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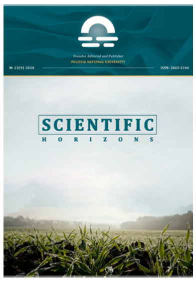

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Features of the Imbalance in the Mass of Components of the Uterine-Vaginal Mucus of Cows Due to the Harmful Effects of Endogenous Factors

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Abstract. The ever-increasing harmful effect of endo- (products of inflammatory processes of genital tissues) and exogenous factors (environmental conditions) on the body of women and animals (cows) leads to a substantial decrease in ova fertilisation during mating and artificial insemination. Therefore, the purpose of this study was to identify changes in the signs of physical condition (colour, consistency, fluidity, impurities, etc.) and ratios (homeostasis) of H_2O mass, organic (OS) and inorganic (IS) substances of uterine-vaginal mucus (UVM) should be used to assess their harmful effect on the fertilisation of cows after their first insemination. The following methods were used for this study: ocular estimate of the physical condition of freshly obtained mucus; gravimetric assessment of the features of changed mass parameters of its dry residue (DR) components; mathematical and statistical analysis of certain indicators. Determined by the gravimetric method, the features of the imbalance of mass (g, mg), its distribution (%) and ratios (Im:1, Ic:1) in the system of the "medium – substance" type due to the harmful effects of endogenous factors (products of inflammatory processes) indicate that the secretions of the genitals released during oestrus are characterised not only by changes in signs, but also ±2-4 times different from the norm (control) indicators of the mass of components. Under such circumstances, the distribution of substances in the DR samples of the experimental group is expressed by the series, where the mass $OS_1 > IS > OS_2$, but in the control group – $OS_1 > IS > OS_2$. This means that the products of inflammatory processes released by the genitals of cows change the norm of homeostasis of the mass (distribution of components) of OS and IS of the biological system of the "medium – substance" type. Indicators of the obtained mass ratios between component pairs H_2O: DR; H_2O: OS_2, H_2O: OS_1, H_2O: IS (control group – 63:1, 586:1, 231:1, 109:1; experiment group – 42:1, 310:1, 87:1, 112:1), except for the H_2O: IS pair ($P<0.05$), indicate the presence of probable changes in the homeostasis of OS and IS in the "H_2O – components" system. The high probability ($P<0.02$; <0.001) of the detected changes is inherent in the "DR – components" system, namely: if the average ratio indicators of pairs DR: OS_2; DR: OS_1; DR: IS samples of the control group are 9:1, 4:1, 2:1, then the same indicators in the experimental group are 7:1, 3:1, 2:1, respectively

Keywords: uterine-vaginal mucus of cows, dynamics and imbalance of homeostasis of the mass of organic and inorganic substances

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INTRODUCTION

Modern researchers associate the issue of reducing the fertilisation rate of ova under conditions of artificial insemination and natural mating of cows and women with an elevated level of microbiocoenosis in the environment of the secretions of their genitals (vagina, uterus) (Srinivasan *et al.*, 2021). The harmful effects of vaginal microflora and products of inflammatory processes (endogenous factors) accumulated by genital tissues (hypotrophy and atrophy of the vaginal mucosa, cervical neoplasia, acute and chronic endometritis) violate the norm of ratios of components of uterine-vaginal mucus (UVM), the parameters of which adversely affect the reproductive ability of females (Armengol & Fraile, 2015; Boby *et al.*, 2017; Emre *et al.*, 2021).

In this regard, it is known that the accumulated products of inflammatory processes increase the level of thiol/disulphide homeostasis, which is a sensitive indicator of oxidative stress in the body (Emre *et al.*, 2021); the pH level changes from acidic to alkaline (Berre *et al.*, 2021; Charonis & Larson, 2006); follicular fluid and UVM contain elevated concentrations of pro-inflammatory interleukins (Boby *et al.*, 2017; Brodzki *et al.*, 2015; Mounir *et al.*, 2018). This leads to changes in the hormonal and enzyme statuses of the body during puberty (Gonchar, 2014; Denisenko *et al.*, 2008), increased risk of miscarriage (Adnane & Chapwanya, 2022; Ki, *et al.*, 2014; Srinivasan *et al.*, 2021), a low-weight foetus is born (Hernandez-Castellano *et al.*, 2020). The level of fertilisation of cows also depends on the quantitative and qualitative composition of the UVM, which contributes to the active movement of sperm through the channels and ducts of the female genital tract towards the ovum (contact) (Maksymyuk *et al.*, 2021; Maksymyuk *et al.*, 2019).

However, even though the functional and biochemical aspects of the above issue are widely covered by the studies of Ukrainian (Gonchar, 2014; Denisenko *et al.*, 2008; Kraevsky *et al.*, 2020) and foreign scientists (Berre *et al.*, 2021; Rodder & Mathew, 2018; Sheldon *et al.*, 2020), there is still no particular information about the features of the correlation between changes in the colour and consistency of the UVM and the mass indicators of its components. Therefore, the task of this study was to assess the physical and chemical state of the samples of the UVM according to the obtained limits of volume parameters (8-40 cm^3), signs of colour (from transparent to grey-white), consistency (from fluid, thick-viscous to liquid), ratios of the content (or homeostasis of components) and their harmful effect on the fertilisation rate of cows after the first insemination.

MATERIALS AND METHODS

Experiments on animals were carried out according to the norms and principles of bioethics of conducting experiments and for other scientific purposes that require compliance with the requirements of directives of the European Parliament and the Council of the European Union (Directives of the European Parliament..., 2010); information of the Verkhovna Rada (IVR) on the protection of animals from ill-treatment (Law of Ukraine "On the Protection", 2021); regulations of the Bila Tserkva National Agrarian University on the treatment of animals in scientific research (Regulations of Bila Tserkva National Agrarian University..., 2018).

The features of volume dynamics (cm^3), colour and consistency characteristics (ocular estimate) and mass (g, mg,%) of the UVM components were established according to the requirements of quantitative (gravimetric) and qualitative analysis methods (Williams *et al.*, 2005; World Health Organisation, 2000). Specially introduced (Maksymyuk *et al.*, 2021; Maksymyuk *et al.*, 2019) formulas (1) and (2) were used to establish the correlation between the UVM signs and the indicators of its physical and chemical state (Δ changes, or an imbalance of homeostasis of a biological system of the "medium — substance" type):

$$\Delta = x_0 + x_i \tag{1}$$

$$\sum \Delta m = \Delta m_1 + \Delta m_2 + \Delta m_3 + \Delta m_i \tag{2}$$

where x_0 and Δm are parameters of the sum ($\sum$) of the masses of the UVM components; Δm_1 are the parameters of the mass of organic substances (OS_1), which burn on an open burner fire at 520-530°C; Δm_2 are the parameters of the mass of organic substances (OS_2), which are burned in a muffle furnace at 650°C; Δm_3 are the parameters of the ash mass, or heat-resistant inorganic substances (IS).

The detected changes were evaluated by indicators (M±m, Cv, P, lim) of the statistical method (Sharaf *et al.*, 1989) of the Microsoft Excel software.

During the mating season (April–June 2021) of the first-third (1-72 hours) days of oestrus, during the detected signs (behavioural arousal, swelling of the external genitalia, mucus discharge) of desire (Bugrov, 2013), UVM samples were taken by gloved hand from the vagina of Ukrainian black-spotted (Holsteinised) breeds of 3-9-year-old cows according to the method of (Williams *et al.*, 2005). The native state of the selected samples was evaluated by volume indicators (cm^3), signs of colour (transparent, grey-white) and consistency (thick-viscous, viscous, liquid), the presence of extrinsic impurities (protein plates, pus, blood, etc.).

Mucus samples selected according to these characteristics were divided into control (n=10) and experimental (n=4) groups. The control group included samples, the signs of which indicate normal function; the experimental group included samples with dysfunction of genital tissues.

Features of changes in the mass of components (N_2O, the total content of OS and IS) of the UVM was determined by drying in a thermostat at 105°C. Changes were recorded until the fourth decimal (0.0001) obtained by a microbalance ceased to change. OS_1 mass was determined after burning powdered samples of dry residue (DR) ground in a mortar on an open burner fire at 520-530°C; OS_2 and IS — in a muffle furnace at 650°C. Relative indicators were calculated by the composite proportion of absolute parameters of the H_2O mass, OS and IS (DSTU B B.2.1-16: 2009, 2010).

The designation of the features of the mass imbalance of the UVM components and its DR is given by non-systemic absolute (Im:1 – g, mg) and relative (Ic:1 –%) indicators. The methodology for determining and assessing the harmful effects of mass imbalance is represented by indicators of fractions of aqueous extracts of powdered samples of the DR of the UVM (Maksymyuk *et al*., 2021; Maksymyuk *et al*., 2019).

RESULTS AND DISCUSSION

Assessment of signs, indicators of the UVM volume, and the number of fertilised cows after the first insemination. Analysis of the parameters of the obtained UVM volume in both groups of cows (control, experimental) shows that its average indicators have different values (20 vs. 14 cm^3). In this regard, it is advisable to note that the volume limit (lim: min=10 vs. 8; max=40 vs. 21) is characterised by a high indicator (43-37%) of the coefficient of variation (Cv), but its difference between the groups is insignificant (6%). This means that with such variability in the UVM volume, the probability of its difference (P>0.2) between groups remains low (Table 1).

Table 1. *Status of UVM samples and results of insemination of cows in groups*

Stat. indicator	Sample volume, cm^3 (m_0)	Percentage of samples by signs: Colour, %	Percentage of samples by signs: Consistency, %	Percentage fertilised cows, %
Samples of the control group of cows (n=10)				
M±m	20.20±2.76	Transparent – 80 Grey-white – 20	Thick-viscous – 30 Viscous and liquid – 70	75
Cv	43			
Lim	10-40			
Samples of the experimental group of cows (n=4)				
M±m	14.12±2.58	Transparent – 50 Grey-white – 50	Viscous – 50 Liquid – 50	30
Cv	37			
Lim	8-21			
P	>0.2			

However, even though the difference in the parameters of the UVM volume of both groups of cows is insignificant, the difference in the signs of transparent and grey-white colour is substantial, namely: if the percentage of samples of transparent colour in the control group is 80%, and in the experimental group – 50%, then grey-white colour is 20% vs. 50%, respectively. Therefore, the difference in the characteristics of the mucus colour scheme between the samples of the control and experimental groups is ±30%.

The difference between thick-viscous and liquid samples of the control group (30% and 70%) and viscous and liquid samples of the experimental group (50% and 50%) is 10% less than the colour signs. Notably, there are no signs of a thick-viscous consistency in the samples of the experimental group. The presence of 70% of viscous and liquid samples in the control group is represented by the same percentage of viscous and liquid samples in the experimental group.

Thus, if considering the results of the first stage of assessment of the physical and chemical state of the UVM samples, different signs of their colour and consistency may be associated with a substantially higher percentage (75%) of fertilised cows of the control group after their first insemination.

Features of distribution of absolute mass parameters (g, mg) of the UVM components and its DR.

After three-day (72 hours) drying of control and experimental UVM samples in a thermostat at 105°C it is established that the distribution of absolute mass parameters H_2O (m_1) and the sum of the masses of the DR components (m_2), respectively, is 19.7 vs. 13.4 g and 329.4 and 325.3 mg, respectively (Fig. 1a, b). It should also be added that provided a sufficiently wide limit of variation (CV=39-61%) of the H_2O and DR mass parameters, the difference between them is unlikely (P>0.2).

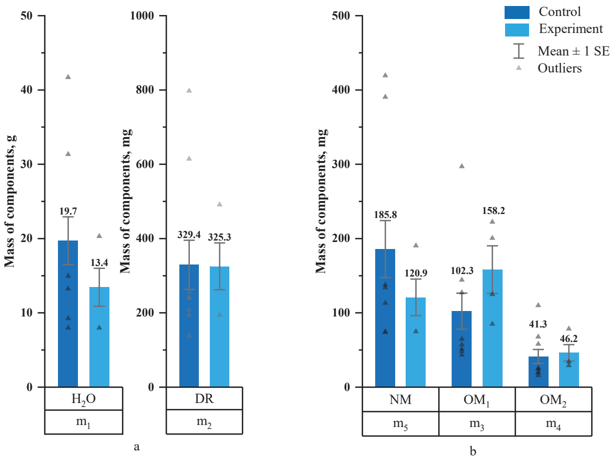

Figure 1*. Absolute mass parameters of the UVM components and its DR*
Note*: a) (m_1, m_2) are the UVM components' masses; b) (m_5, m_3, m_4) are the DR components' masses*

After burning powdered DR samples of the UVM on an open burner fire at 520-530°C and in a muffle furnace at 650°C, it turned out that the average mass index of IS (m_5) of the control group is 1.5 times larger than the experimental group, but for the OS_1 (m_3) and OS_2 (m_4) masses is 1.5 and 1.1 times lesser, respectively. If the mass of the components of the series (IS-OS_1-OS_2) of control samples is 186-102-41, then of experimental samples – 121-158-46 mg. This means that the correlation between the mass parameters of IS and OS of a biological system of the "medium-substance" type is expressed inversely. The harmful and/or protective effect of the products of inflammatory processes accumulated by the tissues of the genitals of cows of the experimental group is characterised by a high mass index of isolated IS, but low OS_1 and OS_2 in the control group. At the same time, even though the coefficients of variation of the mass indicators of OS_2 (76% and 48%) and IS (60 and 41%) are quite high, the probability of their difference between the groups is 97 ($P<0.02$) and 99% ($p<0.001$), respectively.

Features of distribution of relative mass parameters (%) of components of the UVM and its DR

Calculated relative mass indicators N_2O and OS and IS DR samples of the UVM (Fig. 2a, b) indicate that the remainder of the IS mass, which was not burned as a result of burning samples of the control group, is 0.92% of the total content of DR components. Under open fire conditions, 0.48% of the mass of OS_1 substances burns, and after combustion in the muffle – 0.20% of OS_2 substances.

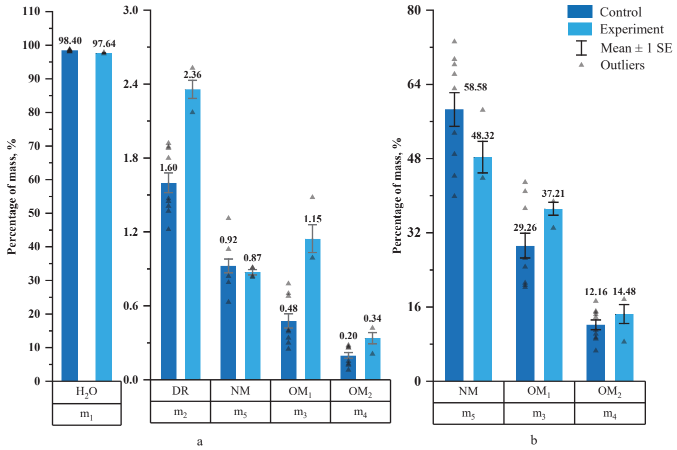

***Figure 2**. Relative mass parameters of the components of the UVM and its DR*

***Note:** a) (m_1, m_2, m_5, m_3, m_4) are the masses of UVM components; b) (m_5, m_3, m_4) are the masses of DR components*

The above means that the dynamics of the distribution of its components (IS – 0.92%>OS_1-0.48%>OS_2-0.20%) in the DR samples of the UVM of the control group of cows characterises a series where the percentage of the remaining mass of refractory IS is 1.8 times greater than the mass of burned OS_1 substances, and OS_1 – 2.5 times larger than the OS_2. However, the percentage of mass burned organic (OS_1, OS_2) and unburned refractory IS of the DR of the UVM of the experimental group are placed differently, namely: the mass index of the OS_1 (1.15%)>IS (0.87%)>OS_2 (0.34%).

The presented changes in the relative (%) parameters of the UVM mass under harmful endogenous factors of influence indicate that the products of inflammatory processes accumulated by the tissues of the genitals of cows of the experimental group do not substantially affect the mass indicators of IS (0.87 vs. 0.92%). However, the mass of OS_1 and OS_2 of the UVM of cows of the experimental group is 2.4 (1.15 vs. 0.48%) and 1.7 (0.34 vs. 0.20%) times greater than that of the control group.

The revealed difference is confirmed the by 3.8-1.4 times greater minimum (19% vs. 5%) and maximum (38% vs. 27%) parameters of the mass variability limit (Cv=19-38% vs. 5-28%) of the UVM components of the control group relative to the experimental group. The probability of their difference is 95-99% ($P<0.05$; $P<0.001$). Notably, the order of placement of mass percentages of the UVM components (Fig. 2a) and its DR (Fig. 2b) in the control group (IS>OS_1>OS_2) and the experimental group (OS_1>IS>OS_2) is similar.

Features of mass ratios of the UVM components and its DR.

The features of the mass distribution of the UVM components illustrated (Fig. 2a, b) a high ($P<0.001$) probability of its difference between the samples of the control and experimental groups of cows. Therefore, to detail and specify the features of the correlation between the imbalance of the mass of the UVM components and the state of reproductive ability of females (cow) and the reaction of genital tissues to the harmful effects of endogenous factors (products of inflammatory processes), the above facts are supplemented by changes in the mass ratios of the components of the biological system of the "medium (H_2O UVM) – substance (OS, IS DR)".

The results presented in Figure 3a, b show that one part of the mass of substances of the DR of the UVM (63:1 vs. 42:1) of the control group of cows bonds 1.5 times the mass of evaporated H_2O, than the cows of the experimental group. This feature is also typical for the OS mass that burns at different temperatures. Thus, if the components of the control group (OS_1), which burn at 520-530°C, bond 2.6 times the mass of H_2O (231 vs. 87:1), then substances (OS_2) burned in the muffle at

650°C – only 1.9 times more (586 vs. 310:1). It is also advisable to emphasise that the high ($P<0.001$) ability of the OS_1 components to bond H_2O is accompanied by a low ($P<0.05$) ability of the components of OS_2 and IS. Under such circumstances, the limit of the coefficient of variation of certain mass ratios of substances in the control group is 16-48%; the experimental group is 5-32%, which is 3.0-1.5 times more.

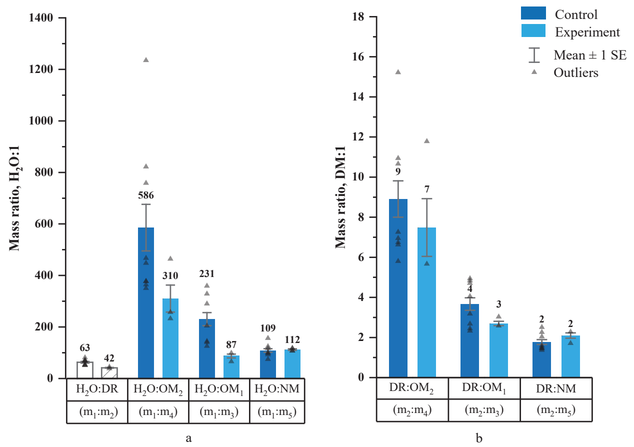

***Figure 3**. Mass ratio of the UVM components and its DR*

***Note:** a) H_2O:1 is the ratio of the mass of the evaporated H_2O (m_1) of the UVM to mass (m_2) of the DR substances that burn under different temperature conditions (OS – m_4, m_3), and to the remaining mass (IS – m_5) of refractory inorganic substances; b) DR:1 is the mass ratio of the DR (m_2) to mass (m_4, m_3) of the burnt organic and refractory inorganic substances (m_5)*

The identified features of the difference in the mass ratios of pairs DR: OS_1 and DR: OS_2 UVM in cows of the experimental and control groups complement the data presented in Figure 3b. The registered mass parameters of the DR of the UVM indicate that the sex glands of cows of the control group (OS_2 and OS_1) synthesise 1.3-2.0 times more mass of components (9 vs. 7 and 4 vs. 3) than the glands of cows of the experimental group. However, if the parameters of the ratios of the pairs DR: OS_1 (4 vs. 3:1) and DR: OS_2 (9 vs. 7:1) are compared with the pair DR: IS (2 vs. 2:1), it turns out that the obtained values indicate their inverse correlation. The limit of the coefficient of variation of the ratios of the mass of DR: OS_1 and OS_2 is 4-32%, DR: IS – 6-22%. Under these circumstances, the probability of differences in the mass ratios of DR substances remains high ($P<0.02$-0.001).

Analysis of the estimated features of raw (not dried) UVM samples of the groups under study indicates that with almost identical volume parameters (20-14 cm^3), its colour and consistency differ: 80% of the samples of the control group have a transparent colour, but 20% – grey-white; their consistency is thick-viscous (30%) or viscous and liquid (70%); 50% of the samples of the experimental group have a transparent or grey-white colour, the consistency is viscous and liquid.

The UVM samples of the experimental group have 0.76% less water. Absolute values of the total OS mass (158+46=204 mg) are 1.43 times higher (102+41=143 mg); IS mass of the control group (186:121 mg) is 1.5 times higher than that of the experimental one. The order of distribution of the mass of the constituent mucus samples of cows of the experimental group is presented in a series where the indicator OS_1>IS>OS_2, but is different in the control group, namely: IS>OS_1>OS_2. The unequal mass of components of the "medium – substance" type system, the change of which is expressed by absolute (Im) and relative (Ic) indicators of H_2O and OS and IS of the DR of the UVM leads to the fact that the correlation (Fig. 3a) H_2O:∑OS of the control group (586281=867:1) is 2.2 times larger than that of the experimental group (310+87==397:1), while H_2O: IS correlations remained almost the same (109-112:1). Under such circumstances, the correlations (Fig. 3b) of the components (9+4:1 vs. 4+3:1) of the DR:∑OS are 1.9 times larger, but those of the DR: IS (2 vs. 2:1) are almost the same.

Summarising the obtained and analysed results of the experiment, it should be expected that an objective indicator of quantitative changes in the tissues of the genitals of women and animals (cows) under the endo- (products of inflammatory processes) and exogenous (feeding, maintenance, etc.) factors of harmful influence, in the future may be the limits of the parameters of the mass of components (H_2O, OS, IS), which indicate an imbalance of their homeostasis in the "medium – substance" system.

Without sources of scientific information on the Internet on certain features of the imbalance of parameters of H_2O content and the sum of masses of OS and IS of the UVM due to the harmful effects of endogenous factors on women and cows, their discussion is limited to analysis of statistical results.

CONCLUSIONS

1. In case of improbable (20 vs. 14 cm^3, $P>0.2$) changes in the UVM volume, the colour and consistency of samples of cows of the experimental group undergo substantial changes: if 50% of experimental samples are

transparent or grey-white with opaque viscous or liquid consistency, 80% of control group are transparent, and 20% are grey-white; 30% have a thick-viscous, and 70% — viscous or liquid consistency.

2. The effect of products of inflammatory processes (endogenous factor of harmful effects) on the functional state of the genitals is expressed by the inverse correlation of the parameters of the mass of OS to IS. This leads to the fact that the order of distribution of the mass of the components of the DR in the experimental group is presented in a row, where the mass indicators are OS_1>IS>OS_2, but in the control group these indicators are IS>OS_1>OS_2.

3. Changes in the homeostasis of the mass components of the UVM in the "medium — substance" system, which are expressed by external signs of its physical and chemical state (colour, consistency, impurities of pus and blood, etc.), is the reason that the percentage of fertilised cows in the experimental group (30%) after the first insemination is 2.5 times smaller than that in the control group (75%).

