10.10217	Serbia		4.436275
Luxembourg	-13.74459	Turkey		108.3585
Hungary	21.20021	Bosnia and Herzegovina		1.913920
Malta	6.526938	Kosovo		2.547697
Netherlands	48.95593	Ukraine		base
R-squared	0.991918	Prob (F-statistic)		0.000000
Adjusted R-squared	0.991491			

Source: *compiled by the authors of this study using Eviews based on data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

The analysis showed that the primary energy consumption per capita CON_ENER_EU_PC is better approximated by FEM models, since the results of the Hausman test indicated that the probability of accepting the null hypothesis about the appropriateness of using REM models is close to zero (Table 8). Furthermore, the Wald test for zero coefficients for dummy variables confirmed the feasibility of using the FEM model as opposed to the data pool model.

The macroeconomic determinants of primary energy consumption per capita in European countries were the unemployment rate and the share of exports in GDP. An increase in both these indicators will reduce primary energy consumption per capita in European countries, while an increase in domestic consumption of natural gas per capita and available electricity for final consumption per capita will lead to an increase in primary energy consumption per capita (Table 9).

Table 8. *Results of the Hausman test for CON_ENER_EU_PC model*

Test Summary	Chi-Sq. Statistic	Prob.
Cross-section random	77.65911	0.0000

Source: *compiled by the authors of this study using Eviews based on the base of data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

Table 9. *Model for estimating of CON_ENER_EU_PC*

DependentVariable: CON_ENER_EU_PC				
Sample: 1995-2021			**Periods included: 27**	
Cross-sections included: 38			**Total panel (unbalanced) observations: 1026**	
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	1363.705	107.3005	12.70921	0.0000
CON_ENER_EU	8.900696	1.363705	6.526851	0.0000
GASCAP	23965.38	1587.116	15.09995	0.0000

Table 9, Continued

DependentVariable: CON_ENER_EU_PC				
Sample: 1995-2021			Periods included: 27	
Cross-sections included: 38			Total panel (unbalanced) observations: 1026	
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
UNEMP	-14.49307	2.943106	-4.924412	0.0000
EXP_GDP	-4.070700	1.033568	-3.938492	0.0001
ELSUP_CAP	240955.6	4789.824	50.30572	0.0000
Dummy variables				
Belgium	1146.091		Austria	-187.1280
Bulgaria	42.51561		Poland	-554.2341
Czech Republic	641.3436		Portugal	-431.5182
Denmark	90.66606		Romania	-894.3206
Germany	-2380.800		Slovenia	439.5151
Estonia	1370.362		Slovak Republic	63.79852
Ireland	-54.64530		Finland	806.4769
Greece	-68.66128		Sweden	417.6613
Spain	-1043.346		Iceland	4265.916
France	-1586.065		Norway	-2200.965
Croatia	-482.1874		Great Britain	-2251.594
Italy	-2085.157		Montenegro	-485.0338
Cyprus	1453.453		North Macedonia	-280.4422
Latvia	-154.0050		Albania	-803.9735
Lithuania	80.01286		Serbia	-224.3687
Luxembourg	2653.527		Turkey	-1631.744
Hungary	-536.5389		Bosnia and Herzegovina	82.32486
Malta	2903.606		Kosovo	-485.0338
Netherlands	109.2699		Ukraine	base
R-squared	0.991091		Prob(F-statistic)	0.000000
Adjusted R-squared	0.990596			

Source: *compiled by the authors of this study using Eviews based on data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

The parameters of the model for estimating gross available energy per capita CON_ENER_TOTAL_PC are presented in Table 11. In this case, the Hausman test (Table 10) confirmed the absence of grounds for rejecting the null hypothesis, and therefore, the REM panel regression model was chosen. The unemployment rate has a negative impact on this indicator, as in the previous model. This can be substantiated by the fact that an increase in the unemployment rate, which also signals a decrease in the level of economic development of the country, will lead to a potential decrease in the total energy consumption per capita in the country. This relationship between the UNEMP unemployment rate and total energy consumption per capita can be clearly observed in Figure 9. Consumption of gas (Fig. 9) and electricity available for final consumption per capita in highly developed countries is generally somewhat higher compared to other European countries, which is also reflected in the model.

Table 10. *Results of the Hausman test for CON_ENER_TOTAL_PC model*

Test Summary	Chi-Sq. Statistic	Prob.
Cross-section random	6.337851	0.1753

Source: *compiled by the authors of this study using Eviews based on data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

Table 11. *Model for estimating of CON_ENER_TOTAL_PC*

Dependent Variable: CON_ENER_TOTAL_PC				
Sample: 1995–2021			**Periods included: 27**	
Cross-sections included: 38			**Total panel (unbalanced) observations: 1026**	
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	944.2367	184.1448	5.127685	0.0000
UNEMP	-14.89694	3.103852	-4.799500	0.0000
EL_CAP	2705063	54424.80	49.70276	0.0000
GASCAP	18020.21	1556.506	11.57735	0.0000
R-squared	0.838757		F-statistic	985.7421
Adjusted R-squared	0.837906		Prob(F-statistic)	0.000000

Source: *compiled by the authors of this study using Eviews based on data form ESMS Indicator Profile (ESMS-IP), Enerdata (2022), World Bank, World Energy & Climate Statistics – Yearbook (2022)*

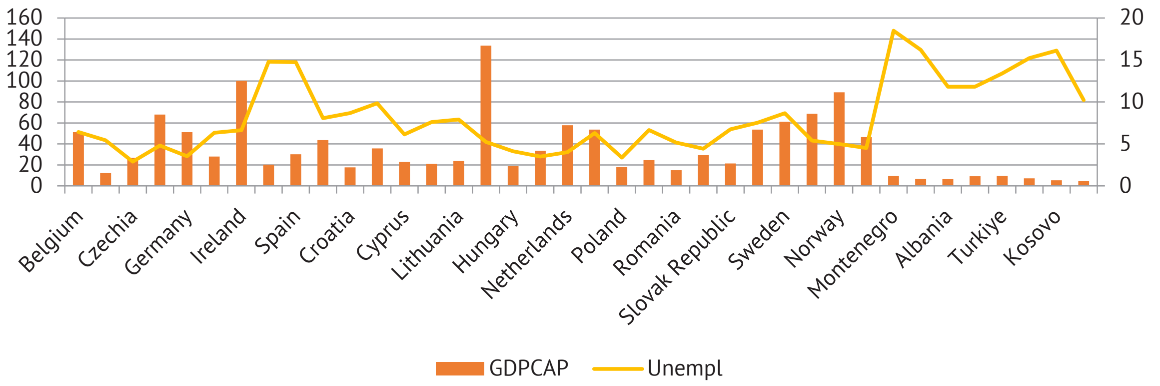

Figure 9. *GDP per capita (thousand USD) and unemployment rate in European countries in 2021*
Source*: compiled by the authors of this study based the base of World Bank statistics (n.d.)*

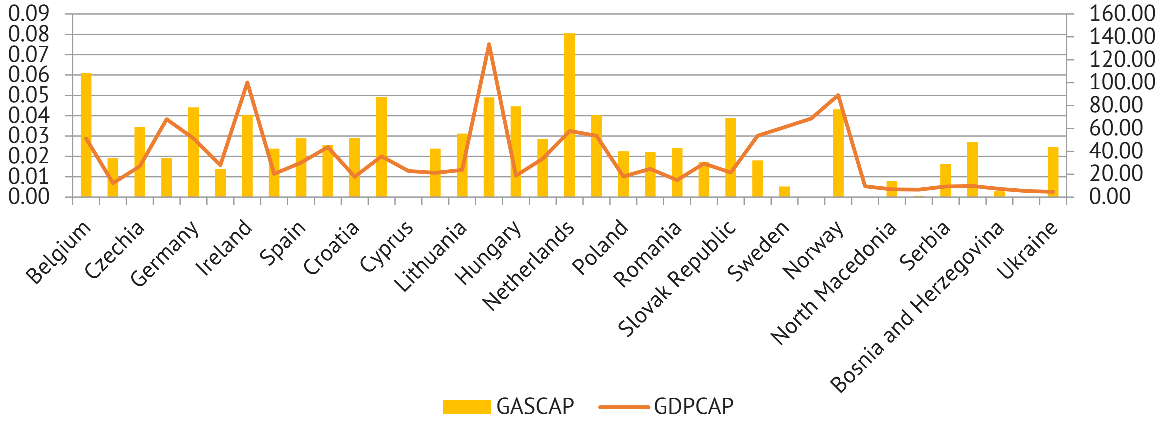

Figure 10. *GDP per capita (thousand USD) and inland consumption of gas GASCAP (Terajoule per capita) in European countries in 2021*
Source*: compiled by the authors of this study based on World Bank statistics (n.d.)*

In 2023, an agreement was signed between the European Parliament and the Council to strengthen the EU Energy Efficiency Directive, highlighting the EU's intention to become climate neutral by 2050. This agreement is the next step towards the implementation of the "Ready for 55 years" package for the performing of the European Green Deal and the REPowerEU plan. Now the EU countries are obliged to consider energy efficiency indicators in domestic and foreign policy, planning and making important investment decisions in the energy and other sectors. (European Green Deal, 2023).