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Особливості дисбалансу маси складових матково-вагінального слизу корів за шкодочинного впливу ендогенних факторів

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Анотація. Постійно зростаюча шкодочинна дія ендо- (продукти запальних процесів тканин статевих органів) та екзогенних факторів (умови зовнішнього середовища) на організм жінок і тварин (корови) призводить до суттєвого зниження заплідненості яйцеклітин при паруванні та штучному осіменінні. Тому метою досліджень було виявлені зміни ознак фізичного стану (колір, консистенція, плинність, домішки тощо) та співвідношень (гомеостаз) маси H_2O, органічних (ОР) і неорганічних (НР) речовин матково-вагінального слизу (МВС) використати для оцінки їх шкодочинного впливу на рівень запліднюваності корів після їх першого осіменіння. Для досліджень застосували методи: окомірної оцінки фізичного стану свіжоотриманого слизу; гравіметричної оцінки особливостей змінених параметрів маси складових його сухого залишку (СЗ); математико-статистичного аналізу визначених показників. Визначені гравіметричним методом особливості дисбалансу маси (г, мг), її розподілу (%) та співвідношень (Im:1, Ic:1) у системі типу «середовище – речовина» за шкодочинної дії ендогенних факторів (продукти запальних процесів) свідчать, що виділеним під час тічки секретам статевих органів властиві не лише зміни ознак, але і в ±2–4 рази інші ніж норма (контроль) показники маси складових. За таких обставин розподіл речовин у зразках СЗ дослідної групи виражено рядом, де маса $ОР_1$>НР>$ОР_2$, але контрольної – НР>$ОР_1$>$ОР_2$. Це означає, що виділені статевими органами корів продукти запальних процесів змінюють норму гомеостазу маси (розподілу складових) ОР і НР біологічної системи типу «середовище – речовина». Показники отриманих співвідношень маси між парами складових H_2O: СЗ; H_2O: $ОР_2$, H_2O: $ОР_1$, H_2O: НР (контроль – 63:1, 586:1, 231:1, 109:1; дослід – 42:1, 310:1, 87:1, 112:1), за винятком пари H_2O: НР ($P<0,05$), свідчать про наявність вірогідних змін гомеостазу ОР і НР у системі «H_2O – складові». Висока ймовірність ($P<0,02$; $<0,001$) виявлених змін властива системі «СЗ – складові», а саме: якщо середні показники співвідношень пар СЗ: $ОР_2$; СЗ: $ОР_1$; СЗ: НР зразків контрольної групи становлять 9:1, 4:1, 2:1, то дослідної – 7:1, 3:1, 2:1

Ключові слова: матково-вагінальний слиз корів, динаміка і дисбаланс гомеостазу маси органічних і неорганічних речовин

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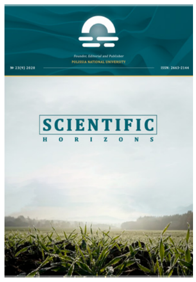

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Yield and Quality of Winter Durum Wheat Grain Depending on the Fertiliser System

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Abstract. At present, winter durum wheat is grown after its unpaired predecessors. Under such conditions, fertiliser is important. Therefore, the study of the yield formation and quality of winter durum wheat grain depending on the fertiliser system is relevant. The purpose of this study was to investigate the yield formation and quality of winter durum wheat grain under various fertiliser systems. The study was conducted in conditions of a stationary field experiment of the Uman National University of Horticulture, located in the Right-Bank Forest-Steppe of Ukraine during 2020-2021. The experiment was founded in 2011. The following crops are grown in the four-course field crop rotation: winter wheat, corn, spring barley, soybeans. The experiment scheme includes 11 variants of combinations and separate application of mineral fertilisers, including the control option without fertiliser. Grain harvest was performed by direct combining, protein content and gluten content were determined by infrared spectroscopy using Infratek 1241. Statistical data processing was performed using the STATISTICA 10 software. Yield of winter durum wheat grain significantly increased from the fertiliser. However, the effectiveness of their use varied depending on the year of study. Thus, in 2020, it increased by 1.1-1.2 times (3.9-4.1 t ha^{-1}) with long-term use of nitrogen fertilisers alone. Long-term use of complete mineral fertiliser ($N_{150}P_{60}K_{80}$) significantly affected the grain yield (4.3 t ha^{-1}) compared to variant N_{150}. In 2021, grain yields increased 1.2-1.4 times, depending on the fertiliser system. Notably, the use of $N_{150}P_{60}K_{40}$ and $N_{150}P_{30}K_{80}$ in terms of impact on grain yield was at the level of the variant $N_{150}P_{60}K_{80}$. Paired combinations of fertiliser application were effective at the level of long-term application of $N_{150}P_{30}K_{40}$. Application of $N_{75}P_{30}K_{40}$ provided the formation of only 4% lower grain yield compared to $N_{150}P_{30}K_{40}$. The protein and gluten content was most affected by the nitrogen component of the complete mineral fertiliser. The conducted studies confirm the high reaction of durum wheat to the use of nitrogen fertilisers. The results obtained can be used to predict the productivity of durum winter wheat depending on soil fertility

Keywords: nitrogen phosphorous and potash fertilisers, winter durum wheat productivity, protein content, protein collection, gluten content.

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INTRODUCTION

Wheat is one of the most important cereals in the world. Durum wheat ranks second in grain production after soft wheat. Currently, the gross production of soft wheat grain is about 765 million tonnes, of which almost 5% is accounted for by durum wheat (Food and Agriculture Organization of the United Nations, n.d.). Durum wheat grain is the main raw material for the production of high-quality pasta. Wheat is a source of carbohydrates, protein, minerals, and fibre (Mefleh *et al.*, 2019). Wheat straw can be used as a litter in mixtures with organic fertilisers or as an organic fertiliser. Furthermore, it has prospects for use in bioenergy purposes (Townsend *et al.*, 2018).

However, wheat grain yield and quality are the main concern of producers, as these indicators determine economic efficiency. To achieve the maximum possible yield and grain quality, agricultural enterprises can apply and combine a wide range of agrotechnical measures. Effective measures include the use of fertilisers (Wang *et al.*, 2017).

The quality of grain products depends on the protein and gluten content of the grain. Currently, winter wheat is usually placed after unpaired precursors, which adversely affects the formation of protein and gluten content in the grain (Gandía *et al.*, 2021). In addition, hard wheat reduces grain yields more strongly due to adverse environmental factors compared to soft wheat (Laurent *et al.*, 2020). One of the ways to improve the quality of wheat grain when growing after unpaired predecessors is to use nitrogen fertilisers (Novak *et al.*, 2019). In the agrotechnology of grain crops, the use of fertilisers is the main component that ensures the formation of a high yield of high-quality grain (Hospodarenko *et al.*, 2019). Nitrogen fertilisers most increase wheat productivity in modern agricultural systems. However, it is known that very high doses of nitrogen fertilisers can pollute the environment, due to the active substance not used by plants. The effectiveness of fertilisation of durum winter wheat depends on many factors, of which weather conditions and the reaction of the variety of this crop are most strongly influenced (Zhang *et al.*, 2016).

In modern conditions, it is important not only to implement measures to increase crop yields, but also to reduce the cost of production, that is, to increase the production of competitive products. Therefore, it is necessary to maximise the use of low-cost techniques in agricultural technologies. Reducing the cost of production can be achieved by using highly productive wheat varieties (Mefleh *et al.*, 2019). C. Li *et al.* (2018) it was found that with the systematic use of fertilisers, high yields of agricultural crops can be obtained by applying considerably lower doses, which is explained by the after-effect of fertilisers applied for previous crops of crop rotation. In the system of applying fertilisers for durum wheat, it is also necessary to consider soil fertility. If the nitrogen content of mineral compounds is higher, the dose of nitrogen fertilisers should be reduced so that there is no overspending (Marinaccio *et al.*, 2016). Prolonged application of fertilisers increases the radioactivity of the soil due to the content of ^{40}K and ^{226}Ra. However, this radiation is safe for human health (Šimanský & Jonczak, 2019). Furthermore, the use of fertilisers improves the quality of grain, which is important for the production of high-quality products (Hrčková *et al.*, 2018).

Thus, the effectiveness of applying fertilisers depends on the doses of their application. The optimal dose of fertilisers should consider the biological features of the durum wheat variety and the planned level of its yield, weather conditions and soil fertility, the level of agricultural technology, the placement of crops in the crop rotation and its saturation with fertilisers, the forms of fertilisers, the timing, and methods of their application, and other factors. Therefore, determining fertiliser doses is one of the most difficult issues of modern agronomic science and practice.

The purpose of this study was to investigate the yield formation and quality of winter durum wheat grain under various fertiliser systems in field crop rotation.

LITERATURE REVIEW

Nitrogen, phosphorus, potassium, and sulphur fertilisers, as well as microfertilisers, are most frequently used for wheat. However, wheat is a nitrogenophilic crop, so the main part of this study is devoted to studying the effectiveness of nitrogen fertilisers. It is established that the application of N_{90} for durum wheat, the grain yield increased on average from 5.10 t ha^{-1} in the variant without fertilisers up to 7.01 t ha^{-1}. Application of N_{180} increased it only to 7.75 t ha^{-1}, application of N_{240} – up to 8.09 t ha^{-1}, while N_{300} did not increase the yield (8.05 t ha^{-1}). In addition, the effectiveness of fertiliser significantly varied depending on weather conditions. Thus, the yield of durum wheat from the use of N_{90} it varied from 6.25 to 8.21 t ha^{-1}. The trend of nitrogen fertilisers affecting protein content was different. Thus, this indicator grew from 10.5 in the version without fertilisers to 11.9% per N_{90}, and when applying N_{300} it grew to 14.4%. The protein content also significantly varied depending on weather conditions. Thus, in the variant of application of N_{90}, this figure ranged from 10.2% to 12.4% (Ma *et al.*, 2019). However, the conditions under which such studies were conducted differ from the Right-Bank Forest-Steppe of Ukraine. Better soil and climatic conditions contributed to the formation of a higher grain yield compared to the experiments of the authors of this paper.

In studies by F. Orlando *et al.* (2017) the use of N_{80-120} was effective. The yield of durum winter wheat under this fertiliser scenario was at the level of 5.30 t ha^{-1}. Czech scientists L. Hlisnikovský *et al.* (2020) found that winter wheat responds well to the use of fertilisers, but their effectiveness varies depending on weather conditions. Thus, in areas without fertilisers, the yield varied from 2.89 to 6.99 t ha^{-1} depending on the year of study. In an unfavourable year, the grain yield was at the level of the fertiliser-free option (2.78-2.86 t ha^{-1}). Application of mineral fertilisers ($N_{120}P_{26}K_{50}$) against the background of pus after-effect (40 t ha^{-1}) was the most effective. Under this scenario, the average yield of winter wheat grain increased to 8.10 t ha^{-1} against 5.73 t ha^{-1} in the control variant. However, there are no variants using smaller and higher doses of nitrogen fertilisers in these studies. With such an experiment scheme, only one experiment option will be effective – $N_{120}P_{26}K_{50}$. Furthermore, nitrogen fertilisers were applied in three periods – before sowing, in the spring, and during the earing of winter wheat. In the conditions of the Right-Bank Forest-Steppe, if there is a lack of moisture and hot temperature, such a fertiliser system is ineffective. Notably, the study was conducted with soft wheat, the fertiliser system of which differs from durum wheat (Hlisnikovský *et al.*, 2020).

The use of phosphorous and potassium fertilisers is less effective than nitrogen fertilisers. In research by S. Turebayeva *et al.* (2022), application of P_{30} increased the yield of winter wheat grain from 1.28 to 1.76 t ha^{-1}. Increasing the dose to P_{45} provided a yield of 1.96 t ha^{-1}. The highest efficiency of phosphorous and potassium fertilisers is provided by nitrogen fertilisers (Turebayeva *et al.*, 2022). Thus, the application of $N_{50}R_{30}$ provided the receipt of 3.18 t ha^{-1} of winter wheat grains (Turebayeva *et al.*, 2022). However, these studies were conducted with soft winter wheat. Given the insufficient study of the issue of optimal fertilisation of durum winter wheat, the purpose of this study is relevant.

MATERIALS AND METHODS

The study was conducted in 2020-2021 in a stationary experiment of the Department of Agrochemistry and Soil Science. The stationary field experiment was carried out at the Uman National University of Horticulture (certificate of the National Academy of Agricultural Sciences No. 87) (Stationary field experiments of Ukraine, 2014) in the Right-Bank Forest Steppe of Ukraine with Greenwich geographical coordinates 48° 46' of northern latitude and 30° 14' of eastern longitude. The experiment was launched in 2011. The following crops were cultivated in the four-field crop rotation: winter wheat, corn, spring barley and soya. The purpose of the field experiment is to establish the efficiency of the action of different types, rates, and proportions of mineral fertilisers on the yielding capacity and quality of grain and seeds of field crops, and fertility of the black soil. The scheme of the experiment includes 11 variants of combinations and separate applications of mineral fertilisers including the control variant without fertilisers (Table 1).

***Table 1**. The design of application of fertilisers in the experiment*

Variant of the experiment: Average rates of nutrients in the crop rotation (kg of active substance ha^{-1} per year)	Application of fertilisers under crops in the crop rotation			
	Winter wheat	Corn	Spring barley	Soy
Without fertilisers (control)	–	–	–	–
N_{55}	N_{75}	N_{80}	N_{35}	N_{30}
N_{110}	N_{150}	N_{160}	N_{70}	N_{60}
$P_{60}K_{80}$	$P_{60}K_{80}$	$P_{60}K_{110}$	$P_{60}K_{70}$	$P_{60}K_{60}$
$N_{110}K_{80}$	$N_{150}K_{80}$	$N_{160}K_{110}$	$N_{70}K_{70}$	$N_{60}K_{60}$
$N_{110}P_{60}$	$N_{150}P_{60}$	$N_{160}P_{60}$	$N_{70}P_{60}$	$N_{60}P_{60}$
$N_{55}P_{30}K_{40}$	$N_{75}P_{30}K_{40}$	$N_{80}P_{30}K_{55}$	$N_{35}P_{30}K_{35}$	$N_{30}P_{30}K_{30}$
$N_{110}P_{60}K_{80}$	$N_{150}P_{60}K_{80}$	$N_{160}P_{60}K_{110}$	$N_{70}P_{60}K_{70}$	$N_{60}P_{60}K_{60}$
$N_{110}P_{30}K_{40}$	$N_{150}P_{30}K_{40}$	$N_{160}P_{30}K_{55}$	$N_{70}P_{30}K_{35}$	$N_{60}P_{30}K_{30}$
$N_{110}P_{60}K_{40}$	$N_{150}P_{60}K_{40}$	$N_{160}P_{60}K_{55}$	$N_{70}P_{60}K_{35}$	$N_{60}P_{60}K_{30}$
$N_{110}P_{30}K_{80}$	$N_{150}P_{30}K_{80}$	$N_{160}P_{30}K_{110}$	$N_{70}P_{30}K_{70}$	$N_{60}P_{30}K_{60}$

In the variant of the experiment with an average rate of nutrients in the crop rotation per ha of $N_{110}P_{60}K_{80}$, the total (100%) compensation with fertilisers of average annual removal of the nutrients by the crops in the crop rotation is planned. The scheme of the experiment was developed so that it could be possible to determine the opportunity to decrease the rates of certain types of mineral fertilisers. The placement of the variants in the experiment is successive. Performance of the experiment simultaneously on four fields provides annual data about yielding capacity of all crops in the four-field crop rotation. The experiment was repeated three times. The total area of the experimental plot is 110 m^2, the accounting area is 72 m^2. Phosphorus (granulated superphosphate) and potassium (potassium chloride) fertilisers were applied during fall tillage, nitrogenous fertilisers (ammonium nitrate) during pre-sowing cultivation and fertilising of winter wheat. Phosphorous and potassium fertilisers were used in autumn for the main tillage, nitrogen fertilisers – in early spring. In the experiment, winter durum wheat (Andromeda variety) was grown after soybeans.

Characteristics of durum winter wheat of the Andromeda variety. Originator – Institute of Irrigated Agriculture (Ukraine). Type of development – winter, early ripening. Plant height 75-100 cm. It is recommended for growing in forest-steppe and steppe. The potential yield is 3.6-6.0 t/ha. Resistance to lodging – 5 points, to shedding – 7, to root rot – 5, to Septoria – 9, to Fusarium – 7, to brown rust – 8, to powdery mildew – 6 points. Pasta properties are high (4.4 points).

The soil on the experimental plot is the black podzolised heavy loamy soil on loess with 3.8% of humus content, the content of nitrogenous hydrolysed compounds (by Cornfield method) is low (105 mg kg), the content of mobile compounds of phosphorus and potassium (by Chirikov method (DSTU 4115-2002, 2003), extraction 0.5 m CH_3COOH) is increased (106 mg kg) and high (132 mg kg) respectively, pH_{KCl} – 5.7.

Combined harvesters were used to harvest the grain. The accounting of the harvest of non-marketable produce was conducted by the method of the trial sheaf. Non-marketable part of the harvest of the crop rotation plants (straw, stems) was left in the field for fertilising. Protein and gluten content were determined by infrared spectroscopy using Infratek 1241.

Statistical data processing was performed using STATISTICA 10. The null hypothesis was confirmed or refuted during the performing of variance analysis. The p-value was determined for this purpose, which showed the probability of the corresponding hypothesis. In cases, where $p<0.05$, 'the null hypothesis' was refuted and the influence of the factor was significant.

Weather conditions differed in precipitation distribution and air temperature (Table 2). In 2020, 44.9 mm of precipitation fell in March-April, and in 2020 – 1.8 times more (82.3 mm). However, in the autumn of 2019, there was no precipitation, and the total amount was 376.6 mm, which is 1.6 times less than the long-term average (586 mm). The air temperature in 2021 in March and April was lower compared to 2020. Notably, winter durum wheat plants were damaged by frost in the first decade of May 2020.

***Table 2**. Weather conditions in 2020-2021*

Month	Year					
	2020	2021	1991-2020	2020	2021	1991-2020
	Precipitation (mm)			Temperature (°C)		
March	23.9	32.4	36	6.3	2.0	2.5
April	21.0	49.9	41	9.2	7.4	9.7
May	101.0	56.4	52	12.5	14.0	15.4
June	70.4	107.7	81	20.9	19.8	19.0
July	21.4	89.8	68	21.6	23.2	20.9

Due to the lack of moisture in autumn 2019, durum winter wheat seedlings were obtained in January 2020, which affected the formation of fewer productive stems (Table 3). Furthermore, the adverse impact of frosts in the BBCH 30 phase led to the formation of lower grain yields compared to 2021.

***Table 3**. Winter durum wheat sowing and harvesting time date during trial years*

Indicators	Year of research	
	2020	2021
Sowing time	October 17th, 2019	October 30th, 2020
BBCH 10	January 25th	November 20th
BBCH 20	February 25th	April 13th
BBCH 30	May 1st	May 10th
BBCH 50	June 5th	June 6th
BBCH 73	June 20th	June 20th
Harvesting time	July 15th	July 22nd

RESULTS AND DISCUSSION

The results of the research show that all fertiliser systems, except for phosphorus-potassium in 2020, significantly increased the yield of winter durum wheat grain compared to the option without fertilisers ($p\leq0.05$) (Fig. 1). The lowest fertiliser efficiency was set in 2020. Thus, the yield of winter durum wheat grain increased by 1.1-1.2 times (3.9-4.1 t ha^{-1}) with long-term use of only nitrogen fertilisers. Long-term use of complete mineral fertiliser ($N_{150}P_{60}K_{80}$) significantly affected the grain yield (4.3 t ha^{-1}) compared to variant N_{150}. However, the yield under this fertiliser scenario was only 5 % higher. Paired combinations of fertiliser use, as well as long-term use of fertiliser systems with incomplete return of phosphorous and potassium fertilisers, provided only 2-5% lower grain yield compared to $N_{150}P_{60}K_{80}$.

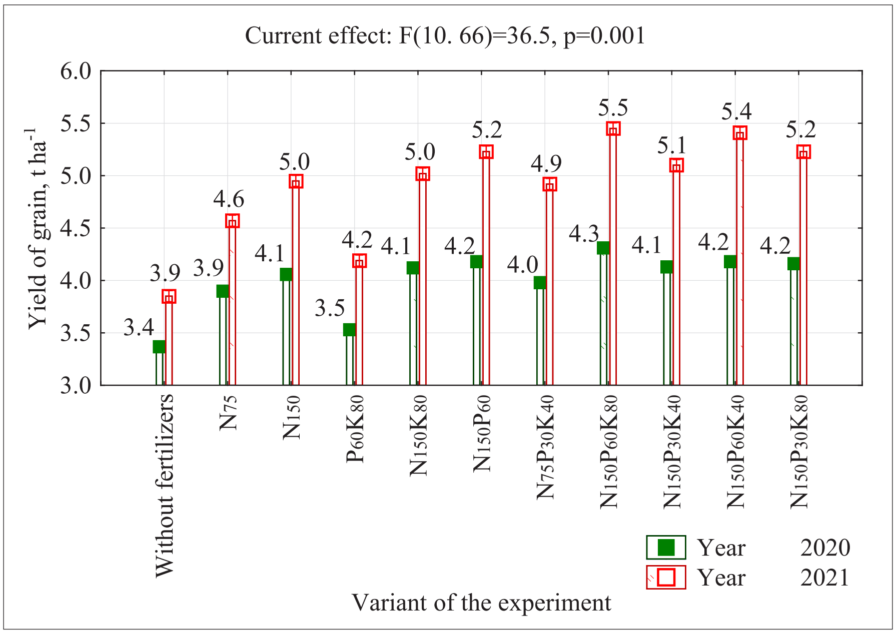

Figure 1. *Winter durum wheat grain yield depending on the fertiliser system*

In the best weather conditions of 2021, grain yields were 15% higher in areas without fertilisers compared to 2020. In the variants of long-term application of fertilisers, it was higher by 18-28%. The yield increased by 1.2 times with prolonged use of N_{75} and 1.3 times – in the variant with N_{150}. Significantly higher yields (by 4-10%) were provided by long-term use of the nitrogen-phosphorus system and variants $N_{150}P_{60}K_{80}$, $N_{150}P_{60}K_{40}$, $N_{150}P_{30}K_{80}$ compared to long-term use of N_{150}. Notably, the use of $N_{150}P_{60}K_{40}$ and $N_{150}P_{30}K_{80}$ in terms of impact on grain yield was at the level of the variant $N_{150}P_{60}K_{80}$. Paired combinations of fertiliser application were effective at the level of long-term application of $N_{150}P_{30}K_{40}$. Application of $N_{75}P_{30}K_{40}$ provided the formation of only 4% lower grain yield compared to $N_{150}P_{30}K_{40}$. The lowest yield was provided by a phosphorus-potassium fertiliser system (4.2 t ha^{-1}).

Nitrogen fertilisers are a crucial factor in the agricultural technology of winter wheat. Their use leads to a considerable increase in grain yield compared to options without fertilisers (Klikocka *et al.*, 2016). The magnitude of the impact of nitrogen fertilisers on winter wheat can be determined by weather conditions. Sufficient moisture during the wheat growing season contributes to higher efficiency of nitrogen fertilisers (Tosti *et al.*, 2016). Furthermore, unfavourable conditions of the autumn-winter period also affect the productivity of the plant. Under conditions of higher individual productivity of wheat plants, the yield increase from fertilisers will also be greater (Rossini *et al.*, 2018).

In the conditions of the research conducted by the authors of this paper in 2020, the lack of moisture during the sowing period caused late shoots. In addition, the plants were affected by low temperatures during the phase of plants entering the tube. It was found that winter durum wheat plants formed a larger number of stems in 2021 compared to 2020 (Table 4). A larger number of stems is conditioned upon the early resumption of spring vegetation. In addition, the tillering phase lasted 65 days, and in 2021 the tillering phase lasted only 27 days. However, the mass of grain in one ear of winter durum wheat in 2020 was the lowest due to the influence of sub-zero temperatures. Therefore, the grain yield in 2020 was the lowest.

Table 4. *Number of plants and productive stems of winter durum wheat under different fertiliser systems, pcs/m^2*

Experiment variant	Year of the study			
	2020		2021	
	1	2	1	2
Without fertilisers (control)	291	1.29	239	1.73
N_{75}	338	1.27	251	1.98
N_{150}	397	1.14	304	1.75
$P_{60}K_{80}$	295	1.33	245	1.87
$N_{150}K_{80}$	404	1.14	310	1.74
$N_{150}P_{60}$	408	1.14	318	1.81
$N_{75}P_{30}K_{40}$	346	1.27	274	1.96
$N_{150}P_{60}K_{80}$	415	1.16	320	1.85
$N_{150}P_{30}K_{40}$	410	1.13	310	1.77
$N_{150}P_{60}K_{40}$	404	1.15	319	1.83
$N_{150}P_{30}K_{80}$	401	1.16	317	1.77

Note*: 1 – number of productive stems, 2 – weight of grain in one ear, g.*

Research by S. Turebayeva *et al*. (2022) showed that wheat has a lower response to the use of phosphorous and potassium fertilisers, especially with an average content of their mobile compounds in the soil. Therefore, the grain yield in variants with incomplete return of phosphorous to potassium fertilisers decreases little compared to full mineral fertilisers. Furthermore, the higher efficiency of fertilisers may be conditioned upon their long-term use in crop rotation, which is confirmed in the article (Šimanský & Jonczak, 2019).

The protein content was most affected by the nitrogen component of the complete mineral fertiliser (Fig. 2). All variants using nitrogen fertilisers significantly increased the protein content in the grain. Thus, this indicator increased by 4-26% in variants with 75-150 kg/ha of fertiliser compared to plots without fertilisers. In conditions of less precipitation during the ripening period of winter durum wheat grain and higher air temperatures in 2020, the protein content was 8-21% higher compared to 2021. Thus, all fertiliser systems, except phosphorus-potassium, significantly affected the growth of protein content in winter durum wheat grain. Notably, the use of a double dose of nitrogen fertilisers (N_{150}) in the composition of a complete mineral fertiliser significantly increased the protein content compared to long-term use of N_{75}. The protein content increased by 18% when N_{75} was added, by 21% – upon adding $N_{75}P_{30}K_{40}$. Application of N_{150} increased protein content by 23%, and options with full mineral fertiliser – by 25-26% compared to plots without fertiliser.

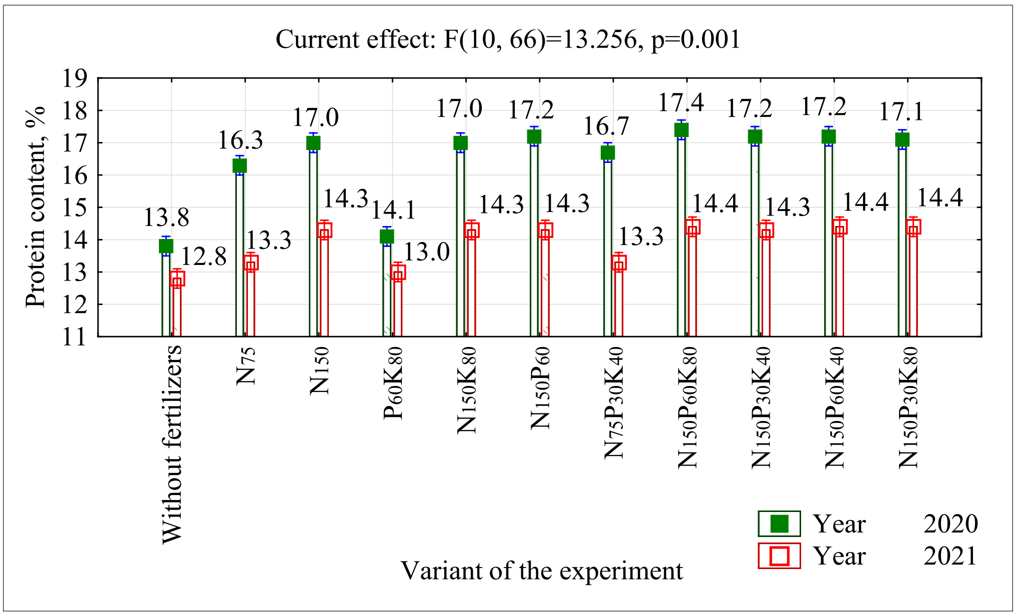

Figure 2*. Protein content in durum winter wheat grain depending on the fertiliser system*

In 2021, protein content in variants using N_{75} increased by 4%, and the use of N_{150} increased it by 12-13%. The protein content of the phosphorus-potassium fertiliser system was at the level of the option without fertilisers since it did not significantly exceed it. In variants with incomplete return of phosphorous and potassium fertilisers, the protein content was at the level of the nitrogen fertiliser system.

Research results of other scientists (Ostmeyer *et al*., 2020) indicate that the use of nitrogen fertilisers increases the protein content in winter wheat grains. With a lower grain yield, the protein content may be higher compared to years where a higher grain yield was formed. Therefore, at a yield of 3.9-4.3 t ha^{-1} protein content was at the level of 16.3-17.4%, and at a yield of 4.6-5.5 t ha^{-1} its content was only 13.3-14.4%. However, the use of nitrogen fertilisers not only increased grain yield, but also increased protein content.

Long-term use of mineral fertilisers in field crop rotation significantly increased protein harvesting from the winter durum wheat crop compared to the variant without fertilisers (Fig. 3). Protein harvesting from the 2021 grain harvest was 6-8% higher compared to 2020, except the application of N_{75} variants. Prolonged use of N_{75} increased protein collection by 1.2 times, and $N_{75}P_{30}K_{40}$ – by 1.3 times compared to the control. According to the nitrogen-potassium and nitrogen-phosphorus fertiliser systems, protein collection was 1.5 times higher. The use of the highest dose of nitrogen fertilisers on a phosphorus-potassium background was 1.5-1.6 times higher. Similarly, protein harvesting changed in 2020. The use of a phosphorus-potassium fertiliser system had the least effect on protein harvesting from the winter durum wheat crop. Despite the high yield of winter durum wheat grain in 2021 variants with long-term use of N_{75} and $N_{75}P_{30}K_{40}$ the highest protein collection in 2020. The protein collection rate is conditioned upon the formation of a higher protein content in 2020.

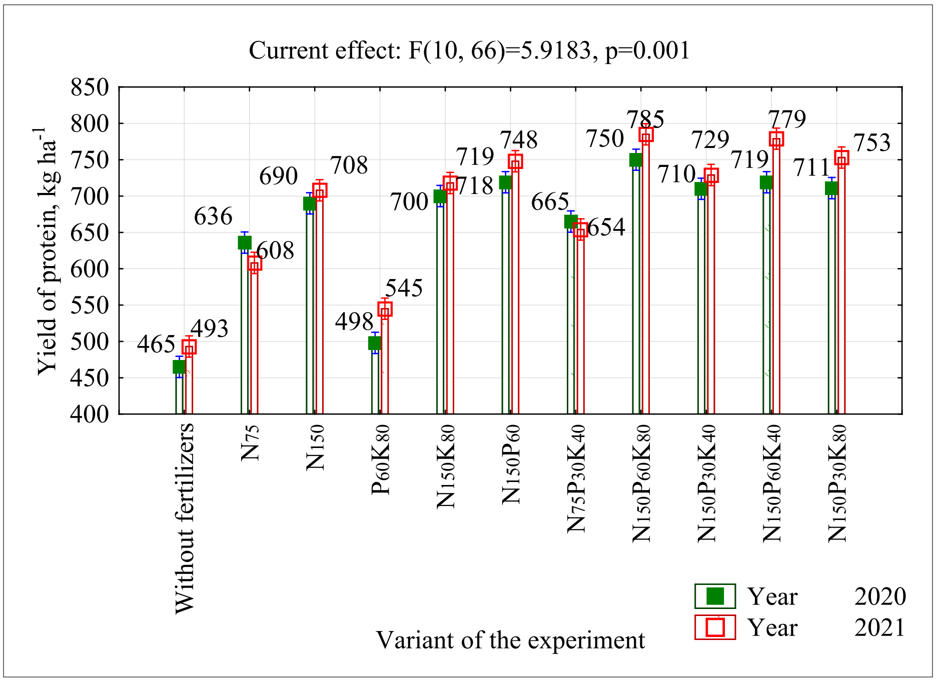

Figure 3*. Protein harvesting from durum winter wheat crops depending on the fertiliser system*

The trend of influence of prolonged fertiliser use in field crop rotation on gluten content was similar to that of grain protein (Fig. 4). Furthermore, the gluten content was influenced by the weather conditions of the years of experiments. In 2021, the gluten content in areas without fertilisers was 17% lower compared to 2020. In fertiliser applications, this indicator was 25-30% lower.

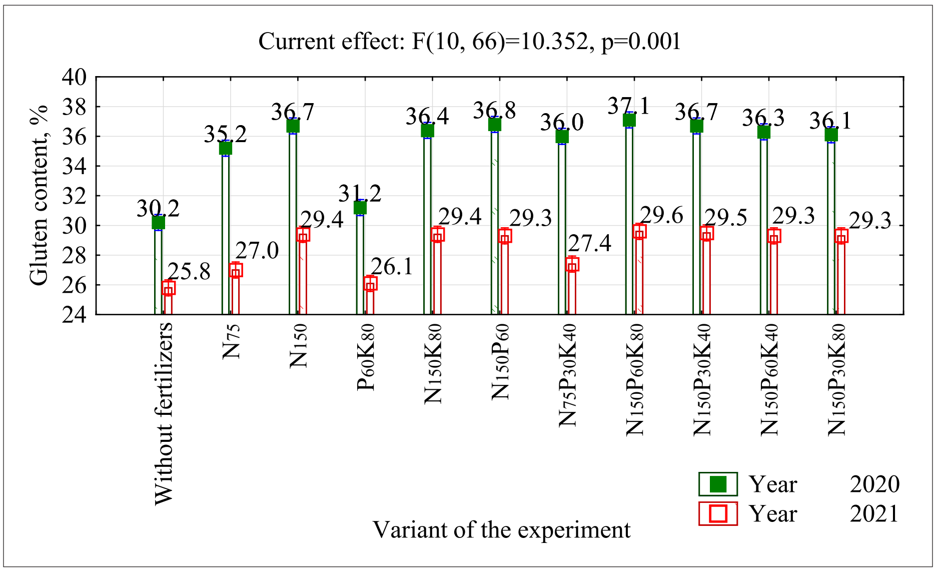

Figure 4*. Gluten content in durum winter wheat grain depending on the fertiliser system*

Notably, all fertiliser systems that contained the nitrogen component significantly increased the gluten content in the grain during both years of experiment. In 2020, this indicator grew by 17-19% in the cases of applying N_{75} variants compared to the fertiliser-free option. In the variants of using the highest dose of nitrogen fertilisers, the gluten content increased by 22-23%. In 2021, this indicator grew by 4-6% for the cases of N_{75} application. In variants using N_{150} the gluten content increased by 14-15%. The use of a phosphorus-potassium fertiliser system did not significantly affect this indicator.

The formation of gluten content in winter wheat grain varies significantly depending on the weather conditions of the growing season, especially during its ripening period (Wu *et al.*, 2019). The effect of nitrogen fertilisers on these indicators also depends on weather conditions. Usually, precipitation during this period reduces the gluten content. Furthermore, an increase in grain yield leads to the formation of a lower gluten content, since the amount of nitrogen of mineral compounds in the soil applied with fertilisers, which can be used for its synthesis, decreases (Yang *et al.*, 2019). If the productive stems are reduced, excess nitrogen mineral compounds can be used by wheat plants to synthesise gluten (Rossini *et al.*, 2020). In the experiments of the authors of this paper, the lack of moisture during the milk ripeness of winter durum wheat grain in 2020 caused the formation of a higher protein and gluten content in the grain compared to 2021. In addition, the grain yield in 2020 was the lowest. In 2021, the grain yield is 5.2-5.5 t ha^{-1} the gluten content was at the level of 29.3-29.6%.

Therefore, the introduction of nitrogen fertilisers is an effective way to improve the quality of grain without reducing the yield of durum winter wheat. However, the results obtained can be applied to conditions similar to the Right-Bank Forest-Steppe of Ukraine. If individual weather elements change, the impact of fertiliser systems on the productivity of durum winter wheat may vary. This should be considered upon conducting research in other soil and climatic conditions. Furthermore, growing more productive varieties of this crop will also change the effectiveness of fertiliser application.

The results of statistical processing of experimental data confirm that paired combinations and variants with incomplete return of phosphorus and potassium fertilisers on the background of N_{150} use have almost the same effect compared with long-term use of $N_{150}P_{60}K_{80}$ (Fig. 5). The optimal protein and gluten content ensures the use of N_{150} regardless of the dose of phosphorous and potassium fertilisers. Considering the grain yield, protein content, its collection and gluten content, variants with prolonged use of $N_{150}P_{60}$, $N_{150}P_{30}K_{40}$, $N_{150}P_{60}K_{40}$ and $N_{150}P_{30}K_{80}$ have almost the same efficiency compared to variant $N_{150}P_{60}K_{80}$.

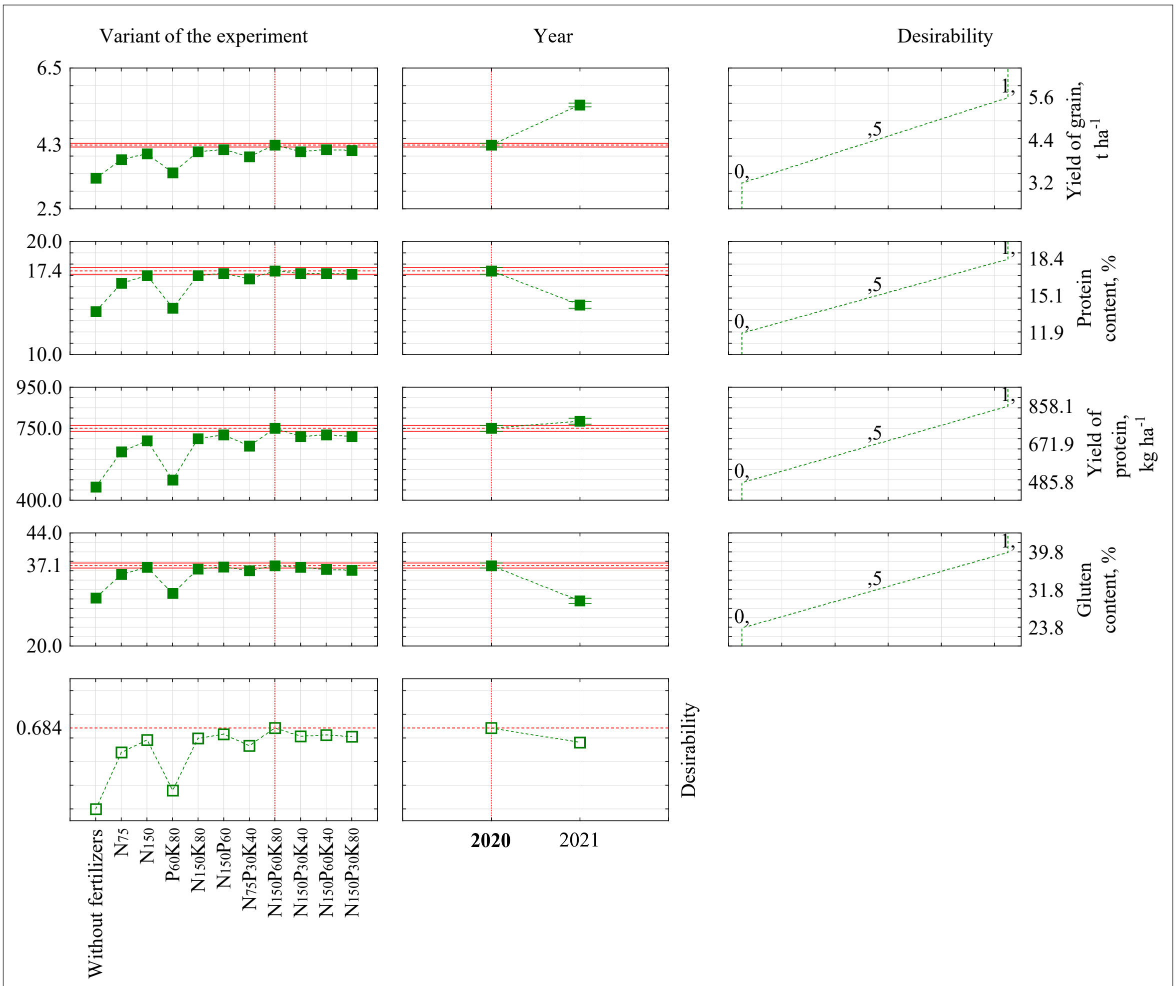

***Figure 5**. Optimisation of the choice of fertiliser system to ensure the formation of high yield and quality of winter durum wheat grain*

CONCLUSIONS

Long-term use of fertilisers, in addition to the phosphorus-potassium system, in field crop rotation significantly affects the formation of the winter durum wheat crop (Andromeda variety). Fertiliser systems with a nitrogen component have the highest efficiency. Phosphorus-potassium fertilisers have the least impact on the yield and quality of winter durum wheat grain. The effectiveness of fertiliser application varies depending on the weather conditions of the growing season. Thus, in less favourable growth conditions, the yield increases from 3.4 to 3.5-4.3 t ha^{-1}, and in the best – from 3.9 to 4.2-5.5 t ha^{-1} ($p \leq 0.05$). Under conditions of hot air temperature and less precipitation, all fertiliser systems with a nitrogen component significantly affected the protein and gluten content in the grain. The protein content increases from 13.8 to 16.3-17.4%, depending on the fertiliser system, and its collection from 465 to 636-750 kg ha^{-1} ($p \leq 0.05$). In conditions of sufficient moisture, fertiliser systems using N_{150} had a significant effect. The protein content in this scenario increases from 12.8 to 14.4%, and its collection from 493 to 785 kg ha^{-1} ($p \leq 0.05$). Prolonged use of phosphorus-potassium fertilisers did not significantly affect the quality of winter durum wheat grain. The gluten content varies similarly to the protein content, depending on the fertiliser system. Thus, in 2020, the gluten content increases from 30.2 to 35.2-37.1%, and in 2021 – from 30.2 to 36.7-37.1% ($p \leq 0.05$), depending on the fertiliser system.

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Урожайність і якість зерна пшениці твердої озимої залежно від системи удобрення

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Анотація. Нині пшеницю тверду озиму вирощують після непарових попередників. За таких умов важливе значення має удобрення. Тому вивчення формування урожайності та якості зерна пшениці твердої озимої залежно від системи удобрення є актуальним. Метою роботи було вивчення формування урожайності та якості зерна пшениці твердої озимої за різних систем удобрення. Дослідження проводили в умовах стаціонарного польового досліду Уманського національного університету садівництва, розміщеного в Правобережному Лісостепу України упродовж 2020–2021 рр. Дослід закладено в 2011 році. У чотирипільній польовій сівозміні вирощуються такі культури: пшениця озима, кукурудза, ячмінь ярий, соя. Схема досліду включає 11 варіантів комбінацій і окремого внесення мінеральних добрив і, в тому числі, контрольний варіант без удобрення. Збирання врожаю зерна проводили прямим комбайнуванням, вміст білка та вміст було визначено методом інфрачервоної спектроскопії, використовуючи Infratek 1241. Обробку статистичних даних було зроблено за допомогою програми STATISTICA 10. Урожайність зерна пшениці твердої озимої достовірно збільшувалась від удобрення. Проте ефективність їх застосування змінювалась залежно від року дослідження. Так, у 2020 р. вона збільшувалась у 1,1–1,2 рази (3,9–4,1 t ha^{-1}) за тривалого застосування лише азотних добрив. Тривале застосування повного мінерального добрива ($N_{150}P_{60}K_{80}$) достовірно впливало на врожайність зерна (4,3 t ha^{-1}) порівняно з варіантом N_{150}. У 2021 р. врожайність зерна зростала в 1,2–1,4 рази залежно від системи удобрення. Варто відзначити, що застосування $N_{150}P_{60}K_{40}$ і $N_{150}P_{30}K_{80}$ за впливом на врожайність зерна було на рівні варіанту $N_{150}P_{60}K_{80}$. Парні комбінації застосування добрив за ефективністю були на рівні тривалого застосування $N_{150}P_{30}K_{40}$. Застосування $N_{75}P_{30}K_{40}$ забезпечувало формування лише на 4 % меншої врожайності зерна порівняно з $N_{150}P_{30}K_{40}$. На вміст білка та вміст клейковини найбільше впливала азотна складова з повного мінерального добрива. Проведені дослідження підтверджують високу реакцію пшениці твердої на застосування азотних добрив. Отримані результати можна використовувати для прогнозування продуктивності пшениці твердої озимої залежно від родючості ґрунту

Ключові слова: азотні фосфорні та калійні добрива, продуктивність пшениці твердої озимої, вміст білка, збір білка, вміст клейковини

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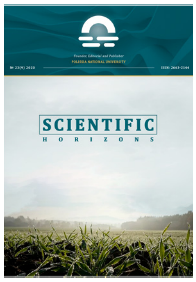

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Definition of Performance Determinants in Spring Barley by Path Analysis

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Abstract. Ambiguous results of pairwise correlation analyses and pathway analyses were obtained from different researchers. Therefore, the study of the correlation of traits and conducting a road analysis of the productivity of new genotypes using different sets of traits is relevant. The purpose of this study was to establish the correlation coefficients between the characteristics of spring barley, their direct and side effects on plant productivity, and to identify the determinants of plant selection. The research used the correlation method to determine the correlation coefficients between traits, and the method of path analysis – to establish the direct and side effects of traits on plant productivity. The positive analysis of plant productivity in the variant using quantitative traits without components of productivity revealed positive direct effects in the action on productivity and positive correlation with it traits productive bushiness as determinants of forecasting the effectiveness of high-yielding plants. In the variant using plant productivity and traits of the mass of grain from the main ear and afterspring, the path analysis found that only these two traits had a considerable direct and indirect effect in interaction with other traits on plant productivity, as well as average and high (respectively) correlation with it. Therefore, in the case of determining the mass of grain from the main ear or from the afterspring, these two separate features can also be used as determinants of the forecast of the efficiency of selection of high-yielding plants

Keywords: *Hordeum vulgare* L., quantitative trait, prediction selection efficiency, correlation, direct and effects of traits, plant performance

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INTRODUCTION

Different studies (Demidov *et al.*, 2017; Gocheva, 2014; Budacli Carpiri, 2017) on barley demonstrate the importance of determining correlations between individual traits (plant constituents, yield, weight spike) and of path analysis of the main trait, namely the plant performance. Oppositely directed (positive or negative) correlation coefficients (Hailu *et al.*, 2016; Shrimali *et al.*, 2017; Abdullah and Rihan, 2018) as well as direct and side effects of individual traits on the plant performance were determined (Gebru *et al.*, 2018; Matin *et al.*, 2019; Fatemi *et al.*, 2019). They were ambiguous depending on the accessions under study and environmental conditions. This justifies the topicality of such studies on new spring barley material, especially, on material that is used in combinatory breeding, and under various conditions of cultivation years. The authors of this paper used different sets of traits in path analysis of the performance. In analysis 1, only seven simple quantitative traits were used.

In path analysis 2, apart from simple traits (as in analysis 1), the authors used the following traits – constituents of the plant performance: grain weights per the main spike and per afterspring (i.e., from other spikes).

The grain weights per afterspring and per the main spike can be used as determinants to predict the selection of high-yielding plants.

Results of authors on the patterns of pair correlations between the individual traits of spring barley cultivars and lines as new stating material in combinatory breeding, as well as on direct and indirect effects of different traits on the plant performance are somewhat different from other researchers' results.

Availability of valuable starting material with desirable characteristics for crossing to obtain recombinant biotypes is one of the main challenges in the combinatory breeding of agricultural crops. Therefore, it is necessary to know its value both by certain traits and by their assemblages in the genotype, where they are interrelated, as the level of each of them depends on the values of other traits. In addition, relationships may depend on both genotype and growing conditions. Therefore, it is feasible to determine correlations between plant traits in cultivars and lines with different genotypic features in variable environmental conditions.

The purpose of this study was to establish the correlation between traits in spring barley cultivars and lines using pair correlation coefficients and path analysis of the plant performance (grain weight) and to define, on this basis, determinants predicting the efficiency of selection of highly productive plants.

LITERATURE REVIEW

At various stages of breeding, the selection of plants with desirable valuable traits (the effectiveness of which depends on the knowledge on correlations between them) is an essential element (Demydov *et al.*, 2017). Different researchers designed their studies to find correlations between quantitative traits of barley plants in various sets of starting materials and under various conditions. They reported positive correlations between the plant performance and other traits, in particular R. Rahimi-Baladezaie *et al.* (2011) reported positive correlations between the plant performance and productive tillering as well as between the plant performance and the grain number per spike; J. Shrimali *et al.* (2017) positive correlations were found in the plant performance with productive tillering, plant height, spike length, 1000-grain weight, and spikelet number per spike; M. Gocheva (2014) showed positive correlations of the plant performance with productive tillering, grain weight per spike, grain number per spike, and 1000-grain weight.

There were also positive correlations between other quantitative traits: between productive bushiness and the grain number per spike in R. Rahimi-Baladezaie *et al.* publication (2011); between the 1000-grain weight and grain weight per spike, between grain weight per spike and plant height, between the grain number per spike and spike length, between the grain number per spike and plant height, between the grain number per spike and spike length as well as between spike length and plant height in a study of Budacli, E. Carpici and N. Celik (2012); between the grain number per spike and grain weight per spike as well as between the grain number per spike and spike length in A. Abdullah and H. Rihan study (2018); between the total and productive tillering and plant height, between the spikelet number per spike and productive tillering, between the spikelet number per spike and plant height, between 1000-grain weight and plant height as well as between 1000-grain weight and total tillering in J. Al-Tabbal and A. Al-Fraihat study (2012); between spike length and the spikelet and grain numbers per spike, between the spikelet number per spike and grain number per spike as well as between 1000-grain weight and grain weight per spike (Gocheva, 2014).