The first principle of energy efficiency means the maximum use of economic measures to improve energy efficiency in the formation of energy policy and making appropriate investment decisions. The agreement sets an EU energy efficiency target of 11.7% by 2030, which exceeds the original proposal by the European Commission and requires Member States collectively to provide further reductions in final and primary energy consumption compared to energy consumption projections made in 2020.

The most explanatory variables appeared in the model of primary energy consumption per capita, namely, primary energy consumption, domestic natural gas consumption per capita, unemployment rate, the ratio of exports of goods and services to GDP and electricity available for final consumption per capita. Gross available energy per capita depends on the unemployment rate, gross electricity production per capita, domestic consumption of natural gas per capita.

The models constructed in this study strongly suggest the dependence of economic growth and energy efficiency of European countries. Since the variables GDPCAP and EXP_GDP, which determine the level of economic growth in the country, are explanatory variables in the CO2_GDP estimation model and their growth negatively affects the intensity of CO2 emissions, it can be argued that the possibility of simultaneously achieving sustainable economic development and reducing the intensity of carbon dioxide emissions. The positive dependence of the energy intensity of EI on the level of unemployment also serves as confirmation that economic growth in European countries is accompanied by an improvement in the level of energy efficiency. It is possible to achieve sustainable economic development while simultaneously reducing greenhouse gas emissions. The existence of such dependence, which is inherent in developed economies, is also evidenced by other studies (e.g., Cherkashina (2020), Klyvienė & Kėdaitienė (2020)). This is also consistent with the ecological-economic Kuznets curve, according to which the country's economic growth causes the growth of pollutant emissions, but after reaching a certain level of its economic development, the country's ecology gradually begins to improve.

CONCLUSIONS

The models obtained in this study help identify the ecological and economic determinants of primary energy intensity, carbon dioxide emission intensity, primary energy consumption and gross available energy per capita in 38 European countries. Thus, according to the models obtained, the factors on which the value of the energy intensity of the GDP for European countries significantly depends include the intensity of carbon dioxide emissions, the unemployment rate, primary energy consumption per capita, and gross electricity production per capita. The determinants of primary energy consumption were domestic consumption of solid fossil fuels per capita, domestic consumption of natural gas per capita and primary energy per capita. As a result, the existence of a positive relationship between energy efficiency and economic growth in European countries was generally confirmed as well as the possibility of simultaneously achieving sustainable economic development and reducing the intensity of carbon dioxide emissions. Monitoring of macroeconomic and other factors that have a statistically significant impact on energy efficiency will make it possible to form a flexible system for managing the energy efficiency of the national economies in European countries.

Therefore, the development of such monitoring systems at the macro level, first of all, can be the subject of subsequent scientific research devoted to the analysis of the relationship between energy efficiency and economic growth.

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None.

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Екологічні та економічні детермінанти енергоефективності в європейських країнах

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Анотація. Оскільки економічний розвиток часто пов'язаний зі збільшенням викидів парникових газів, особливо важливо відповісти на питання, чи можливо досягти сталого економічного розвитку і одночасно підвищити енергоефективність, що передбачає скорочення викидів парникових газів. Метою цього дослідження була побудова моделей, які можуть допомогти знайти еколого-економічні детермінанти енергоефективності в європейських країнах. Екологічні та економічні детермінанти показників енергоефективності 38 європейських країн були знайдені на основі панельних регресійних моделей. Моделі побудовані на основі статистичних даних, що характеризують рівень їх економічного розвитку та споживання різних видів енергії за 1995-2021 роки. Для отримання необхідних апроксимацій показників енергоефективності використовувався один з трьох типів моделей: метод випадкових ефектів, метод фіксованих ефектів або об'єднана модель. Для цього використовувалися відповідні статистичні тести. В результаті було виявлено, що до факторів, які мають статистично значущий вплив на енергоємність ВВП в європейських країнах, належать інтенсивність викидів вуглекислого газу, рівень безробіття, споживання первинної енергії на душу населення та валове виробництво електроенергії на душу населення. Результати дослідження показали, що визначальними факторами споживання первинної енергії є внутрішнє споживання твердого викопного палива на душу населення, внутрішнє споживання природного газу на душу населення та споживання первинної енергії на душу населення. Результати дослідження в цілому підтверджують сучасну тезу про те, що економічний розвиток може бути досягнутий при одночасному скороченні викидів парникових газів. Моніторинг факторів, які мають статистично значущий вплив на досліджувані показники, може стати важливим елементом сучасної системи управління енергоефективністю національних економік європейських країн

Ключові слова: енергоємність; економічне зростання; викопне паливо; споживання первинної енергії; ВВП; споживання електроенергії; споживання газу; викиди CO_2

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