In contrast to the above positive correlations, there were negative correlations between plant height and 1000-grain weight, between plant height and spike length, between 1000-grain weight and spike length as well as between 1000-grain weight and grain number per spike Budacli, E. Carpici and N. Celik (2012); between 1000-grain weight and the spikelet and grain numbers per spike A. Abdullah and H. Rihan (2018); between the spikelet number per spike and total tillering as well as between the spikelet number per spike and 1000-grain weight J. Al-Tabbal and A. Al-Fraihat (2012); between productive tillering and grain weight and number per spike, between 1000-grain weight and spike length, between 1000-grain weight and the spikelet number per spike as well as between 1000-grain weight and grain number per spike (Gocheva, 2014).

Correlations may be changed by growing conditions: between different elements of the plant structure depending on a growing location in A. Hailu *et al.*

experiments (2016), between plant characteristics under various watering conditions (Shrimali *et al.*, 2017).

Although pair correlation coefficients are important in determining relationships between individual quantitative traits of plants, they cannot detect relationships between trait assemblages. To evaluate the contribution of each trait to the plant performance (direct effects and side or indirect effects), path analysis of the main trait is used, analysis of the plant performance (grain weight) according to Wright's method (1934). Due to this, determinant traits are defined as criteria for predicting effective selection of plants for the main trait.

Different researchers pointed out the importance of path analysis as an effective method of statistical analysis of causes and effects in the system of interrelated characteristics of barley (plant performance, its constituents, yield, etc.) (Tawfiq *et al.*, 2016; Mirosavljević *et al.*, 2016; Bocianowski *et al.*, 2016).

In researchers' different quantitative traits were found to have positive direct effect on the plant performance: productive tillering, grain number per spike, plant height, spike, and growing period in T. Setotaw *et al.* (2014) experiments; productive tillering, as R. Drikvand published (2011); and biological yield of the plant in R. Tanaka and H. Nakano study (2019).

Different researchers used path analysis and detected different determinants as criteria of selection driven by a high positive effect on the performance and a significant correlation with it: M. Ataei (2006) suggested spike length and spikelet number per spike; R. Drikvand (2011) – productive tillering; and T. Setotaw *et al.* (2014) – vegetation period.

Thus, different researchers have proven the feasibility of determining the relationships between the main and other traits of plants using both pair correlation coefficients and path analysis of the main trait to establish direct and indirect effects of interrelated traits. However, in their studies on different barley cultivars, in different geographical locations and under various growing conditions, ambiguous results (positive or negative, moreover for different traits) were obtained on pair correlations between the performance and other quantitative traits; the same can be said about the results of path analysis the performance. Therefore, studies of correlation between traits and path analysis of the performance of new genotypes with various levels of features in different years are relevant.

MATERIALS AND METHODS

Twenty-two cultivars (Vzirets, Amil, Avhur, Ahrarii, Khors, Troian, Rezerv, Sviatomykhailivskyi, Talisman Myronivskyi, KWS Bambina, Datcha, Grace, Gladys, Quench, Margret, Merlin, Gatunok, Akhiles, Yavir, Kontrast, Krechet and Modern) and three lines (15-1246, 14-561 and 15-139) of spring barley were studied. Among them, there were two-row and six-row, awny and awnless, chaffy and naked accessions.

The cultivar trials were conducted according to the methods of qualification examination of plant varieties in 2018-2020. The predecessor was grain pea. Barley was sown with a breeding seeder SSFK-7. The plot area was 10 m^2. The experiments were carried out in four replications. The farming techniques were traditional for the crop (ploughing, tilling, spraying herbicide against weeds). Grain was harvested with a breeding combine harvester Hege-125. Plants were manually selected for analysis.

During the growing periods, phenological observations were made to determine the growing period length and to assess lodging resistance on a 9-point scale.

The plant habitus was analysed on 30 plants of each accession for 8 traits (height, productive tillering, spike length, grain number per spike, grain weight per the main spike, grain weight per afterspring (i.e., from other spikes), 1000-grain weight, grain weight per plant (performance).

In 2018-2020, the weather during the growing period of spring barley was very variable: very hot and dry in 2018; hot and dry, but with significant rainfall in May in 2019; relatively favourable in 2020. This allowed for objective evaluation of the test material.

Correlation coefficients and path analysis of performance was conducted by Wright's (1934) method and by Bryman and Cramer's method (1990) in *STATISTICA 10* to calculate the path coefficients of direct effects, as well as by factorising the correlation coefficients between the performance and each of the seven (nine) traits on the direct effect of the trait and side effects of others to obtain a matrix of corresponding path coefficients.

RESULTS AND DISCUSSIONS

In 2018-2020, the peculiarities of the pair correlation coefficients for 10 quantitative traits in 22 cultivars and three lines of spring barley were established and path analysis of the plant performance (grain weight) was conducted.

Pair correlation coefficients of the quantitative traits

Over the three study years, the relationships between the plant performance (main trait), its constituents (productive tillering, grain number per the main spike and 1000-grain weight), its components (grain weight per the main spike and grain weight per after spring), other traits (plant height and spike length), the growing period length and lodging resistance were determined (Table 1).

***Table 1**. Correlation coefficients between the traits in spring barley*

Trait	Year	Plant height	Productive tillering	Spike length	Grain number per the main spike	Grain weight per the main spike	Grain weight per afterspring	1000-grain weight	Growing period	Lodging resistance
Productive tillering	2018	0.44*	1	–	–	–	–	–	–	–
	2019	-0.08	1	–	–	–	–	–	–	–
	2020	0.25	1	–	–	–	–	–	–	–
Spike length	2018	0.68*	0.64*	1	–	–	–	–	–	–
	2019	0.60*	0.19	1	–	–	–	–	–	–
	2020	0.19	0.37	1	–	–	–	–	–	–
Grain number per the main spike	2018	0.24	0.15	0.03	1	–	–	–	–	–
	2019	0.03	-0.20	-0.13	1	–	–	–	–	–
	2020	0.14	-0.30	-0.03	1	–	–	–	–	–
Grain weight per the main spike	2018	0.30	0.31	0.34	0.77*	1	–	–	–	–
	2019	0.03	-0.20	-0.11	0.85*	1	–	–	–	–
	2020	0.08	-0.11	0.22	0.49*	1	–	–	–	–
Grain weight per afterspring	2018	0.43*	0.81*	0.43*	0.33	0.29	1	–	–	–
	2019	0.06	0.76*	0.23	0.18	0.28	1	–	–	–
	2020	0.13	0.49*	-0.10	-0.05	0.32	1	–	–	–
1000-grain weight	2018	0.07	-0.23	-0.07	-0.06	0.07	-0.19	1	–	–
	2019	0.37	0.04	-0.13	-0.24	-0.04	0.03	1	–	–
	2020	0.39	0.02	-0.09	-0.05	0.35	0.23	1	–	–
Growing period	2018	-0.06	0.04	0.19	-0.15	-0.13	-0.10	-0.46*	1	–
	2019	-0.18	-0.03	0.12	-0.20	-0.21	0.02	-0.29	1	–
	2020	-0.60*	0.00	0.21	-0.23	-0.04	-0.18	-0.29	1	–
Lodging resistance	2018	-0.08	0.20	0.06	0.21	0.37	0.23	-0.24	0.38	1
	2019	-0.36	-0.01	0.02	0.14	0.08	0.10	-0.35	0.31	1
	2020	-0.20	-0.16	-0.03	0.10	0.35	0.01	0.45*	-0.02	1
Performance (Grain weight per plant)	2018	0.47*	0.79*	0.48*	0.56*	0.61*	0.94*	-0.14	-0.13	0.32
	2019	0.06	0.46*	0.12	0.56*	0.71*	0.87*	0.00	-0.10	0.12
	2020	0.14	0.39	-0.03	0.10	0.57*	0.96*	0.30	-0.17	0.10

***Note**: * – significant at P=0.05*

The plant performance significantly, positively, and moderately correlated with productive tillering in 2018 and 2019 (r=0.79, 0.046 and 0.39 in 2018, 2019 and 2020, respectively); with the grain number per the main spike in 2018 and 2019 (r=0.056, 0.50 and 0.10, respectively), grain weight per the main spike (r=0.61, 0.71 and 0.57, respectively). The correlation was significant, positive and very strong between the performance and the grain weight per after spring (r=0.94, 0.87 and 0.96, respectively).

The 'performance – plant height' correlation was rather ambiguous across the years: significant in 2018 only (r=0.47, 0.06 and 0.14, respectively); the 'performance – spike length height' correlation was also significant in 2018 only (r=0.48, 0.12 and −0.03, respectively). The 'performance – 100-grain weight' correlation (r=−0.14, 0.00 and 0.30, respectively), the 'performance – lodging resistance' correlation (r=0.32, 0.12 and 0.10, respectively) and the 'performance – growing period' correlation (r=– 0.13, −0.10 and −0.17, respectively) were insignificant.

Thus, the pair correlation coefficients demonstrated positive correlations between the performance, productive tillering, and grain weight per afterspring. The correlation coefficients were also positive in 2018 and 2019 for the 'performance – grain number' correlation (significant in 2018 and 2019), for the 'performance – grain weight per the main spike' correlation, for the 'grain weight per the main spike – and the grain number per the main spike' correlation, for the 'spike length – plant height' correlation (significant in 2018 and 2019), and for the 'grain weight per afterspring – productive tillering' correlation. The '1000-grain weight – growing period' and 'grain number per the main spike – growing period' correlations were insignificant, with a negative trend.

Path analysis of the plant performance

As a result of determining the correlation coefficients for

2018, 2019 and 2020 between one of the 9 traits and other traits, between performance (main trait) and each of the 9 traits, as well as the path coefficients of each trait as direct effects on the performance, the correlation coefficients between the performance and each of the 9 quantitative traits were fractionalised on their direct and side (indirect) effects of the other 8 traits in the 22 varieties and three lines of spring barley under investigation.

In path analysis 1 of the performance, only seven simple quantitative traits were used (productive tillering, grain number per the main spike, 1000-grain weight, plant height, spike length, growing period, and lodging resistance). The results of the correlation fractionalisation are summarised in Table 2 – the matrix of path coefficients of each of the seven traits directly affecting the performance and side effects of the other six traits that make up a "cause-effect" system.

Table 2. *Path analysis 1 of the spring barley plant performance (Grain weight per plant) using seven traits*

Trait	Year	Plant height	Productive tillering	Spike length	Grain number per spike	1000-grain weight	Growing period	Lodging resistance	Grain weight per plant
Plant height	2018	0.099	0.289	-0.005	0.089	0.000	0.009	-0.014	0.468*
	2019	-0.110	-0.046	0.120	0.023	0.100	-0.019	-0.012	0.056
	2020	-0.261	0.144	0.010	0.029	0.155	0.070	-0.012	0.135
Productive tillering	2018	0.043	0.662	-0.004	0.056	0.000	-0.006	0.037	0.789*
	2019	0.009	0.562	0.039	-0.160	0.011	-0.003	0.000	0.458*
	2020	-0.066	0.573	-0.047	-0.091	0.009	0.000	0.012	0.389
Spike length	2018	0.067	0.425	-0.007	0.013	0.000	-0.030	0.011	0.480*
	2019	-0.066	0.109	0.200	-0.105	-0.036	0.012	0.001	0.115
	2020	-0.049	0.212	-0.126	-0.010	-0.034	-0.025	0.002	-0.027
Grain number per spike	2018	0.023	0.099	0.000	0.375	0.000	0.025	0.037	0.560*
	2019	-0.003	-0.114	-0.027	0.789	-0.064	-0.021	0.004	0.564*
	2020	-0.036	-0.170	0.004	0.305	-0.020	0.027	-0.008	0.095
1000-grain weight	2018	0.007	-0.149	0.001	-0.023	-0.002	0.074	-0.043	-0.135
	2019	-0.040	0.023	-0.027	-0.186	0.272	-0.030	-0.012	0.000
	2020	-0.103	0.013	0.011	-0.016	0.394	0.034	-0.034	0.303
Growing period	2018	-0.005	0.024	-0.001	-0.058	0.001	-0.162	0.069	-0.133
	2019	0.020	-0.015	0.023	-0.160	-0.079	0.104	0.010	-0.097
	2020	0.156	0.000	-0.026	-0.070	-0.114	-0.117	0.001	-0.169
Lodging resistance	2018	-0.007	0.135	0.000	0.078	0.000	-0.062	0.181	0.325
	2019	0.039	-0.004	0.005	0.107	-0.096	0.032	0.033	0.115
	2020	0.053	-0.091	0.004	0.031	0.179	0.002	-0.074	0.105
Performance (Grain weight per plant)	2018	0.468	0.789	0.480	0.560	-0.135	-0.133	0.325	1.0
	2019	0.057	0.458	0.115	0.564	0.000	-0.097	0.115	1.0
	2020	0.139	0.389	-0.027	0.095	0.303	-0.169	0.105	1.0

Note: *unaccounted factors (residues) ranged from 0.001 to 0.01;* – significant at P=0.05*

The matrix structure corresponds to a system of seven equations with seven direct effects multiplied by the correlation coefficient of the respective seven traits.

Path analysis of the performance showed that the direct effects of each of the seven traits on the performance (on the central diagonal of Table 2), side effects of the other six traits in the 'each of the seven traits – performance' correlations (horizontally of each of the seven traits), and side effects of each of the seven traits in the 'performance – the other six traits' correlations (vertical of each of the seven traits) were not equal, and their values and directions depended on the years of plant cultivation.

Thus, it was found that the strong or moderate in 2018-2019 and insignificant in 2020 correlation coefficients between the performance and productive tillering (r=0.789, 0.458 and 0.389, respectively, across the years) depended on a significant direct positive effect of the latter (0.662, 0.562 and 0.573, respectively) and on insignificant in 2018 positive side effects of the plant height, grain number per main spike, and lodging resistance (0.043, 0.056 and 0.037, respectively); in 2019, on a negative effect of the grain number per main spike (–0.160) and a positive effect of the spike length (0.039); in 2020; slight negative effects of the plant height (–0.066), spike length (–0.0147) and the grain number per main spike (–0.091).

The moderate in 2018 and 2019 and insignificant in 2020 correlation coefficient between the performance and grain number per the main spike (r=0.560, 0.564 and 0.095, respectively, across the years) depended on the significant direct effect of the latter (0.375, 0.789 and 0.305, respectively); in 2018, on the cumulative slight positive side effects of the plant height (0.023), productive tillering (0.099), growing period (0.025) and lodging resistance (0.037) (the sum amounted to 0.184); in 2019 – on negative side effects of productive tillering (−0.114), spike length (−0.027), 1000-grain weight (−0.064), and growing period (−0.021) (the sum amounted to −0.226); in 2020, on negative side effects, mainly of productive tillering (– 0.170), which considerably offset the direct effect (0.305), so the correlation was very weak (r=0.095).

The correlation coefficient between the performance and plant height was ambiguous across the years, reaching significance in 2018 only (r=0.468, 0.056 and 0.135, respectively). This can be attributed to the fact that in 2018 there was a positive direct effect of the plant height, a slight side effect of the grain number per the main spike, and a significant effect of productive tillering (0.099, 0.089 and 0.289, respectively).

In the three years, the direct effect of the spike length on the performance varied (−0.007, 0.200 and −0.126, respectively): it was negligibly small in 2018 (but with a significant positive side effect of productive tillering (0.425) and slight effects of the plant height and other traits), positive in 2019 (with a positive side effect of productive tillering (0.109), but with a negative effect of the grain number per spike, plant height and 1000-grain weight (−0.105, −0.066 and −0.036, respectively), negative in 2020 (with a positive side effect of productive tillering (0.212), but with negative side effects of the plant height (−0.049), 1000-grain weight (−0.034) and growing period −0.025). All this resulted in various levels of correlation between the performance and spike length: moderate in 2018, very weak in 2019 and negligibly small in 2020 (r=0.480, 0.115 and −0.027, respectively).

Thus, under the arid conditions of 2018 and 2019, was a positive direct effect of productive tillering on the performance and a positive significant correlation between the performance and productive tillering (an constituent of the performance), which may be used as a determinant for prediction and selection of highly productive plants in arid conditions (which were in 2018 and 2019, while under the more favourable conditions in 2020, we only noticed a trend).

In path analysis 2 of the performance, all possible traits were used: not only seven simple traits (as in analysis 1), but also traits – components of the performance: grain weight per the main spike and grain weight per afterspring (i.e., grain from other spikes), which sum to the plant performance.

The results of fractionalisation of the correlations between the performance and nine traits are summarised in Table 3 – the matrix of path coefficients as direct effects of each of the nine traits on the performance and side effects of the other eight traits.

***Table 3**. Path analysis 2 of the spring barley plant performance using 10 traits*

Trait	Year	Plant height	Productive tillering	Spike length	Grain number per spike	Grain weight per spike	Grain weight per afterspring	1000-grain weight	Growing period	Lodging resistance	Correlation with the performance
Plant height	2018	0.011	0.002	-0.018	-0.004	0.116	0.362	-0.001	-0.001	0.001	0.468*
	2019	-0.003	-0.001	0.007	0.000	0.015	0.041	0.000	0.002	-0.004	0.056
	2020	0.006	0.001	-0.003	-0.001	0.025	0.114	-0.001	-0.001	0.003	0.135
Productive tillering	2018	0.005	0.005	-0.017	-0.002	0.121	0.682	0.002	0.000	-0.004	0.789*
	2019	0.000	0.008	0.002	0.002	-0.100	0.548	0.000	0.000	0.000	0.458*
	2020	0.002	0.003	-0.006	0.002	-0.035	0.416	0.000	0.000	0.002	0.390
Spike length	2018	0.007	0.003	-0.026	-0.001	0.134	0.358	0.001	0.002	-0.001	0.480*
	2019	-0.002	0.002	0.012	0.001	-0.056	0.168	0.000	-0.001	0.000	0.115
	2020	0.001	0.001	-0.015	0.000	0.068	-0.090	0.000	0.000	0.000	-0.027
Grain number per spike	2018	0.003	0.001	-0.001	-0.016	0.304	0.278	0.001	-0.002	-0.004	0.560*
	2019	0.000	-0.002	-0.002	-0.008	0.438	0.129	0.000	0.003	0.001	0.564*
	2020	0.001	-0.001	0.001	-0.007	0.151	-0.046	0.000	0.000	-0.001	0.095
Grain weight per spike	2018	0.003	0.002	-0.009	-0.012	0.393	0.242	-0.001	-0.001	-0.007	0.609*
	2019	0.000	-0.002	-0.001	-0.007	0.515	0.199	0.000	0.003	0.001	0.708*
	2020	0.000	0.000	-0.003	-0.003	0.308	0.276	-0.001	0.000	-0.005	0.572*
Grain weight per afterspring	2018	0.005	0.004	-0.011	-0.005	0.113	0.837	0.002	-0.001	-0.004	0.940*
	2019	0.000	0.006	0.003	-0.001	0.143	0.718	0.000	0.000	0.001	0.869*
	2020	0.001	0.001	0.002	0.000	0.099	0.858	-0.001	0.000	0.000	0.960*

Table 3, Continued

Trait	Year	Plant height	Productive tillering	Spike length	Grain number per spike	Grain weight per spike	Grain weight per afterspring	1000-grain weight	Growing period	Lodging resistance	Correlation with the performance
1000-grain weight	2018	0.001	-0.001	0.002	0.001	0.026	-0.161	-0.011	-0.005	0.004	-0.135
	2019	-0.001	0.000	-0.002	0.002	-0.018	0.018	-0.001	0.004	-0.004	0.000
	2020	0.002	0.000	0.001	0.000	0.109	0.198	-0.003	0.000	-0.006	0.303
Growing period	2018	-0.001	0.000	-0.005	0.002	-0.052	-0.085	0.005	0.010	-0.007	-0.133
	2019	0.001	0.000	0.001	0.002	-0.110	0.012	0.000	-0.013	0.003	-0.097
	2020	-0.004	0.000	-0.003	0.002	-0.012	-0.156	0.001	0.001	0.000	-0.169
Lodging resistance	2018	-0.001	0.001	-0.002	-0.003	0.147	0.189	0.003	0.004	-0.019	0.325
	2019	0.001	0.000	0.000	-0.001	0.043	0.072	0.000	-0.004	0.011	0.115
	2020	-0.001	0.000	0.000	-0.001	0.107	0.005	-0.001	0.000	-0.013	0.105

***Note**: unaccounted factors (residues) ranged from 0.001 to 0.01; * – significant at P=0.05*

Path analysis of the performance showed that the direct effects of the nine traits and side effects of the other eight traits indirectly related to the performance through each of the nine traits unequally contributed to the performance.

The grain weight per the main spike had a positive direct effect on the performance in the three study years (2018-2020) (0.393, 0.515 and 0.308, respectively). In the relationships of this trait with the performance (horizontally), the side effect of the grain weight per afterspring (0.242, 0.199 and 0.246, relatively) was positive and the side effects of the other seven traits were insignificant. This was manifested as a significant positive correlation between the performance and the grain weight per spike (r=0.609, 0.708 and 0.572, respectively). For the three years, the side positive effect of the grain weight per spike in the relationships of the performance with other traits (vertically in Table 3) was with the grain number per spike (0.304, 0.438 and 0.151, respectively), grain weight per afterspring (0.113, 0.143 and 0.099, respectively), and lodging resistance (0.147, 0.043 and 0.107, respectively).

In all three years, the positive direct effect of the grain weight per afterspring (0.837, 0.718 and 0.858, respectively) on the performance was significant. In the relationships of this trait with the performance (horizontally), the positive side effect was exerted by the grain weight per the main spike (0.113, 0.143 and 0.099, respectively), while the side effects of the other traits were negligible. This was ultimately expressed in a very strong correlation between the performance and the grain weight per afterspring (r=0.940, 0.869 and 0.960, respectively). For all three years, the positive side effect of this trait in the relationships of the performance with other traits (vertically in Table 3) was noticed with the grain weight per spike (0.242, 0.199 and 0.246, respectively), productive tillering (0.682, 0.548 and 0.416, respectively) and plant height 0.362, 0.041 and 0.114, respectively).

The direct effects on the performance in the action of the other eight traits were negligible. Only due to significant, moderate, or weak, side effects of the grain weight per spike and the grain weight per afterspring, the correlation coefficient of some of them with the performance were positive.

Thus, there was a positive, mainly moderate, correlation between the performance and productive tillering (significant in 2018 and 2019 (r=0.793, 0.460 and 0.385, respectively), with almost zero direct effect of the latter (0.005, 0.008 and 0.003, respectively), but with a significant side effect of the grain weight per afterspring (0.682, 0.548 and 0.416, respectively). There was a moderate positive correlation between the performance and grain number per the main spike in 2018 and 2019 (r=0.563 and 0.559, respectively), which can be attributed to the side effects, mainly of the grain weight per the main spike (0.304 and 0.438, respectively) and the grain weight per afterspring (0.278 and 0.129, respectively). There was a moderate significant in 2018 and weak insignificant in 2019 correlation (r=0.477 and 0.124, respectively) between the performance and the spike length, mainly due to the positive side effect of the grain weight per afterspring (0.358 and 0.168, respectively). In 2018-2020, there was a positive correlation between the performance and the plant height (significant in 2018 (r=0.468, 0.056 and 0.135, respectively) due to the side effects, mainly of the grain weight per afterspring (0.362, 0.041 and 0.114, respectively) and the grain weight per the main spike (0.116, 0.015 and 0.025, respectively). There was a weak insignificant correlation in all three years between the performance and the growing period (r=−0.132, −0.104 and −0.171, respectively) mainly due to the negative side effects of the grain weight per the main spike (−0.052, −0.110 and −0.012, respectively) and the grain weight per afterspring (−0.085, −0.012 and −0.156, respectively). The correlation between the performance and the 1000-grain weight was insignificant and ambiguous across the years (r=−0.144, −0.002 and 0.302, respectively), with the ambiguous side effects of the grain weight per afterspring (−0.161, 0.028 and 0.198, respectively) and the grain weight per the main spike (0.096, −0.018 and 0.109, respectively).

Thus, the 'grain weight per the main spike' and 'grain weight per afterspring' traits as constituents of the plant performance have significant direct effects on the performance and significantly correlate with it. Therefore, these two traits are determinants predicting the effectiveness of selection of highly productive plants.

Different studies on barley demonstrated the importance of determining correlations between individual traits (plant constituents, yield, weight spike) and of path analysis of the main trait, in particular the plant performance. Oppositely directed positive correlation coefficients between different elements of the plant structure depending on a growing location (Hailu *et al.*, 2016), between the plant performance with productivity tillering, plant height, spike length, 1000-grain weight (Shrimali *et al.*, 2017), between the grain number per spike and grain weight per spike (Abdullah and Rihan, 2018) were showed. As well as direct and side effects of individual traits on the plant performance were determined (Gebru *et al.*, 2018; Matin *et al.*, 2019; Fatemi *et al.*, 2019). They were ambiguous depending on the studied accessions and environmental conditions. This justifies the topicality of such studies on new spring barley material, especially, on material that is used in combinatory breeding, and under various conditions of cultivation years.

Our results on the patterns of pair correlations between the individual traits of spring barley cultivars and lines as new stating material in combinatory breeding, as well as on direct and indirect effects of different traits on the plant performance are somewhat different from other researchers' results.

Thus, for all three years, there was a positive pair correlation between the plant performance and productive tillering and between the performance and the grain number per the main spike (significant under the arid conditions in 2018 and 2019). like in the experiments of R. Rahimi-Baladezaie *et al*. (2011), Shrimali (2017) (in addition, he found correlations of the plant performance with the plant height, spike length and 1000-grain weight), M. Gocheva (2014) (she also had a correlation between the plant performance and 1000-grain weight). In our study, there was also a positive correlation between the performance and the grain weight per the main spike, like in Gocheva' experiments (2014); and a positive correlation between the performance and the grain weight per afterspring.

These four traits (productive tillering, grain number per the main spike, grain weight per the main spike, and grain weight per afterspringt), proceeding from the positive pair correlation, but without taking into account the indirect effects of other traits, could be used as "guidepost" to select productive plants.

For all three years, there was a positive correlation between the grain weight per the main spike and the grain number per the main spike (but not between the grain weight per the main spike and the plant height) and between the spike length and the plant height (similar results were obtained by Budacli, E. Caprici and N. Celik (2012).

There was an insignificant, with a tendency to negative, correlation between the 1000-grain weight and the growing period and between the performance and the growing period. However, in Budacli Caprici and Celik' experiments (2012), there were negative correlations between other traits (plant height and 1000-grain weight, plant height and spike length, 1000-grain weight and spike length, 1000-grain weight and grain number per spike) and J. Shrimali *et al*. (2017) reported about negative correlations between the 1000-grain weight and the grain number per spike.

As different researchers pointed out, to establish the correlations between several traits, it is important to determine not only correlations between individual traits, but also their contributions to the main trait, namely to the plant performance, by their direct effects and side effects of other traits. In this regard, different researchers reported conflicting data: R. Drikvand *et al*. (2011) reported about a direct effect of productive tillering on the plant performance; M. Ataei (2006) – about direct effects of the spike length and spikelet number per spike on the performance; T. Setotaw *et al*. (2014) – about direct effects of productive tillering, grain number per spike, plant height, spike length and growing period; R. Tanaka and H. Nakano (2019) revealed the direct effect of the biological productivity of the plant. These traits also positively correlated with the plant performance and were therefore considered as predicting determinants or as selection criteria.

The authors of this study used different sets of traits in path analysis of the performance. In analysis 1, only seven simple quantitative traits were used. These traits (three constituents of the performance – productive tillering, grain number per spike ear and 1000-grain weight; other traits – plant height, spike length, growing period, and lodging resistance).

Here, the authors of this paper noticed the unequal direct and side effects of different quantitative traits on the performance; values and directions of these effects depended on the conditions of cultivation of 22 cultivars and three lines of spring barley in the study years.

In all three years, the positive direct effects on the performance were exerted by the following traits: productive tillering (0.662, 0.562 and 0.573, respectively) and the grain number per the main spike (0.375, 0.789 and 0.305, respectively).

Considering the positive and negative side effects of the other six traits, the results summed to the positive correlation coefficients between the performance and productive tillering (significant in 2018 and 2019, under the arid conditions (r=0.789, 0.458 and 0.389, respectively). These traits can be used as a predicting determinant in selection of highly productive plants, mainly under arid conditions, while under the more favourable conditions (in 2020), a tendency was only observed.

In path analysis 2 of the performance, we used, in addition to simple signs (as in analysis 1), the following traits – constituents of the plant performance: grain weights per the main spike and per afterspring (i.e., from other spikes).

These two components of the performance had significant direct and side (in interaction with other traits) effects on the performance. The positive side effect of these traits was with each other: grain weight per the main spike – grain number per the main spike, grain weight per afterspring – productive tillering; in two years, the positive side effects were with the plant height, spike length and grain number per the main spike. This was expressed in their positive correlations with the performance. The other traits did not have significant direct or side effects on the performance.

Another component of the performance, the grain weight per afterspting had a very strong direct effect (0.837, 0.718 and 0.858, respectively) on the plant performance and strongly correlated with it (r=0.940, 0.718 and 0.858, respectively). The grain weight per the main spike, as a component of the performance, had a significant direct effect on the performance (0.393, 0.515 and 0.308, respectively) and moderately correlated with it (r=0.609, 0.708 and 0.572, respectively). Therefore, the grain weights per afterspring and per the main spike can be used as determinants to predict selection of high-yielding plants.

CONCLUSIONS

According to the purpose of this study and the task to establish independence of the plant traits for three years (2018-2020), there were positive moderate coefficients of pair correlation between the plant performance and productive tillering (significant for 2018 and 2019 (r=0.789, 0.458 and 0.390, respectively, across the years), moderate coefficients (2018-2019) between the plant performance and the grain number per the main spike (r=0.789 and 0.458, respectively; insignificant r=0.095 in 2020), moderate coefficients (2018-2020) between the plant performance and the grain weight per the main spike (r=0.609, 0.708 and 0.572, respectively), and high coefficients between the plant performance and the grain weight per afterspring (r=0.940, 0.869 and 0.960, respectively). The positive interdependence of the following three traits was revealed: plant performance, productive tillering, and grain weight per afterspring.

The study established direct and side effects of the traits in path analysis of the plant performance using seven simple traits (productive tillering, grain number per the main spike, 1000-grain weight, plant height, spike length, growing period, and lodging resistance) and for all three years (2018-2020), the results showed the significant positive direct effects of productive tillering on the performance (significant in arid 2018 and 2019 [0.662, 0.562 and 0.573, respectively, across the years]) and positive moderate correlations with it (r=0.789, 0458 and 0.389, respectively), and therefore productive tillering constitutes a determinant predicting selection of highly productive plants.

Path analysis of the plant performance using both simple traits of plants and traits – constituents of the plant performance (grain weight per the main spike and grain weight per afterspring) established that only these two traits-components had significant direct effects (0.393, 0.515 and 0.308, respectively, and 0.837, 0.718 and 0.858, respectively, by traits and years) and side effects in interaction with other traits on the plant performance and moderately or strongly, respectively, correlated with it (r=0.609, 0.708 and 0.572, respectively, and r=0.940, 0.869 and 0.860, respectively). Therefore, the grain weights per the main spike and per afterspring can also be used as determinants to predict the effectiveness of selection of high-yielding plants, which are able to become valuable lines in the breeding process.

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Визначення детермінантів продуктивності ячменю ярого шляховим аналізом

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Анотація. В різних дослідників було одержано неоднозначні результати аналізів парної кореляції та шляхового аналізу. Тому дослідження кореляції ознак і проведення шляхового аналізу продуктивності нових генотипів з використанням різних наборів ознак є актуальним. Метою дослідження було встановлення коефіцієнтів кореляції між ознаками ячменю ярого, прямих і побічних їх ефектів на продуктивність рослини та визначення детермінантів добору рослин. У дослідженнях використано метод кореляції для визначення коефіцієнтів кореляції між ознаками, а метод шляхового аналізу — для встановлення прямих і побічних ефектів ознак на продуктивність рослини. Шляховим аналізом продуктивності рослин у варіанті з використанням кількісних ознак без складових продуктивності установлено позитивні прямі ефекти в дії на продуктивність і позитивну кореляцію з нею ознаки продуктивна кущистість як детермінанти прогнозу ефективності добору високопродуктивних рослин. У варіанті з використанням в шляховому аналізі продуктивності рослин також і ознак-складових її (маси зерна з основного колоса та підгону) установлено, що лише ці дві ознаки-складові мали значний прямий і побічний у взаємодії з іншими ознаками ефект в дії на продуктивність рослини, а також середній та високий (відповідно) рівень кореляції з нею. Тому, в разі визначення маси зерна з основного колоса або з підгону, ці дві окремі ознаки також можна використати як детермінанти прогнозу ефективності добору високопродуктивних рослин

Ключові слова: *Hordeum vulgare* L., кількісна ознака, прогноз ефективності добору, кореляція, прямий і побічний ефект ознак, продуктивність рослини

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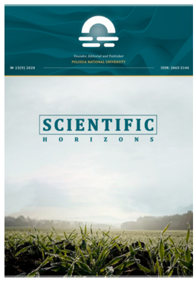

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Herbicidal Effects of *Chenopodium murale* and *Coronopus didymus* Sm. Residues Against Germination and Early Growth of *Hordeum vulgare*

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Abstract. This study reports the common problems of weed species that adversely affect the crop productivity of the agriculture crops at a large scale. The purpose of this study is to investigate the impact of dried application of *Chenopodium murale* and *Coronopus didymus* on seed germination and early growth of *Hordeum vulgare*. The experiment was performed in a randomised block design with three replications under the greenhouse condition in pot culture. Shoots and roots materials were separately dried in shade for 15-20 days, dry powdered shoot and root residues of *C. murale* and *C. didymus* were applied at 5 and 10 g kg^{-1} doses to barley seeds in 6 pots with control for three weeks. *C. didymus* (10 g) shoot residues were most inhibitive against germination (31.16%), GVI (0.85), SVI (4.90) and leaf area (3.94 cm^2) of barley while 5 g root residues of the weed had least pronounced effect. Root length, shoot length, and dry biomass were most inhibited by *C. murale* 10 g in both shoot and root residue treatments. Shoot residues were more inhibitive of germination and growth than root residues of both weeds. Chlorophyll accumulation patterns showed mixed results with some treatments even stimulating their concentrations. Root treatments were in general more inhibitive than shoot treatments. All treated seedlings exhibited higher levels of proline accumulation compared to control. At lower dose, *C. murale* treatments were more inhibitive than *C. didymus* treatments. There is a great scope of research on these species to isolate and identify the active factors and also to understand their implication in the biocontrol of weeds apart from their potential negative effects on agricultural crops, especially cereal crops, which can be useful to increasing crop production in northern India, namely in Uttar Pradesh

Keywords: agriculture activity, allelopathy, seed germination, proline estimation, biomass production, weed residues

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INTRODUCTION

Weeds are undesirable as they compete with crops for moisture, nutrients, and light. Although these are non-native plants, but their spreading and fast-growing nature makes it as a huge threat to the growing crop species. They have persisted as a huge problem for farmer ever since the beginning of agriculture because they cause high economic loses of crop producers in crops yield, increase costs of crop production and reduced crop quality (Bhular *et al.*, 1998). Identification of distinct species of weed plants with allelopathic potential and characterisation of their adverse effects on associated crops are essential to understand weed-crop interactions in agro-ecosystems. The crop growth can also be influenced through exudates secreted from weeds commonly known as allelochemicals into the surrounding habitat (Kadioglue *et al.*, 2005). Farmers are thus compelled to use chemical weedicides which adversely affect the yield, consumer health, and the environment. Allelochemicals are secondary metabolites released from leaves, stem, roots, fruits, and seeds which may delay or completely inhibit seed germination of target plant and result in stunted root and shoot proliferation. They represent a wide pool of chemical compounds with an equally wide range of possible uses. Plants having allelopathic properties may be prospered as a cover crop or their residues incorporated to prevent other weeds/pests. They may increase fertility because it is organic matter being added. Some workers are exploring their use as bioherbicides as they are considered safer than synthetic chemicals. In such ways their negative properties can be used in positive ways (Zeng *et al.*, 2008).

Barley ranks 5th among the world-wide produced crops (Soleymani & Shahrajabian, 2011). An annual crop, it is used for food, brewing malt beverages, and livestock feed. *Chenopodium murle* is an annual weed that can grow in most environmental and soil conditions (Guertin, 2003). It produces cyanogenic glycosides, saponins, tannins, naphthoquinones, alkaloids, and flavonoids (Verma & Agarwal, 1985). *Coronopus didymus* has some medicinal uses (Prabhakar *et al.*, 2002). It belongs to family Brassicaceae known to produce allelochemicals such as glucosinolates (Bones & Rossiter, 1996). Such compounds restrict their value as a feed or fodder but indicate their potential use as a natural weedicide.

The purpose of this study was to explore the potential of shoot and root residues with allelopathic properties of *C. murale* and *C. didymus* against germination, growth, and biochemical parameters of barley and to make comparisons based on plant, plant part, and dosage used.

MATERIALS AND METHODS

The greenhouse experiment was set up to assess the allelopathic potential of the two weeds selected for the study of seed germination and productive physiological growth of barley at the Department of Botany, School of Life Sciences, Dr. B.R. Ambedkar University, Khandari Campus, Agra during February–June 2015.

Two weeds (*Chenopodium murale* and *Coronopus didymus*) were collected in polythene bags, brought to laboratory, and air-dried in shade for about 15-20 days and then powdered and stored at 5°C till further use. Pots (6” diameter) were filled with soil (soil sand ratio 3:1) previously sterilised in an autoclave at 121ºC and 12-14 psi for about 25 minutes. Shoot/root powder from each selected weed was applied separately to all treated pots at 5 g and 10 g soil. The control set up was maintained with no residual treatment.

A completely randomised block design (RBD) was laid out on the whole experiment with three replicates and control. Barley seeds were washed with distilled water and surface sterilised with 5% Bavistin (2.5 g/100ml distilled water) and 0.1% mercuric chloride (0.10 g/80 ml distilled water). Fifteen seeds were sown in each pot and observed for three weeks. All pots were watered with tap water. Number of seeds germinated was recorded every day. The measurement of the experiment started when the seedlings reached 2 mm in height. After three weeks of germination, shoot/root length and dry biomass were measured. To obtain the dry biomass, the samples were thoroughly washed with water, dried on blotting paper, and were then placed in an oven.

Germination percentage was computed according to AOSA (1990); Germination Velocity Index [GVI] according to AOSA (1983) and Seedling Vigour Index [SVI] according to A. Abdul-baki and J. Anderson (1973). Leaf area was determined by using graph paper method where the leaves were outlined on graph paper and the covered square area was measured (Taghipour & Salehi, 2008). The dry biomass was taken after thorough washing and drying at 60ºC to constant weight. Chlorophyll (Chlorophyll a and Chlorophyll b) and proline estimation was done as per D. Arnon (1949) and L.R.P. Bates *et al.* (1973), respectively. Three ways of variance analysis were performed for the data and the mean differences were separated using Fisher’s LSD test at 5% probability level. Graphical representation of the data was made, and standard errors were computed using MS Excel.

RESULTS AND DISCUSSION

Treatment with *C. didymus* (10 g) shoot residue was most inhibitive against germination (31.16%), GVI (0.85), and SVI (4.90) of barley while 5 g root residues of the weed had the least pronounced effect. Maximum reduction in shoot length (15.44 cm) was observed in seedlings treated with 10 g shoot residues of *C. murale*, slightly more than in those treated with 10 g of *C. didymus* root residues (15.67 cm) (Table 1). Least inhibition was observed in 5 g root residue treatment of *C. didymus* (25.23 cm). Root length and dry biomass were most inhibited by *C. murale* 10 g treatments in both shoot and root residue treatments. In general, shoot residues were more inhibitive of growth parameters with least inhibition observed in 5 g root residue treatments of *C. didymus*. The effects were dose dependent.

***Table 1**. Germination and growth parameters of barley seedlings*

Weeds	Part used	Concentration	Germination %	GVI	SVI	Leaf Area (in cm²)	Shoot Length (in cm)	Root Length (in cm)	Dry Biomass (in g)
Control		–	95.6±3.81	10.4±1.03	26.3±2.59	12.06±0.75	27.47±1.7	20.24±1.8	36.54±1.16
C. murale	Shoot	5 g	75.6±15.40	4.92±0.17	14.97±3.07	8.8±0.46	19.8±0.5	12.27±1.5	28.04±0.87
		10 g	62.23±36.71	2.6±2.11	9.39±5.30	7.53±0.65	15.44±0.9	6.97±1.8	25.44±0.65
	Root	5 g	91.16±3.87	8.98±2.09	21.98±1.63	11.13±1.19	24.1±1.0	15.3±1.2	34.0±0.72
		10 g	88.93±4.0	6.86±2.22	19.89±1.33	10.7±0.56	22.36±0.6	14.8±0.3	29.84±2.22
C. didymus	Shoot	5 g	86.7±6.70	6.70±2.14	20.79±2.06	10.83±1.27	23.97±0.7	15.2±0.6	31.44±1.74
		10 g	31.16±20.37	0.85±0.65	4.90±3.20	3.94±0.64	15.67±0.7	8.6±1.3	29.9±4.52
	Root	5 g	93.36±6.65	10.29±0.39	23.55±2.77	11.93±1.15	25.23±2.4	19.17±2.3	35.4±3.46
		10 g	91.16±3.87	9.95±2.40	22.2±2.59	11.23±2.17	24.26±2.7	17.97±3.9	32.2±0.50

Thus, at the higher dose, *C. didymus* shoot residues in soil inhibited the germination of barley seeds the most (germination %, GVI, and SVI). At the same dose, *C. murale* affected growth parameters of growth in root length, shoot length, and dry biomass the most. Thus, the two weeds had different effects on different parameters of the test plant (Table 1). Allelochemicals can reduce cell division or interfere with auxin, the phytohormone which influences shoot and root growth (Gholami *et al.*, 2011). A. Enyew and R. Nagapan (2015) found that leaf powder of *Lantana camara* at higher dose (75 g) inhibits the germination percentage, root and shoot length, stem thickness and biomass of *Zea mays* and *Triticum aestivum*. *Ocimum basilicum* shoot residues in soil have been demonstrated to reduce plant height, leaf number, root length and total biomass of cereal crops (Dafaallah *et al.*, 2017).

Leaf area trends were similar to GVI and SVI. Least leaf area of barley was observed in. *C. didymus* (10 g) shoot residue treatments, while highest readings were observed in 5 g root residue treatment of the same weed. Shoot treatments were more inhibitive while the difference in leaf area patterns among the root residue treatments of both species was not very pronounced. Such reduction in leaf area of test plants in response to different allelopathic species has been reported earlier on *Convolvulus arvensis* due to powder treatments of *Ricinus communis*, *Nicotiana tabacum*, *Datura inoxia,* and *Sorghum vulgare* (Nekoman *et al.*, 2013).

Apart from maximum inhibition of growth parameters at a higher dose, it is interesting to note that at a lower dose, both shoot and root treatments of *C. murale* were more inhibitive than *C. didymus* treatments. Such effects of this weed on growth and photosynthesis of barley have been reported by N. Al-Johani *et al.* (2012). In other studies, *C. murale* extracts suppressed shoot length, shoot biomass, total root length, number of roots and root biomass of test plants (Shafique *et al.*, 2011; Gautam *et al.*, 2018).

Allelochemicals can stimulate chlorophyll degrading pathways and affect the photosynthetic potential and thus the growth of target plant. Chlorophyll accumulation trends in test seedlings under study were variable (Fig. 1 A-C). Root treatments were generally more inhibitive than shoot treatments. Root residue treatments at 10 g dose of *C. murale* affected chlorophyll 'a' content the most while those of *C. didymus* inhibited chlorophyll 'b' and total chlorophyll contents. Effect of higher doses of *C. didymus* root and *C. murale* shoot on total chlorophyll content was almost similar (0.245 and 0.246 μg g^{-1} fw, respectively). Despite their inhibitory effect on most test seedling parameters, most treatments of. *C. didymus* and some of *C. murale* showed a positive effect and enhanced chlorophyll content in test seedlings. Three out of eight treatments showed increased chlorophyll 'a' content over control; five showed increased chlorophyll 'b' content and four showed increased levels in total chlorophyll. This again indicates the complex nature of the interactions evaluated and their sensitivity to plant part, dose, and test plant used. Both inhibitory and stimulatory activities of *Mimosa pigra* leaf residues have been reported on *Ruellia tuberosa* and *Portulaca oleracea* (Koodkaew & Rottasa, 2017). W. Al-Taisan (2014) reported inhibition of total chlorophyll in leaves of *Oryza sativa* and *Teucrium polium* due to *Heliotropium bacciferum* leaf extract at higher dose but stimulation of same total chlorophyll at lower doses. T. Vaithiyanathan *et al.* (2014) recorded the highest inhibition of photosynthetic pigments of *Abelmoschus esculentus* due to root extracts of *Azadirachta indica.* Similar findings have also been reported in the case of *C. didymus* leaf extract on *Triticum aestivum* (Khaliq *et al*., 2015) and *Azadirachta indica* leaf extracts on *Vigna radiata* seedlings (Shruthi *et al*., 2015).

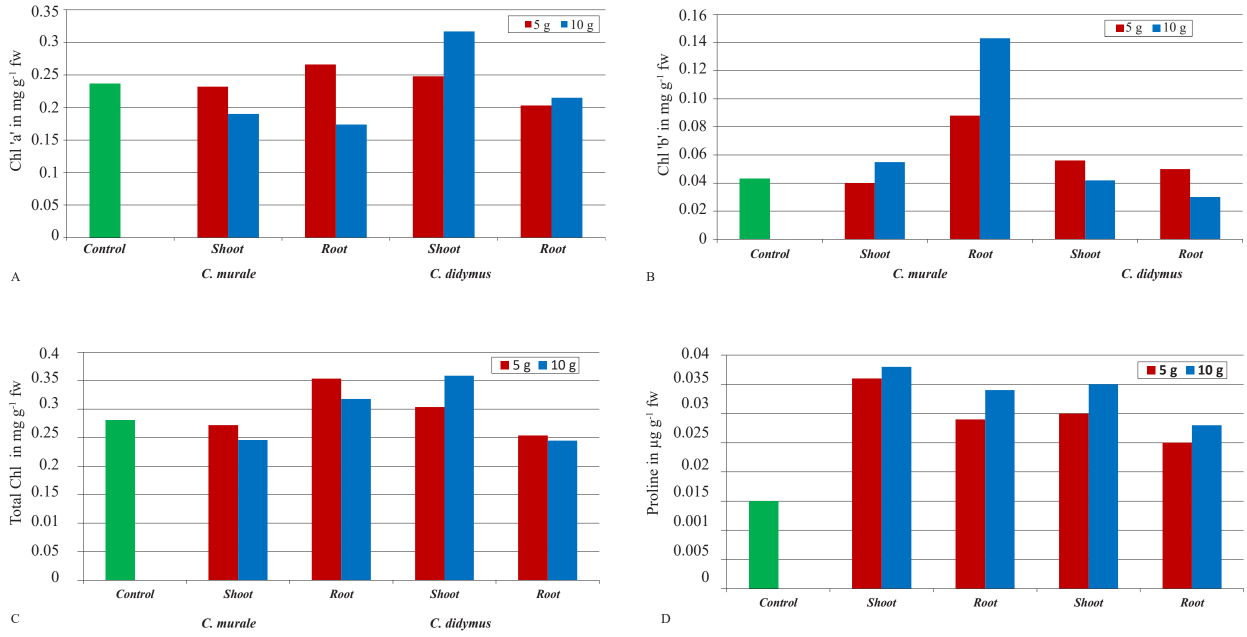

Figure 1. *Biochemical parameters of barley seedlings (A) chlorophyll 'a' (B) chlorophyll 'b' (C) total chlorophyll and (D) proline*

Proline is an osmoprotectant which increases tolerance of plants as an important part of structural proteins and enzymes. All treated seedlings showed increased proline accumulation in leaves, which was directly proportional to dose applied (Fig. 1 D). Shoot residues of *C. murale* (10 g and 5 g) promoted maximum proline content. Proline accumulation due to *C. didymus* 10 g shoot treatment was comparable to that of *C. murale* 5 g shoot treatment. Similar mode of effectiveness was inspected in case of root treatments too. In general, shoot residues caused greater proline accumulation indicative of greater stress as was clearly seen in germination and growth parameters. The effect was dose dependent. W. Al-Taisan (2014) reported dose dependent proline accumulation in leaves of *Oryza sativa* and *Teucrium polium* due to *Heliotropium bacciferum* leaf extracts. Similar increased proline levels have been documented in *Vigna unguiculata* (Oyeniyi *et al.*, 2016) and *Phaseolus aureus* (Christobel *et al.*, 2017) in response to allelochemicals.

Results show a statistically significant difference ($P \leqslant 0.01$) in the mean values of root length, shoot length and dry biomass of barley, based on the weed residue used. Similar findings were received for GVI, and dry biomass based on plant part (root/shoot) and concentrations used. The effect of different weed on mean chlorophyll 'a', chlorophyll 'b' and total chlorophyll concentrations depended on the plant part (shoot/root) used as indicated by the statistically significant interaction between weed and plant part. Significant interaction between weed and concentration was also seen for mean chlorophyll 'a' and 'b' concentrations; and between plant part and concentration for germination percentage, root length, shoot length, and chlorophyll 'a'. The interaction between weed × plant part × concentrations was statistically significant for mean values of SVI, leaf area, and proline.

Fisher's Least Significant Difference (LSD) test indicated significant difference between mean values of root length, shoot length, dry biomass, chlorophyll 'a', chlorophyll 'b' and proline based on weed (*C. murale* vs. *C. didymus*) used. Similar differences were obtained in values of germination percentage, GVI, SVI, root length, shoot length, dry biomass, leaf area, chlorophyll 'a' and 'b' based on plant part (root vs. shoot) used; and in values of germination percentage, GVI, SVI, root length, shoot length, dry biomass, leaf area, and proline based on concentration (5 g vs. 10 g) used.

CONCLUSIONS

In-vitro studies attempt to understand plant-soil-microbe interactions in a somewhat isolated microhabitat and the results are sometimes oversimplified. This study recommends the dry powder application of the selected these two weed species; *C. murale* and *C. didymus* had measurable inhibitory effect on most of the testing parameters of barley. The results obtained indicated that the higher applied dose had more negative effects. *C. murale* at 10 g dose was found most effective against shoot length, root length, dry biomass, chlorophyll 'a' and total chlorophyll content while germination percentage, GVI, SVI and leaf area were most affected under the application of *C. didymus* at 10 g dose. On the other hand, lower doses of both weeds considerably reduced the chlorophyll 'b' and proline content. Exceptionally, chlorophyll 'a' and total chlorophyll content were found to show positive effect at 5 g and 10 g doses of *C. murale* and *C. didymus,* respectively. Furthermore, the degree of inhibition of allelopathic plants depends not only on the dose applied but also on the plant part used due to different concentrations of allelochemicals. Thus, the scope for work on *C. murale* and *C. didymus* is much bigger to further identify and isolate the active factors responsible for their allelopathic properties to explore their possible use as biocontrol agents of weeds. Greenhouse and field studies are important to confirm such results to encompass the more subtle and complicated social environment of soil and plants.

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Гербіцидна дія *Chenopodium murale* та залишків *Coronopus didymus* Sm. проти проростання та раннього росту *Hordeum vulgare*

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Анотація. У цьому дослідженні розглядаються загальні проблеми тих видів бур’янів, які негативно впливають на продуктивність сільськогосподарських культур у великих масштабах. Мета роботи – дослідити вплив висушеного коріння *Chenopodium murale* та *Coronopus didymus* на проростання насіння та ранній ріст *Hordeum vulgare*. Експеримент проводили у рандомізованому блочному плані з трьома повтореннями в умовах теплиці в горщиковій культурі. Пагони і коренеплоди окремо сушили в тіні протягом 15–20 днів, сухі порошкоподібні залишки пагонів і коренів *C. murale* і *C. didymus* вносили в дозах 5 і 10 г кг$^{-1}$ на насіння ячменю в 6 горщиках з контролем протягом трьох тижнів. Залишки пагонів *C. didymus* (10 г) найбільше пригнічували проростання (31,16 %), GVI (0,85), SVI (4,90) та площі листя (3,94 см^2) ячменю, а 5 г кореневих залишків бур’яну мали найменш виражену дію. Довжина кореня, довжина пагона та суха біомаса найбільше пригнічувалися *C. murale* 10 г при обробці як пагонів, так і кореневих залишків. Залишки пагонів пригнічували проростання та ріст, ніж залишки коренів обох бур’янів. Патерни накопичення хлорофілу показали неоднозначні результати, у деяких зразках їх концентрація навпаки посилювалася. Обробка коренів загалом була більш гальмівною, ніж обробка пагонів. Усі оброблені проростки демонстрували вищі рівні накопичення проліну порівняно з контролем. При меншій дозі застосування *C. murale* було більш інгібуючим, ніж застосування *C. didymus*. Існує великий обсяг досліджень цих видів, щоб виділити та ідентифікувати активні фактори, а також зрозуміти їх вплив на біоконтроль бур’янів, крім їх потенційного негативного впливу на сільськогосподарські культури, особливо зернові культури, які можуть бути корисними для збільшення виробництва сільськогосподарських культур. на півночі Індії, а саме в Уттар-Прадеші

Ключові слова: сільськогосподарська діяльність, алелопатія, схожість насіння, оцінка проліну, виробництво біомаси, залишки бур'янів

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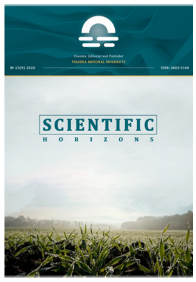

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Influence of Various Forms of Absorbent and Mulching Materials on the Yield of Vining Cucumber and Fruit Quality in the Forest-Steppe of Ukraine

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Abstract. Against the background of global climate change, most of the territory of Ukraine today is semi-arid, which causes a decrease in the efficiency of the vegetable growing industry. Due to aridity and elevated temperatures in summer, the normal growth and development of plants, namely vining cucumber, is disrupted. The efficiency of artificial irrigation is also decreasing due to the rise in the price of fresh water and energy carriers for its supply to plants. Soil absorbents and the use of mulching can solve these issues. The purpose of this study was to investigate the effect of various forms of soil absorbent against the background of the use of various mulching materials of organic and synthetic origin on the productivity of vining cucumber. This study involved field, laboratory, statistical, and computational-analytical methods. Studies have established that upon mulching the soil with black polyethylene film together with the introduction of a soil absorbent in the form of a gel, phenological phases of growth and development occur most quickly in vining cucumber plants, and the fruiting period increases by 11 days compared to the control. The combination of film mulching and absorbent gel allowed increasing the height of the main stem by 15.2%, the number of leaves on the plant by 43.9%, and the leaf area by 26.5% compared to the control version. It was established that the highest commercial yield is provided by mulching the soil with a black film together with the introduction of an absorbent in the form of pellets and gel – 56.6-56.8 t/ha, which is 27.5-27.9% more than the control. The marketability of the yield was 99.2-99.4%. Cucumber fruits for mulching with a film and applying an absorbent in the form of a gel had a high content of dry matter (5.3%) and the sum of sugars (2.20%). Lowest nitrate level ($N\text{-}NO_3$) in cucumber fruits provided mulching with black agrofibre without an absorbent (53.0 mg/kg)

Keywords: gel, pellets, biometric indicators, plant productivity, correlations, yield marketability, chemical composition of fruits

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INTRODUCTION

Ukraine is one of the leading agricultural countries in Europe (Chryniewicz *et al.*, 2016). The soil conditions are very favourable for growing many types of plant production, primarily vegetables. That is why, by the decision of the UN Food and Agriculture Commission, Ukraine is ranked among the states that in the future should become the main food donors in the world against the background of continuous population growth on the planet. According to the National Academy of Agrarian Sciences of Ukraine, if the land is used efficiently, Ukraine can feed about 1.2 billion people (National Academy of Agricultural Sciences of Ukraine).

Global climate change affects various spheres of life and industry, especially agriculture, as it causes a decrease in the efficiency of the plant production industry (Cherlet *et al.*, 2018). Due to aridity and high air temperatures in the summer months, the normal growth and development of plants is disrupted, their suppression and productivity decrease occur.

Water management is a major challenge for all countries. It is estimated that by 2030, the total need for water on the globe will be 50% higher than today, which will lead humanity to water scarcity (Laxmi *et al.*, 2019).

The modern climate in most of the territory of Ukraine is semi-arid. It was found that 46.05% of acreage cannot provide sustainable crop production without irrigation, and 42.65% need irrigation to grow plants with high water use (Lykhovyd, 2021). The need to increase the production of vegetables against the background of a constant decline in soil quality and climate change to a more arid one, causes elevated interest in finding new measures that would provide plants with sufficient water. The productivity of vegetable plants and the accumulation of high vitamin content in food organs directly depends on environmental factors, primarily on moisture (Abd El-Aal, 2010).

To meet the biological needs of plants, the agricultural sector uses a large amount of fresh water, which accounts for two-thirds of what is used on a global scale. Against the background of a decrease in world reserves, fresh water is the most valuable resource on the planet, as evidenced by its constant rise in price. The efficiency of artificial irrigation is constantly decreasing due to the growing cost of water and energy carriers, which are necessary for its supply to plant growing areas. Humanity needs to reduce the use of fresh water for irrigation, increase the rationality of its use in agriculture because this area will soon experience a strong shortage of water. The solution to this issue depends on new methods and elements of technology that contribute to the rational use and optimisation of water resources. First, this problem can be solved by using hydrogels (Shubhadarshi & Kukreja, 2020) and soil superabsorbents, which, apart from preserving moisture in the soil crossover, can considerably improve irrigation efficiency (Wehbahani *et al.*, 2006). The use of absorbents in the cultivation of plant organisms plays a vital role in promoting an innovative approach to human habit and culture in relation to water (Sannino *et al.*, 2009) and a major role in all agricultural production (Dehkordi, 2017).

The use of absorbent polymers (hydrogels) or superabsorbing polymers (SAP) can increase the ability of the topsoil to retain moisture and nutrients for a long time, which may be available for plant growth and development (Yu *et al.*, 2011; Qu & Varennes, 2009). The analysis proves that the use of superabsorbent polymers increases the water content available to plants on different soil types (Banedjschafie & Durner, 2015; Montesano *et al.*, 2015).

Mulching the soil surface is also one of the most efficient measures to preserve moisture in the soil and influence its temperature regime. Covering the soil reduces moisture evaporation, protects the upper soil section from soil erosion, inhibits weed germination, enhances microbiological processes and reproduction of beneficial microorganisms (Zaniewicz-Bajkowska *et al.*, 2012), preserves the structure of the soil and reduces its temperature during the hot summer months (Chakraborty *et al.*, 2008; Kęsik *et al.*, 2007), prevents the penetration of water and nutrients into deeper horizons (Abobatta, 2018).

Therefore, a water conservation strategy is key to sustainable population living in arid regions (Chen *et al.*, 2016). *The purpose of this study* was to investigate the influence of various forms of soil absorbent against the background of the use of various mulching materials of organic and synthetic origin on the productivity of vining cucumber and the quality of its fruits in the conditions of Ukrainian forest-steppes.

LITERATURE REVIEW

Superabsorbents are three-dimensional hydrophilic polymers that can absorb and retain large amounts of water and aqueous solutions (Wehbahani *et al.*, 2006; Milani *et al.*, 2017). That is, absorbents are not nutrients, but act as tiny reservoirs for storing water, which ensures normal growth and development of plants. Their application more fully realises the natural varietal potential of plants (Polischuk *et al.*, 2018).

Modern-day agricultural producers can access different varieties of absorbents: hydrogel, water-retaining pellets, ecosoil, agrogel, aquasoil, aquasorb, etc. Their composition and moisture retention are different. Superabsorbents can be produced in the form of pellets, tablets, gel, or as a powdered substance.

Depending on the source of origin, hydrogels are classified into natural, synthetic, and semi-synthetic. Synthetic materials are created based on acrylates and acrylamides, they have high mechanical strength, but due to problems of decomposition and safety for the environment, they are trying to replace them with biopolymers (alginate, agar, cellulose, chitosan, starch) (Skrzypczak *et al.*, 2020). The industry practices the creation of absorbents based on ecological and biodegradable starch, which does not have phytotoxicity and after a certain period completely decomposes in the soil.

To produce hydrogels, natural materials are used, such as carob gum, dextrin, hyaluronic acid, okra gum, etc. Examples of synthetic absorbents are polymethacrylic acid (PMAA), polyacrylic acid (PAA), Poly-N-vinylpyrrolidone (PVP), polyethylene glycol diacrylate/polyethylene glycol dimethacrylate (PEGDA/PEGDMA), polyethylene glycol acrylate/methacrylate (PEGA/PEGMA), polystyrene (PS) (Saini, 2016). Less material and production resources are spent on an absorbent made from natural chitosan material, compared to synthetic absorbents. It can hold up to 610 g of water per 1 g of gel (Alam & Christopher, 2018).

The use of absorbent polymers (hydrogels) or superabsorbing polymers (SAP) increases the ability of the upper soil section to retain moisture and nutrients for a long time, which is available for plant growth and development (Wehbahani *et al.*, 2006; Dehkordi, 2017). This helps them tolerate the heat more easily, and with a large amount of precipitation, the effect of "flooding" is eliminated.

The use of hydrogel polymers is an effective means of improving the efficiency of irrigation water (Moslemi *et al.*, 2011; Lao *et al.*, 2016). It was found that the use of a superabsorbent type A200 polymer reduces the use of irrigation water by 35-45% without reducing the yield, compared to full irrigation without an absorbent (Sakaki *et al.*, 2020). It is known that excessive use of fertilisers and agrochemicals can lead to contamination of groundwater and deterioration of the ecological balance. Absorbent polymers help reduce the rate of application of agrochemicals and increase the efficiency of their use (Skrzypczak *et al.*, 2020; Srivastava *et al.*, 2018).

The results of experiments have shown that by improving the state of soil aggregates, preserving the structure of the soil, increasing and strengthening the state of porosity, ensuring soil moisture, increasing soil permeability and increasing water permeability in it, superabsorbents reduce or even stop soil erosion (Moslemi *et al.*, 2011).

In Ukraine, many scientists are engaged in the study of various forms of absorbents on the productivity of vegetable plants, namely in the cultivation of vining cucumber (Ternavskyi *et al.*, 2017), turnip-rooted celery and salad celery (Polischuk *et al.*, 2018; Ulianych *et al.*, 2019), spinach (Ulianych & Shevchuk, 2020). Scientific progress in the study of absorbents has been achieved by other scientists on black pepper (Rasanjali *et al.*, 2019), soy (Ryan *et al.*, 2020), potato (Salavati *et al.*, 2018) and cotton (Papastylianou, 2020). Soil absorbents improved physiological processes, increased yields, improved seed suitability and root system development. Other scientists have stated that absorbents increase the moisture content of greenhouse soil (regardless of the species) by 14% and improve the absorption of trace elements by plants (Ostrand *et al.*, 2020).

Scientists have studied a biocompatible cellulose-based absorbent that is non-toxic and completely decomposes in the soil. Its ability to absorb moisture up to 400 times its own weight is noted, as well as its positive effect on plant growth and development (Montesano *et al.*, 2015). Other researchers have established the potent effect of AgroHydroGel and AquaSave superabsorbents on soil moisture, which was applied before sowing peas. This contributed to an increase in the number of nodules on the root system of plants, which increased its commercial yield (Gamajunova & Tuz, 2017).

Mulching is a continuous or inter-row coating of the soil surface with materials of organic or synthetic origin. It is considered one of the most efficient measures to preserve moisture in the soil and regulate the temperature regime. Soil temperature changes the absorption of elements by directly affecting the growth and physiology of the root system and the entire plant in general. When the soil temperature is lowered, the plant's moisture absorption decreases, which is caused by an increase in viscosity and a decrease in the level of water absorption by the plant. As a result, this adversely affects photosynthesis, and therefore all processes in the plant (Toselli *et al.*, 1999). Due to the positive impact on the physical properties of the soil and the preservation of moisture in it, it is considered that this measure follows the rules of organic farming (Zaniewicz-Bajkowska *et al.*, 2012).

Mulching materials protect the soil cover from erosion, preserve the soil structure, reduce the adverse impact of temperature fluctuations during the day, inhibit the germination of weeds, provided that opaque synthetic materials are used or a layer of organic materials with a thickness of at least 5-7 cm is applied. Theoretically, various materials can be used to cover the soil surface: polyethylene film of assorted colours, white and black agrofibre, sawdust, peat, straw, dry grass, compost, humus, parchment, etc.

When growing cucumbers, mulching with black plastic wrap is often used, the soil temperature under it is more stable, the microclimate in the surface layer of the soil improves, and the relative humidity of the air increases. Today, eight types of polyethylene film are used in agricultural developed countries: transparent, white, black, yellow, black and white, silver, thermal brown, herbicidal green. Each type of film has its own specific features and characteristics, knowing them can influence the creation of favourable conditions for many agricultural plants, considering their biological requirements. Black polyethylene film helps increase the temperature of the soil, light-coloured film can reduce the heating of the soil during the day, enhance biochemical processes, which has a positive effect on plant nutrition (Hallidri, 2001).

Scientists investigated the effect of a polyethylene film of black, transparent, and silver colour on cucumber plants (Yaghi *et al.*, 2013). All types of films increased the length of the main stem of plants and the number of leaves, and the thickness of the stem was slightly affected. The highest soil temperature was under the black film at a depth of 10 cm and 30 cm, which had a positive effect on cucumber plants. Of all types, the best result was achieved by using black polyethylene film, which allowed obtaining the highest total yield, although the highest early harvest was obtained under transparent polyethylene film.

In Syria, the effect of transparent and black polyethylene films on the water demand of cucumber plants under drip irrigation conditions was studied. It was found that the use of light polyethylene film and drip irrigation was the best in terms of the efficiency of water use by plants. Soil temperature and humidity in this variant had the highest rates, and the yield was almost twice as high as in the variant without mulching and watering along furrows (Nimah, 2007).

MATERIALS AND METHODS

The research was carried out during 2018-2021 in the experimental field of the Department of Vegetable Farming of the Uman National University of Horticulture in the forest-steppe of Ukraine according to the methods of G. L. Bondarenko (Bondarenko & Yakovenko, 2001) and Z. M. Gritsayenko (Hrytsayenko *et al.*, 2003).

The soil of the experimental site is podzolised heavy loamy chernozem on the forest with a humus soil section of 40-45 cm. The humus content is 3.2%, pH 6.0-6.2, the degree of soil saturation with bases is 91.0%. The content of mobile forms of nitrogen is 64 mg/kg of soil (according to Kornfield), phosphorus – 119 mg/kg of soil (according to Chyrikov), potassium – 101 mg/kg of soil (according to Chyrikov) (Table 1).

***Table 1**. Physical and chemical parameters of the soil of the experimental site*

Indicators	Factual content
Organic matter (humus),%	3.2
pH	6.0-6.2
NO_3	64
P_2O_5	119
K_2O	101

The study was conducted on the cultivation of an early maturing hybrid of foreign selection Bettina F_1 by seedling method. This hybrid is listed in the State Register of Plant Varieties of Ukraine suitable for distribution in Ukraine. Seedlings were grown in a film spring greenhouse using black plastic cassettes with a cell size of 8×8 cm (64 cm^2). Pre-disinfected cells of cassettes were filled with a soil mixture consisting of turf and humus in a 1:1 ratio. One seed was sown in each cell. In the open ground, seedlings in the phase of two real leaves were planted in the third decade of May according to the placement scheme of 140×15 cm.

The study was carried out using the method of a two-factor experiment with randomised placement of variants in four-fold repetition. The area of one experimental site was 8.4 m^2. The area of the entire experimental site was 403.2 m^2. Technological practices were carried out according to the requirements of the culture and agroclimatic growing zone.

The experiment scheme included the following factors and variants:

Factor A – mulching material: no mulching (A_1); mulching with black polyethylene film (A_2); mulching with black agrofibre (A_3); mulching with sawdust (A_4).

Factor B – absorbent form: without absorbent (B_1); pellets (B_2); gel (B_3).

Combination of variants in the experiment:
– A_1B_1 (control)
– A_1B_2
– A_1B_3
– A_2B_1
– A_2B_2
– A_2B_3
– A_3B_1
– A_3B_2
– A_3B_3
– A_4B_1
– A_4B_2
– A_4B_3

Methods of applying various forms of absorbent

MaxiMarin ready-made gel and Dari Dar moisture-retaining pellets were used as an absorbent. The gel was applied according to the manufacturer's recommendations to the bottom of each seedbed at the rate of 4 g/plant, pellets – to the zone of future placement of the root system at 0.5 g/plant.

Use of mulching materials

A black polyethylene film (50 microns thick) and A-50 grade black agrofibre (50 g/m^2 density) were taken and wood sawdust (deciduous wood species) were taken for the experiment. The width of the mulching strip was 70 cm. The film and agrofibre were prepared with a width of 100 cm, since 15 cm of edges on both sides were laid in prepared furrows and carefully covered with a thin layer of soil. Immediately before planting seedlings in the places of future placement of plants, cross-shaped incisions were made, gel and pellets were added to the bottom of each seedbed. Sawdust was covered with a 5-6 cm thick layer immediately after applying the absorbent and planting seedlings.

Phenological observations

The following phenological phases of growth and development of cucumber plants were noted: the formation of the third real leaf, mass flowering of female flowers, and the beginning of the formation of the first fruits. The beginning of each phenophase was the date when 15% of plants entered it, and the date of mass onset of the phase was considered to be 75% of plants.

Biometric parameters

The height of the main stem, the number of leaves and their area were determined during the mass fruiting of cucumber plants, which fell on the third decade of July. The height of the main stem was determined using a measuring ruler. The number of leaves on the plant was carried out by mathematical calculation. The leaf area was determined by the method of V. I. Kamchatny (Kamchatny & Sinkovets, 1997). Biometric indicators were measured for 10 control plants in four repetitions of each of the variants.

Yield accounting

The yield was calculated selectively as the technical maturity of the fruit on the plots by weight. Products from the accounting plots for each harvest were divided into commodity and non-commodity parts according to the requirements of the current cucumber standard (DSTU 3247-95, 1995).

Laboratory tests

In the laboratory, the content of dry matter in the fruit, the sum of sugars and the level of nitrates (N-NO_3) were determined as follows:

— dry matter was determined by thermograviometric method (Peterburzhskij, 1973);

— the sum of sugars — by the ferricyanide method (Hrytsayenko *et al.*, 2003);

— nitrate level — by ion-selective method using the EV-74 device (Najchenko, 2001).

Statistical analysis

Statistical analysis was performed using Microsoft Office Excel, version 2016 (MicrosoftCorp., USA) and methods of B.A. Dospekhov (Dospekhov, 1985). The results were calculated at a significance level of 0.05.

RESULTS AND DISCUSSION

According to phenological observations, it was found that among the mulching materials, the third real leaf was previously formed when covering the soil with a black polyethylene film — on the 9th day from planting seedlings. When mulching with sawdust, this phase occurred 2-3 days later, compared to the variant without mulching (Table 2). The forms of the absorbent within each mulching material did not affect the passage of this phase since this is the initial phase of growth and development of cucumber plants.

Table 2*. The value of interphase periods of cucumber plant development depending on the influence of various forms of absorbent and mulching materials, days from seedling planting (average for 2018-2021)*

Variant: Mulching material	Variant: Absorbent form	Formation of the third real leaf	Mass flowering of female flowers	Start of formation of first fruits
Without mulching	Without absorbent (control)	11	39	45
	Pellets	10	37	43
	Gel	10	36	42
Black polyethylene film	Without absorbent	9	31	37
	Pellets	9	29	35
	Gel	9	27	33
Black agrofibre	Without absorbent	9	34	40
	Pellets	10	33	39
	Gel	10	32	38
Wood sawdust	Without absorbent	13	41	47
	Pellets	13	39	45
	Gel	13	39	45

During the mass flowering of female flowers, a considerable difference in its passage was observed both from the mulching material and from the shape of the absorbent applied. Thus, earlier, plants covered with a black polyethylene film and black agrofibre entered this phase — respectively, for 27-31 days and 30-34 days from planting seedlings. When mulching with wood sawdust, the flowering of female flowers occurred 2-3 days later, compared to the variant without mulching. Notably, the use of different forms of absorbent within each mulching material contributed to the acceleration of this phase by an average of 1-4 days, compared to the variant without the use of absorbent. Among the forms of absorbent, this phase previously occurred in the gel variant.

The first cucumber fruits were formed on average 6 days after the mass flowering phase of female flowers. The first fruits began to arrive from the variant of mulching the soil with a black polyethylene film together with the introduction of an absorbent in the form of a gel — 33 days after planting seedlings, which is 12 days earlier than the control.

This acceleration in the passage of phenological phases of growth and development of cucumber plants under black polyethylene film and black agrofibre can be explained primarily by the higher soil temperature, which is confirmed by the data of other authors (Bucko

& Siwek, 2019). According to them, in the initial period of growth of cucumber plants, the soil temperature at a depth of 10 cm under a black film and black agrofibre was higher by 1.9°C and 0.5°C, respectively, compared to the variant without mulching.

Depending on the forms of absorbent and mulching materials, the duration of fruiting of cucumber plants varied. Thus, the longest fruiting period was upon mulching the soil with a polyethylene film using an absorbent in the form of a gel – 69 days, which is 11 days longer than the control variant (Fig. 1). Among the mulching variants, black film and black agrofibre contributed to prolonging the period of fruit formation of plants. Characterising the forms of the absorbent, within each mulching material, their use increased the duration of fruiting, which was due to a better supply of cucumber plants with moisture during the periods necessary. In the gel application variants, compared to pellets, the fruit formation period was 1-2 days longer.

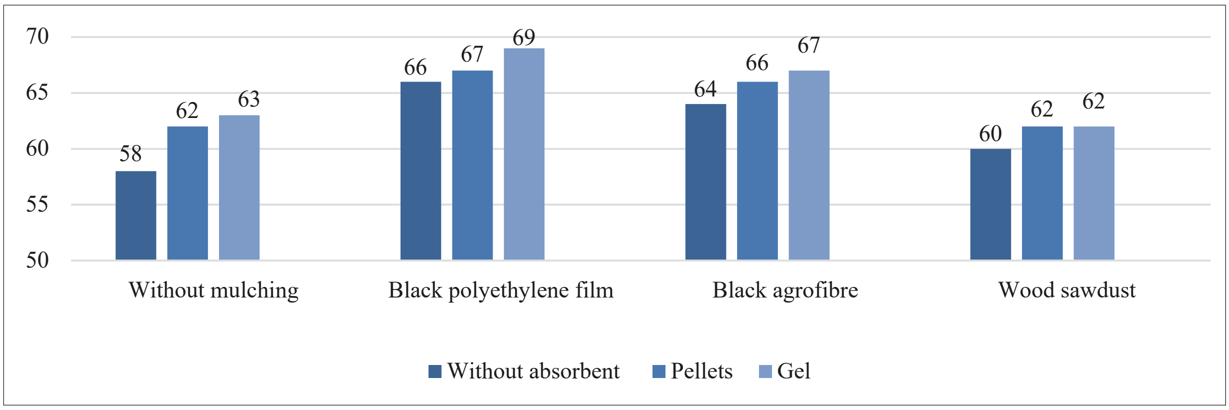

***Figure 1**. Duration of cucumber fruiting depending on the influence of various forms of absorbent and mulching materials, days (average for 2018-2021)*

Forms of absorbent and various mulching materials affected the value of biometric indicators of plants, which were determined during their mass fruiting. The highest height of the main stem was when mulching with a film using an absorbent in the form of a gel – 180.8 cm. In the same variant, the largest number of leaves and the area of their assimilation surface was formed – 36.4 pcs/plant and 4,290 cm^2/plant, respectively (Table 3). The worst indicators of plant biometrics were when mulching the soil with sawdust without an absorbent: the height of the main stem was 145.8 cm, the number of leaves – 21.9 pcs/ plant, leaf area – 2,490 cm^2/plant. Among mulching materials, the use of polyethylene film and agrofibre helped improve the biometric parameters of plants, while the use of sawdust, on the contrary, worsened them. Biometric indicators on average for four years of research increased under the influence of absorbent pellets by 3.7-8.3%, while the absorbent in the form of a gel contributed to their increase by 6.1-11.8%.

***Table 3**. Biometric indicators during mass fruiting of plants depending on the influence of various forms of absorbent and mulching materials (average for 2018-2021)*

Variant: Mulching material (factor A)	Variant: Absorbent form (factor B)	Height of the main stem, cm	Number of leaves, pcs/plant	Leaf area, cm^2/plant
Without mulching	Without absorbent (control)	156.9	25.3	3,390
	Pellets	164.1	27.4	3,610
	Gel	170.3	28.6	3,720
Black polyethylene film	Without absorbent	171.9	33.5	4,050
	Pellets	178.0	36.0	4,250
	Gel	180.8	36.4	4,290
Black agrofibre	Without absorbent	166.5	28.9	3,770
	Pellets	175.4	32.9	3,910
	Gel	178.3	33.8	4,140
Wood sawdust	Without absorbent	145.8	21.9	2,490
	Pellets	149.3	23.0	2,610
	Gel	151.8	23.7	2,680
HIP_{05}	A	5.4	1.4	149
	B	4.7	1.2	129
	A×B	9.3	2.5	258
	CV%	7.93	17.81	18.15

Other scientists also prove that the addition of hydrogel to the soil promotes the growth of plant habit, which is caused by an increase in the amount of available moisture in the area where the root system is located (Helalia & Letey, 1989). Hydrogels increase the efficiency of irrigation water, reduce soil density, and improve its drainage (Ekebafe *et al.*, 2011). All this certainly affects the improvement of biometric parameters of cucumber plants. Mulching, in turn, also affects the biometric parameters of plants. Studies have shown that black polyethylene film, compared with silver and transparent film, has a greater effect on improving the vegetative growth of cucumber plants (Hallidri, 2001). Other scientists have shown that under black plastic wrap, moisture evaporation is 81% lower compared to a site without mulch (Zribi *et al.*, 2015).

On average, over four years of research, the highest commercial yield was obtained for mulching the soil with a polyethylene film against the background of using an absorbent in the form of a gel – 53.2 t/ha, which is 8.8 t/ha more than production control (Table 4). The lowest commercial yield was for mulching with sawdust without an absorbent – 41.7 t/ha, which is 2.7 t/ha less than the control variant. Among the mulching materials, polyethylene film and agrofibre contributed to an increase in plant productivity, while sawdust reduced it. The absorbent considerably increased the commercial yield of plants, especially in the form of a gel. Thus, water-retaining pellets increased the commercial yield of plants by 4.1-8.1% relative to the variant without an absorbent, while gel – by 5.0-11.0%.

***Table 4**. Cucumber yield depends on the influence of various forms of absorbent and mulching materials, t/ha (average for 2018-2021)*

Variant		Total yield	Commercial yield	Early harvest as of 07/20
Mulching material (factor A)	**Absorbent form (factor B)**			
Without mulching	Without absorbent (control)	45.2	44.4	27.3
	Pellets	48.8	48.0	31.0
	Gel	50.1	49.3	32.2
Black polyethylene film	Without absorbent	54.6	54.1	31.7
	Pellets	56.9	56.6	34.2
	Gel	57.3	56.8	35.8
Black agrofibre	Without absorbent	49.9	49.2	30.5
	Pellets	52.6	52.0	33.9
	Gel	53.7	53.2	35.1
Wood sawdust	Without absorbent	42.5	41.7	20.5
	Pellets	44.1	43.4	21.9
	Gel	45.8	45.0	23.6
HIP_{05}	A	1.7	2.3	2.1
	B	1.5	2.0	1.8
	A×B	2.9	4.0	3.6
	CV%	10.35	11.17	18.86

The highest early harvest yield was obtained upon covering the soil with a black polyethylene film with an absorbent in the form of a gel – 35.8 t/ha, which prevailed over the control by 8.5 t/ha. Notably, film and agrofibre contributed to an increase in the size of the early harvest, while sawdust reduced the yield of the early harvest. Under the action of the absorbent, the early yield increased, to a greater extent from its use in the form of a gel.

Other scientists also prove the positive effect of black film on the productivity of cucumber plants. Thus, under black polyethylene film and black polypropylene film, commercial cucumber yields increased by 184.1% and 138.4%, respectively, compared to the variant without mulching (Siwek, 2002). The advantage of black film as a mulching material was also proved in hot climates (Mexico), where it increased the commercial yield of cucumber by 50%, early yield by 34.6% and total yield by 42.6%, compared to the variant without mulching (López-Tolentino *et al.*, 2016).

In terms of productivity, the greatest yield stability was in the variants of mulching the soil with agrofibre and polyethylene film without an absorbent – (K_{sf}=1.06-1.07). The lowest yield stability was achieved by mulching the soil with sawdust using an absorbent in the form of pellets (K_{sf}=1.21) (Fig. 2).

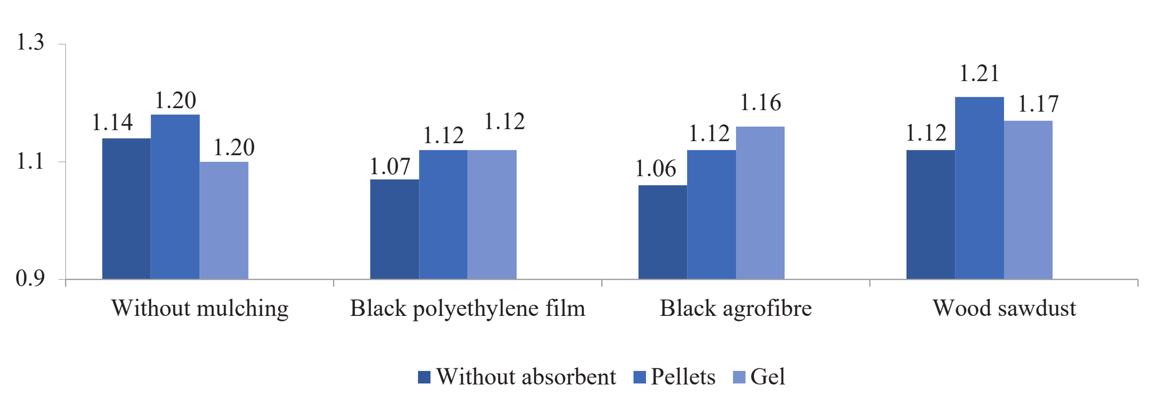

***Figure 2**. Levis stability factor (K_{sf}) by commercial cucumber yield depending on various forms of absorbent and mulching materials (average for 2018-2021)*

As a result of the conducted dispersion analysis of data, it was found that the value of commercial plant yield was most affected by factor A – mulching material – 73.0%, factor B – form of absorbent affected with a force of 8.0%. The interaction of both factors in the experiment determined the value of commercial yield by 1.0%. Other factors (plant disease, pest damage, mechanical injury to plants, yield losses, level of agricultural technology) accounted for 19.0% (Fig. 3).

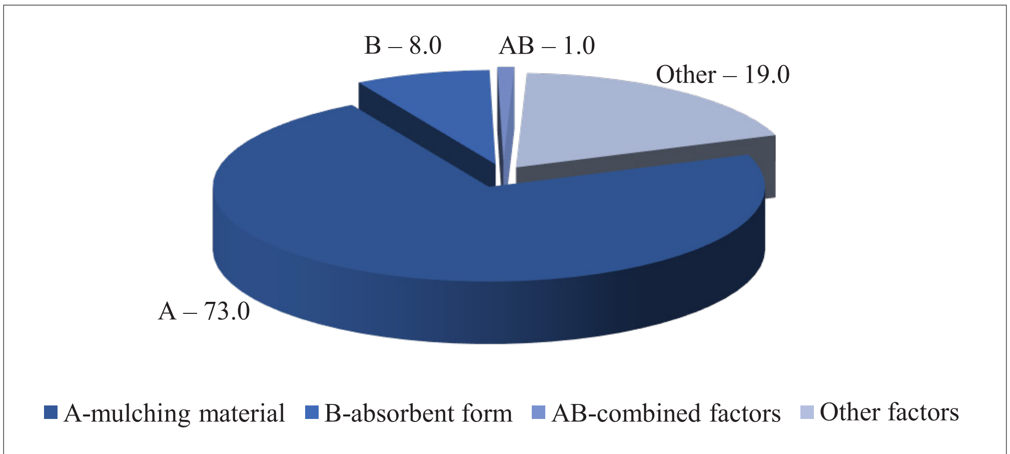

***Figure 3.** Strength of influence of factors on the value of commercial cucumber yield, % (average for 2018-2021)*

The correlation coefficients between different indicators in the experiment were calculated according to the method of correlation analysis. Strong direct correlations were established between the height of the main leaf and the number of leaves on the plant (r=0.97); between the height of the main stem and the area of the leaves (r=0.97); between the number of leaves on the plant and the area of their assimilation surface (r=0.95). The analysis also showed that the value of commercial yield has a strong direct dependence on the leaf area (r=0.93), the height of the main stem (r=0.96) and the number of leaves per plant (r=0.99) (Table 5).

***Table 5**. Matrix of correlations between indicators depending on different forms of absorbent and mulching materials (average for 2018-2021)*

Indicator	Height of the main stem, cm	Number of leaves, pcs/plant	Area leaves, cm^2/plant
Number of leaves, pcs/plant	0.97	–	–
Leaf area, cm^2/plant	0.97	0.95	–
Commercial yield, t/ha	0.96	0.99	0.93

All fruits collected in the experiment for each harvest were divided into standard and non-standard parts according to the DSTU requirements (DSTU 3247-95, 1995). Non-standard products included deformed fruits affected by diseases and damaged by soil pests. This also included underdeveloped and overgrown cucumber fruits.

The highest yield marketability was obtained by mulching the soil with a black polyethylene film using an absorbent in the form of a gel – 99.4%. It was the lowest in the variant of mulching with sawdust without an absorbent – 98.1% (Fig. 4).

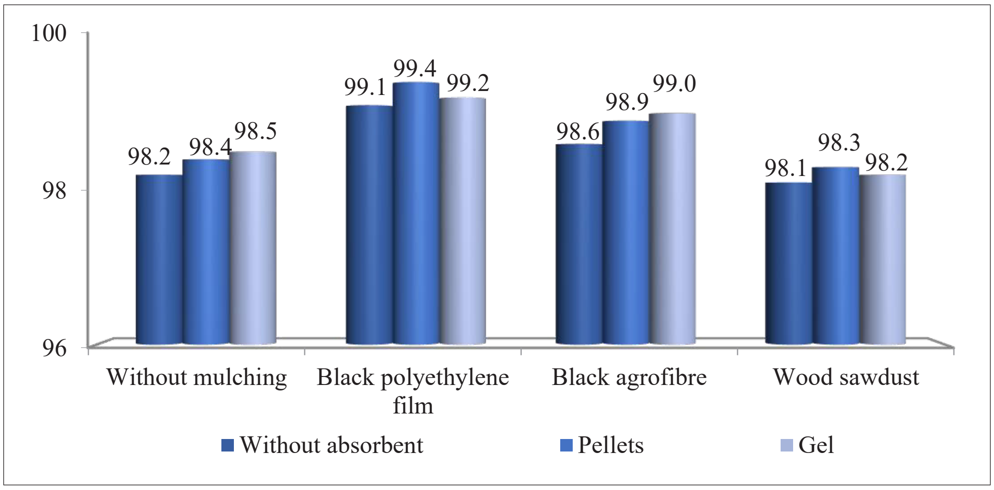

***Figure 4**. Yield marketability of cucumber depending on the influence of various forms of absorbent and mulching materials, % (average for 2018-2021)*

Analysis of marketability depending on mulching showed that the use of polyethylene film and agrofibre contributed to an increase in the yield of marketable products. When various forms of absorbent were added to the soil, the marketability of fruits also increased. In the variant without mulching and upon mulching the soil with black agrofibre, gel had a greater positive effect on marketability, and upon mulching with film and sawdust – water-retaining pellets. The use of various forms of absorbent increased marketability by an average of 0.1-0.4 percentage points, compared to the variant where the absorbent was not introduced. This was due to better moisture supply of plants during the growing season, as a result of which plants experienced less lack of water on hot and critical days, the functionality of the root system was better, and therefore plants formed less crooked and deformed fruits.

Depending on the effect of different forms of absorbent and mulching materials, some biochemical parameters of cucumber fruits changed. The highest dry matter content was due to mulching with a black film against the background of applying an absorbent in the form of pellets and gel – 5.3% each. The lowest amount of dry matter was contained in fruits from the sawdust mulching variant without an absorbent – 4.5% (Table 6).

***Table 6.** Chemical composition of cucumber fruits depending on the influence of various forms of absorbent and mulching materials (average for 2018-2021)*

Variant: Mulching material (factor A)	Variant: Absorbent form (factor B)	Dry matter, %	Sum of sugars, %	Nitrate level *(N-NO_3), mg/kg
Without mulching	Without absorbent (control)	4.8	2.02	79.0
	Pellets	4.9	2.06	82.0
	Gel	5.0	2.09	88.0
Black polyethylene film	Without absorbent	5.2	2.14	58.0
	Pellets	5.3	2.18	61.0
	Gel	5.3	2.20	63.0
Black agrofibre	Without absorbent	5.0	2.10	53.0
	Pellets	5.2	2.13	59.0
	Gel	5.2	2.15	62.0
Wood sawdust	Without absorbent	4.5	1.95	71.0
	Pellets	4.7	1.99	72.0
	Gel	4.7	2.01	74.0
HIP_{05}	A	0.14	0.05	2.1
	B	0.12	0.04	1.8
	A×B	0.24	0.08	3.6
	CV%	5.96	4.34	15.63

***Note**: * – MDR (no more than 150 mg/kg)*

The highest sugar content was observed when mulching with a film against the background of applying an absorbent in the form of a gel (2.20%). Notably, mulching with polyethylene film and black agrofibre increased the content of dry matter and the sum of sugars in the fruit. Mulching with sawdust reduced the dry matter content and sugar content compared to the variant without mulching. The use of an absorbent also helped improve the chemical composition of cucumber fruits, to a greater extent this applies to the gel. The improvement in the biochemical parameters of cucumber fruits is explained by the fact that mulching with black film and black agrofibre had a higher soil temperature, which considerably improves the absorption of nutrients by the root system, especially against the background of the use of an absorbent. Better absorption of nutrients has a direct impact on the growth and physiology of the root system, as well as the entire plant in general. When the soil temperature is lowered, the plant's moisture absorption decreases, which is caused by an increase in viscosity and a decrease in the level of water absorption by the plant, which adversely affects photosynthesis, and therefore all processes in the plant (Toselli *et al*., 1999). In addition, the use of hydrogel affects the improvement of chemical parameters of fruits, as it reduces the leaching of trace elements from the soil, increases the efficiency of water consumption (Dehkordi, 2017).

The nitrate content in the fruits of all variants of the experiment did not exceed MDR (no more than 150 mg/kg) and ranged from 53.0 mg/kg to 88.0 mg/kg. However, the reduction of nitrates in fruits was influenced by all mulching materials, especially black polyethylene film. When various forms of absorbent were added to the soil, the level of nitrates slightly increased. The lowest nitrate content was in the variant of mulching the soil with black agrofibre without an absorbent – 53.0 mg/kg, and the highest was in the variant without applying covering materials against the background of using an absorbent in the form of a gel – 88.0 mg/kg.

CONCLUSIONS

It was found that during mulching with a polyethylene film and the use of an absorbent in the form of a gel, the phenological phases of growth and development of cucumber plants occurred most rapidly. The longest fruiting period (69 days) was in the variant of mulching the soil with a film and applying an absorbent gel.

When mulching the soil and using various forms of absorbent, the biometric characteristics of cucumber plants were considerably improved. In particular, the introduction of gel into the soil against the background of its mulching with a black film increased the height of the main stem, the number of leaves on the plant and their area by 15.2%, 43.9%, and 26.5%, respectively, compared to the control.

The highest commercial yield was obtained by mulching the soil with a black film and applying an absorbent in the form of gel and pellets – 56.8 t/ha and 56.6 t/ha, respectively. In the same variants, the largest early harvest was obtained – 35.8 t/ha and 34.2 t/ha, respectively. According to the Levis stability coefficient (K_{sf}) the most stable yield was in the variants of mulching the soil with black agrofibre and black film without an absorbent – 1.06 and 1.07, respectively.

According to the method of dispersion analysis, it was found that among the two factors in the experiment, factor A – mulching material (73.0%) had a decisive influence, while factor B – the form of the absorbent determined the value of commercial yield with a force of 8.0%. Correlation analysis showed a strong direct correlation between commercial yield and the number of leaves per plant (r=0.99). Correlations of similar strength were also found between the height of the main stem (r=0.96) and the leaf area (r=0.93).

The use of black polyethylene film and black agrofibre as mulching materials contributed to an increase in the yield marketability. The introduction of various forms of absorbent using all mulching materials also improved marketability. The highest yield marketability was achieved by mulching with polyethylene film and applying an absorbent in the form of granules to the soil – 99.4%.

Mulching materials and various forms of absorbent affected the chemical properties of the fruit. The highest content of dry matter and the sum of sugars was upon coating the soil with a black film and the introduction of an absorbent in the form of a gel. The lowest nitrate content in cucumber fruits was upon mulching with black agrofibre without an absorbent.

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Вплив різних форм абсорбенту та мульчувальних матеріалів на урожайність шпалерного огірка та якість плодів в умовах лісостепу України

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Анотація. На фоні глобальної зміни клімату більша частина території України сьогодні є напівпосушливою, що викликає зниження ефективності галузі овочівництва. Через посушливість та високі температури влітку порушується нормальний ріст і розвиток рослин, зокрема, шпалерного огірка. Знижується і ефективність штучного зрошення через подорожчання прісної води та енергоносіїв для її подачі до рослин. Вирішити ці проблеми можуть ґрунтові абсорбенти та застосування мульчування. Метою досліджень було вивчення впливу різних форм ґрунтового абсорбенту на фоні застосування різноманітних мульчувальних матеріалів органічного та синтетичного походження на продуктивність шпалерного огірка. У процесі досліджень було використано польові, лабораторні, статистичні та розрахунково-аналітичні методи. Дослідженнями встановлено, що за мульчування ґрунту чорною поліетиленовою плівкою разом із внесенням ґрунтового абсорбенту у формі гелю, у рослин шпалерного огірка фенологічні фази росту і розвитку відбуваються найшвидше, а період плодоношення, порівняно з контролем, збільшується на 11 діб. Комбінація мульчування плівкою та абсорбенту-гелю дозволила збільшити на 15,2 % висоту головного стебла, на 43,9 % кількість листків на рослині та на 26,5 % площу листків, порівняно з контрольним варіантом. Визначено, що найбільшу товарну урожайність забезпечує мульчування ґрунту чорною плівкою разом з внесенням абсорбенту у формі гранул та гелю — 56,6—56,8 т/га, що на 27,5—27,9 % більше контролю. Товарність урожаю при цьому становила 99,2—99,4 %. Плоди огірка за мульчування плівкою та застосування абсорбенту у форму гелю мали високий вміст сухої речовини (5,3 %) та суми цукрів (2,20 %). Найнижчий рівень нітратів ($N\text{-}NO_3$) у плодах огірка забезпечило мульчування чорним агроволокном без застосування абсорбенту (53,0 мг/кг)

Ключові слова: гель, гранули, біометричні показники, продуктивність рослин, кореляційні зв'язки, товарність урожаю, хімічний склад плодів

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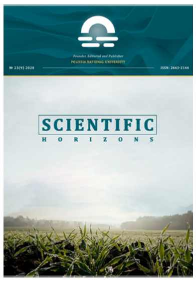

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Evaluation of Methods of Heat Treatment of Black Currant Fruits to Increase Juice Production

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Abstract. Black currant is a multivitamin crop with high dietary and medicinal properties and is a source of exceptionally valuable raw materials for juice production. The essence of the problem of this paper is the scientific substantiation of ways and methods of efficient juice extraction while preserving the natural chemical composition and biologically active substances. The purpose of this study is to compare the methods of heat treatment of black currant fruits to increase juice production. Evaluation of the efficiency of juice output from black currant fruits should be carried out differentially according to the level of desirability of Harrington: exceptionally good – more than 55%, good – 48-55%, satisfactory – 40-48%, unsatisfactory – 35-40%, very unsatisfactory – less than 35%. The fruits of black currant, as a rule, yield 18-24% of the juice, which is devoid of its inherent colouring. Heat treatment of raw materials increases the juice yield by 1.5-2.5 times compared to grinding, and at the same time, at 50-55°C, the cells die within 5 minutes. Good juice yield indicators upon pressing the pomace of crushed fruits (49-55%), satisfactory – upon heating whole fruits with the addition of 15% water (38-45%), as well as blanching fruits in water with a temperature of 95-100°C (42-45%). Juice extraction by blanching fruits and pomace in their own juice is inefficient (33-36%). In terms of chemical composition, freshly pressed juices, regardless of the method of processing raw materials, are close to fresh fruits. Heat treatment of raw materials does not adversely affect the taste and aroma of juices. The content of ascorbic acid in juices (142-225 mg/100 g) depends on the variety of fruits and weather conditions of the year. Its preservation in freshly pressed juices during heat treatment is 95-97%, including blanching – 83-90%. In juices with sugar, its content is 1.7 times lower, but the preservation is 98-99%. During the storage of juices with sugar, the preservation of ascorbic acid decreases during the first three months – by 1.5-2%, in 6 months – by 5.5-7%, in 9 months – by 10-13%, in 12 months – by 16-19% or 7-10 times. Factors for stabilising ascorbic acid in juices are sugar, hot bottling, and short-term heating at elevated temperatures

Keywords: juice yield, juice quality, ascorbic acid preservation

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INTRODUCTION

In modern environmental conditions in the field of nutrition, there is an urgent task of organising health-improving nutrition for the population. Scientific developments (Sloan, 2022; Veerapandi *et al.*, 2022; Osokina *et al.*, 2019) aimed at searching for raw materials with a high content of biologically active substances and developing new food technologies using it.

A valuable technical raw material is a multivitamin culture of black currant, the fruits of which have high dietary and medicinal properties with a natural content of functional ingredients, as a complex non-medicinal complex that provides a reliable therapeutic and preventive effect. In terms of the content of essential substances that should regularly enter the human body — ascorbic acid (100-300 mg/100g) and polyphenolic substances (over 1,000 mg/100g), it has no equal among fruit and berry crops (Veerapandi *et al.*, 2022; Osokina *et al.*, 2019; Ongkowijoyo *et al.*, 2018).

The Ukrainian juice market is developing extremely dynamically. And this applies not so much to the capacity of the market, but to its assortment content. The juices presented on the market are close to the world standard in terms of not only taste, but also the appearance of packaging.

Blackcurrant juices belong to one of the main categories of natural food products of high and low calories, which are carriers of biologically active substances. They can considerably diversify your daily diet. However, the range of blackcurrant juices on the market is limited. This is primarily due to the lack of proper technology that would consider the specific features of raw materials. Classical methods of obtaining juices are inefficient in this case. There are numerous factors involved, which are listed below.

Due to the phenomena of adsorption and capillarity, some juice remains in the pomace and reduces the percentage of yield. At the same time, solid particles also enter the extracted liquid. Juice losses in pomace are not only quantitative, but also qualitative ones. The latter are conditioned upon that taste, aroma and colour substances are mainly found in cells that are difficult to destroy during juice extraction (Osokina *et al.*, 2020; Deinychenko *et al.*, 2020).

The chemical composition of fruit juice from different tissues is dissimilar. If for most types of raw materials, it is desirable to extract biologically active substances of juice from the main tissue, trying not to occupy the juice of the integumentary and mechanical tissues, then for black currant fruits, on the contrary, as much as possible from the integumentary tissue, in which colouring substances are mainly localised. The so-called extractives determine the value of the juice (Ongkowijoyo *et al.*, 2018).

The cell wall comprises plasma and cellulose-pectin layers. The latter is mainly permeable to solubles, and the plasma layer is the main barrier to them. It is mainly represented by hydrophilic colloids (proteins, lipids), which constantly interact during vital activity. Therewith, processes of partial coagulation, dissolution, or compaction are often observed. Changes in the internal structure of the plasma layer occur not only during natural die-away, but also during destruction at high temperature (Newman & Cragg, 2020). Therefore, fruit juice production depends on the cellular permeability of the fruit tissue. The juice in fruits is located in cellular vacuoles, protoplasm and partially in intercellular spaces and is firmly retained by a living cell (Osokina *et al.*, 2021). The main factor that inhibits juice production is the protoplasm of cells.

Natural blackcurrant juices are highly acidic. Considering the high extractive ability of natural blackcurrant juice, it is considered as a semi-product for the manufacture of juices with sugar.

In addition, the data presented in the scientific literature on changes in the quality indicators of blackcurrant juices are ambiguous (Osokina *et al.*, 2019; Osokina *et al.*, 2021; Flaumebaum *et al.*, 1986), they are difficult to compare due to the lack of research in the dynamics of production; there is no single approach to evaluating the results.

The purpose of this study is to establish rational methods of preliminary heat treatment of raw materials to increase the yield of juice and their impact on changes in quality indicators. For this, it is necessary to develop criteria for evaluating the efficiency of extracting juice from black currant fruits and investigate the preservation of ascorbic acid, which determines the biological value during cooking.

LITERATURE REVIEW

According to N.M. Osokina *et al.* (2021), the content of cellular juice in blackcurrant fruits is 88-94%. However, upon extracting the juice, it has never been possible to completely separate the liquid and solid phases of the fruit. Furthermore, natural blackcurrant juice has its differences, the objective reasons for which are as follows:

1. According to the biophysical theory of juice production B.L. Flaumenbaum *et al.* (1986), with the loss of semi-permeable properties of the protoplasm, the ability of raw materials to retain juice is lost, which is conventionally achieved by mechanical grinding of fruits. A comparative evaluation of mechanical impact methods (Ongkowijoyo *et al.*, 2018), such as cutting, hitting, crushing, abrasion, showed that for quinces and apples with the appropriate degree of grinding, it is possible to achieve considerable juice yields, for fruits of black currants, plums, gooseberries, apricots, the degree of cell damage is not great: upon cutting — 20-30%, upon crushing — up to 40%. It was found that for black currant fruits, the degree of cell damage upon grinding is 31%, upon crushing — 40%. Other types of mechanical impact are even less efficient. Therefore, after mechanical grinding, it is possible to extract only up to 25% of the juice (Backhall *et al.*, 2018; Deinychenko *et al.*, 2020; Conidi *et al.*, 2020b).

One of the components of the juice output is the degree of grinding. Upon pressing a well-ground mass, the juice is released from its outer parts, compaction (moulding) occurs, which prevents the juice from flowing out of the inner parts, and the juice extraction is noticeably reduced. Upon a uniform loose state, drainage is provided during pressing, which contributes to the flow of juice. The degree of grinding under the same conditions affects the amount of sediment, turbidity, and emergence of the juice (Paniuta, 2019).

There are limits to the grinding of slices, at which the best juice production is observed. The lower limit – under 0.1 mm is limited by the very nature of fruits and berries. Depending on the type of raw material, the particle size is from 1 to 8 mm. When studying the degree of grinding of black currant fruits (from 1.25 to 7 mm), the best juice output in terms of particle size was established – 3.5 mm (Flaumenbaum *et al.*, 1986).

1. According to the anatomical structure in the juicy part of the black currant pericarp, only the mesocarp with bubble-like cells is filled with watery cell juice, and the endocarp, which is factually fruit pulp, due to the sliming of arillus cells represented by pectin gel, has a slimy consistency that complicates the separation of juice (Cherevko *et al.*, 2020).

2. The completeness and speed of juice extraction from black currant fruits is associated with pectin substances. Their splitting can loosen the tissues, reduce the viscosity of the juice, and facilitate its separation. Forms of pectin substances in raw materials are in a mobile state and largely determine the physical and mechanical properties of fruit tissue. As a hydrophilic biopolymer, pectin increases the water retention capacity of plant tissue (Deinychenko *et al.*, 2020; Conidi *et al.*, 2020b).

The destruction of structural polymers that make up the median plates of plant cells leads to the breakdown of connections between cells and causes the breakdown of tissue into individual cells. The intercellular protopectin of the median plates is connected to each other by ionic and covalent bonds. The destruction of ionic bonds is ensured by heating at pH≤4.5 (Castro-Munoz, 2019).

1. The juice in black currant fruits is a biological fluid belonging to a heterogeneous dispersed system. Adsorption processes occur on the surface of the dispersed phase particles, which lead to stabilisation of the colloidal juice solution, which prevents the outflow of juice upon pressing (Blackhall *et al.*, 2018).

2. The shape, nature, and degree of strength of water bonds with fruit pulp affects juice extraction. In black currant fruits, the total amount of bound water in the form of osmotically bound and colloidal bound is 78%. Osmotically bound water in currant fruits occupies only about 46%, while in apple, pear, and cherry fruits – 60-70% (Osokina *et al.*, 2021). It forms flabby fibrous structures of pectin substances between which there is a spatial grid, the cells of which are filled with water molecules, which can be extracted during the production of juice under conditions of preliminary preparation of raw materials – heat treatment and others that destroy the structural grid.

The proportion of colloidal-bound (adsorption) water in currant fruits is 32%, while in apple, pear, and cherry fruits it is 15-25% (Osokina *et al.*, 2021). It occurs because of the concentration of water molecules in the surface layer of colloidal particles of the product, which is part of the micelles of various hydrophilic colloidal solutions – proteins, polysaccharides. Extracting such water is quite difficult.

1. Heat treatment of juices substantially affects the preservation of biologically active substances. Pasteurisation of juices for inactivation of enzymes and destruction of microorganisms is carried out without oxygen access to prevent a decrease in their quality. However, it adversely affects the taste and aroma of juices and causes the "boiled" taste (Vishnikin *et al.*, 2019).

2. Upon the production and storage of juices, various biochemical changes occur associated with hydrolysis, condensation, oxidation, reduction, and other processes (Conidi *et al.*, 2020a; Savas Bahceci, 2022; Denisenko *et al.*, 2018). Some of them are desirable for the formation and improvement of the taste properties of juices, but most of them lead to the formation of undesirable or harmful substances and, thus, to a deterioration in the quality of juice. The intensity of changes depends primarily on the shelf life of the product. The chemical composition of juices undergoes noticeable changes within the first 3 months of storage. The preservation of ascorbic acid in black currant juices is 39-81%. According to other sources, after 6 months of juice storage, the ascorbic acid preservation is 54-73%, after 8 months – 37-43%. After 12 months of storage, the ascorbic acid content in the juice decreased from 186.70 to 62.86 mg/100 g, or the preservation was 35-45% (Savac Bahceci, 2022; Denisenko *et al.*, 2018).

MATERIALS AND METHODS

Research on juice extraction was conducted during 2003-2010 with black currant fruits of the varieties Minai Shmyrev, Belarus Sweet, Novyna Prykarpattia in the laboratory of the Department of technology of storage and processing of crop production, in the Educational and Production Department of the Uman National University of Horticulture. Black currant plantations are located in the central part of the Right-Bank Forest-Steppe of Ukraine.

According to the Uman Weather Station, the region's climate is temperate continental with unstable moisture, uneven precipitation, and unstable temperatures. Features of geographical location and atmospheric processes cause adverse weather events in some years: heavy rains, hail, strong winds, droughts, high temperatures in summer and low in winter, which affects both the crop and its quality.

For this study, black currant fruits without brushes were collected at the end of June in boxes-trays weighing 4-5 kg in dry cool weather and transported to the laboratory. The weight of black currant fruits of each variety is 60 kg.

Juice extraction was carried out by pressing with a screw press (pressure 0.3-0.4 MPa) after inspection and washing of fruits, preparation of raw materials according to the following methods of preliminary heat treatment:

1. Mechanical grinding to the pomace (control).
2. Heating the pomace of ground fruits at 50-55°C, 65-70°C (5 min).
3. Heating the pomace of crushed fruits at 50-55°C (5 min).
4. Heating whole fruits with 15% water at 50-55°C (5 min).
5. Blanching of fruits in water at temperatures of 50-55°C, 95-100°C (5 min).
6. Blanching of fruits in juice at 50-55°C (5 min).
7. Blanching of pomace in the juice of pre-pressed fruits at 50-55°C (6 h).

The mass of the sample for pressing is 1.5-2 kg. Repeatability – three times.

The juice yield was estimated using the generalised Harrington desirability function (Weishtord & Pritykina, 1992).

To harmonise the taste of freshly pressed natural juices by chemical composition, they were used to prepare juices with sugar. According to the content of dry substances and acids that are regulated by DSTU 4150: 2003, they corresponded to the highest grade. According to the technological instructions (Shirokov, 1974), the composition was as follows: 60% juice + 40% sugar (30%) syrup.

The method of preparation of blackcurrant juices with sugar provided for mixing boiling syrup with juice, packaging, pasteurisation at 85°C in a thermal cabinet for 35 min, encapsulation.

In raw materials, freshly pressed natural juices and juices with sugar (after 15 days of storage), the content of dry soluble substances, total sugar content, acid content, and ascorbic acid content were determined. The preservation of ascorbic acid in juices was calculated. The sugar-acid index was calculated. Organoleptic evaluation of juices was performed.

The content of ascorbic acid was determined in blackcurrant juices with sugar for 3 months, 6 months, 9 months, 12 months of storage. Its preservation in juices was calculated using the following formula (1):

$$P_{AA} = \frac{AA_1 \times m_1}{AA_2 \times m_2} \times 100\% \quad (1)$$

where AA_1 is the ascorbic acid content in the finished product, g; AA_2 is the ascorbic acid content in the raw product, g; m_1 is the mass of the finished product, g; m_2 is the mass of raw product, g.

Determination methods:

– for the content of dry soluble substances – refractometric (Shirokov, 1974);

– for acid content – titrimetric (Shirokov, 1974);

– for total sugar content, invert sugar content, glucose – ferricyanide (Shirokov, 1974);

– for the content of ascorbic acid – iodometric (according to B.P. Pleshkov (1976));

– for fruit juiciness – acidimetric (Pleshkov, 1976);

– for preservation of ascorbic acid – according to B.L. Flaumenbaum *et al*. (1986).

The repeatability of chemical analyses is threefold. The mass of the sample for analysis is 2 kg of fruit or 1.5 kg of product.

Statistical processing of research results was performed using variance analysis.

RESULTS AND DISCUSSION

To exclude subjectivity in evaluating the juice yield from black currant fruits, the authors applied the generalised Harrington desirability function (Weishtord & Pritykina, 1992).

When indicating the percentage of juice yield, the authors assumed that according to their data, the juiciness of black currant fruits is, on average, 90.7% (fruits of the Minai Shmyrev variety – 90.5%, fruits of the Belarus Sweet variety – 89.3%, fruits of the Novyna Prykarpattia variety – 92.3%). The yield of blackcurrant juice should be considered efficient starting from 40%. According to the level of desirability, juice extraction efficiency indicators are distributed as follows: under 35% – very unsatisfactory; 35-40% – unsatisfactory; 40-48% – satisfactory; 48-55% – good; over 55 % – exceptionally good. The Harrington desirability function can be a criterion for evaluating methods for pre-treatment of blackcurrant fruits to increase juice yield.

Influence of mechanical grinding on the yield and quality of blackcurrant juices

The first and mandatory operation in preparing raw materials for juice extraction is grinding. However, the need for grinding is quite obvious where the fruit pulp is hard and tough, but there is doubt regarding the need for grinding soft berries. In particular, the degree of damage to the cells of black currant fruits under the influence of mechanical grinding is small.

The studies have shown that when ground, black currant fruits did not produce loose pomace, which would comprise small pieces and juice, which is consistent with the data of other scientists (Deinychenko *et al*., 2020; Cherevko *et al*., 2020; Shirokov, 1974). The pomace had a solid, homogeneous mass, from which no juice was released at all. The degree of grinding could only be estimated by the size of the pieces of skin outlined against the background of the pomace. Their size was from 2 to 4 mm. Pressing such a pomace is quite difficult.

According to Table 1, the juice yield during mechanical grinding of fruits to pomace is low (very unsatisfactory) – from 17.8% to 24.3%. On average, over 8 years of study, depending on the variety, it was 20-22%. Fruits of the Novyna Prykarpattia variety yielded 4-10% more juice than fruits of other varieties.

Table 1. *Juice output from black currant fruits of different varieties,%*

Year	Variety		
	Minai Shmyrev	Belarusian Sweet	Novyna Prykarpattia
2003	21.8	19.0	23.4
2004	19.2	17.8	20.3
2005	20.1	18.6	22.4
2006	20.6	20.3	22.8
2007	22.0	21.3	24.3
2008	23.1	21.8	22.5
2009	22.0	20.7	20.4
2010	20.8	21.2	20.5
Average	21.2	20.1	22.1
HIP_{05}		2.7	

The resulting juice had a light pink colour, high viscosity, pleasant taste and aroma inherent in black currant fruits. However, it was devoid of the most inherent feature – intense colouring. Since the colouring substances in black currant fruits are located in the peel, they did not pass into the juice upon cold pressing and were removed with pomace (Ozola & Duma, 2020).

The chemical composition of freshly pressed juices was different from that of fruits. On average, the dry matter content decreased by 2.4-3.1%, the total sugar content – by 2.1-2.6%, and acids – by 4.8-7.3%. Due to high acid losses, the sugar-acid index of juices increased by an average of 3.7%. The content of ascorbic acid in juices decreased by 15-21%. The low preservation of the C-vitamin value of juices is associated with the high activity of oxidative enzymes during the main technological techniques – grinding and pressing.

According to the indicators regulated by the DSTU 4150:2003 standard, freshly pressed natural fruit juices and juices with sugar met the requirements.

The addition of sugar syrup to natural juices considerably improved their taste qualities due to a 3-4.5-fold increase in the sugar-acid index. Depending on the variety of fruit, it was 11.3-18.7, and in some years it increased to 20.4-22.1 or decreased to 8.5-9.9.

The C-vitamin content of juices with sugar in comparison with natural ones is 1.7 times lower. But considering the recipe for the product, the preservation of ascorbic acid, regardless of the fruit variety, was about 98%.

However, the key difference between blackcurrant juices extracted by pressing mechanically ground pomace is related to their organoleptic assessment. In appearance, they did not correspond to natural juices due to a considerable deviation from the inherent colour. However, the juices had a pronounced smell, and the taste was very pleasant. Over time, during three months of storage, they quickly lost colour. The latter first turned dirty pink, and then dirty light-brown and never once resembled the inherent colour of blackcurrant juice. Therefore, the use of the method of pressing ground black currant pomaces, as an independent one, is not economically and technologically expedient.

Effect of pomace heating on the yield and quality of blackcurrant juices

Literature data on the dependence of black currant fruit juice production on heat treatment are quite contradictory (Osokina *et al.*, 2021; Deinychenko *et al.*, 2020; Vyshnikin *et al.*, 2019), and require clarification of temperatures and processing methods. Results of heat treatment of black currant pomace at 65-70°C (5 min) are presented in Table 2.

Table 2. *Juice yield depending on the method of pre-treatment of black currant fruits of different varieties,% (three-year data are sufficient to confirm the reliability of the results)*

Pre-processing method	Minai Shmyrev			Belarusian Sweet			Novyna Prykarpattia		
	2003	2004	2005	2003	2004	2005	2003	2004	2005
Mechanical grinding to pomace (control)	21.8	19.2	20.1	19.0	17.8	18.6	23.4	20.3	22.4
Heating of the pomace at 65-70°C, 5 min	40.4	37.1	38.9	38.3	36.4	38.0	42.3	38.5	41.0
HIP_{05}					2.0				

The juice output of raw materials depended on the specific features of the variety and the year of harvest, but the greatest impact was exerted by heat treatment of pomace – 83%.

The yield of juice from fruits, on average, was about 38-41%, which is 1.8-2.0 times more than in the control (19-22%). The advantages of the Novyna Prykarpattia fruit variety are clear: 19% more juice than from the Belarus Sweet variety and 8% more than from the Minai Shmyrev fruit variety in the control and 8% and 5% in the experimental variety, respectively.

Genetic features of the variety related to its anatomical structure and chemical composition directly affected the extraction of juice. This was more evident in the control version. Warming up the pomace, which caused cell die-away, somewhat levelled the difference between the varieties, but remained substantial.

The juice yield varied depending on the year of black currant harvest. The highest rate was recorded in 2003-40.3% (control – 21.4%), which is 12% more in the control and 8% more in the experimental variants.

Qualitative evaluation of juices (Table 3) showed that natural juice is close to fresh fruit in terms of chemical parameters. The main components of the chemical composition were transferred to the juice by 97-99%.

Heat treatment of the pomace before pressing allowed obtaining natural juices, in which the loss of dry soluble substances is almost threefold, sugars and acids are 2.5 times less compared to the juices of the control version.

***Table 3.** Indicators of the chemical composition of black currant fruits of various varieties and juices from them (three-year data are sufficient to confirm the reliability of the results)*

Pre-processing method	2003				2004				2005			
	Dry soluble substance content, %	Total sugar content, %	Acid content[1], %	Sugar-acid index	Dry soluble substance content, %	Total sugar content, %	Acid content[1], %	Sugar-acid index	Dry soluble substance content, %	Total sugar content, %	Acid content[1], %	Sugar-acid index
Minai Shmyrev												
Fruits	16.0	7.26	3.32	2.19	15.8	7.01	3.05	2.30	16.4	8.91	2.65	3.36
Fruit grinding to pomace (control)	15.6[2] / 21.4	7.06 / 16.24	3.20 / 1.92	2.21 / 8.46	15.4 / 21.2	6.83 / 16.1	2.92 / 1.75	2.34 / 9.20	16.0 / 21.6	8.68 / 17.2	2.50 / 1.52	3.47 / 11.3
Heating of the pomace at 65–70 °C, 5 min.	15.8 / 21.6	7.18 / 16.28	3.25 / 1.95	2.21 / 8.35	15.6 / 21.4	6.94 / 16.1	3.00 / 1.81	2.31 / 8.93	16.4 / 21.8	8.88 / 17.3	2.68 / 1.60	3.31 / 10.8
Belarusian Sweet												
Fruits	16.0	8.82	2.55	3.46	14.2	6.56	2.31	2.84	16.8	9.21	1.86	4.95
Fruit grinding to pomace (control)	15.6 / 21.4	8.68 / 17.2	2.42 / 1.45	3.59 / 11.8	13.8 / 20.4	6.38 / 15.8	2.12 / 1.27	3.01 / 12.4	16.4 / 21.8	9.12 / 17.4	1.76 / 1.05	5.18 / 16.5
Heating of the pomace at 65-70°C, 5 min	15.8 / 21.6	8.76 / 17.2	2.50 / 1.50	3.50 / 11.4	14.0 / 20.4	6.44 / 15.8	2.25 / 11.3	2.86 / 11.6	16.8 / 22.0	9.25 / 17.5	1.82 / 1.09	5.08 / 16.1
Novyna Prykarpattia												
Fruits	14.6	7.91	2.61	3.03	13.2	6.01	2.18	2.76	13.8	8.40	1.79	4.69
Fruit grinding to pomace (control)	14.0 / 20.4	7.65 / 16.6	2.41 / 1.45	3.17 / 11.5	12.8 / 19.6	5.80 / 15.4	2.10 / 1.25	2.76 / 12.3	13.4 / 20.0	8.26 / 16.9	1.65 / 1.00	5.01 / 16.9
Heating of the pomace at 65-70°C, 5 min	14.4 / 20.6	7.85 / 16.6	2.54 / 1.51	3.08 / 11.1	13.0 / 19.8	5.9 / 15.5	2.18 / 1.30	2.71 / 11.9	13.6 / 20.2	8.34 / 17.0	1.71 / 1.03	4.88 / 16.5
HIP_{05}	0.033 / 0.043	0.48 / 0.47	0.09 / 0.12	0.23 / 0.75	0.033 / 0.043	0.48 / 0.47	0.09 / 0.12	0.23 / 0.75	0.033 / 0.043	0.48 / 0.47	0.09 / 0.12	0.23 / 0.75

***Note:** 1) in terms of citric acid; 2) above dash – natural juice, under dash – juice with sugar*

Juices with sugar, which were prepared from the fruits of the varieties Belarus Sweet and Novyna Prykarpattia, were distinguished by high taste properties. Their sugar-acid index is from 12 to 17. In years when the acidity of black currant fruits increases above 2.5%, one should use blending juices with those containing a lower acid content, especially less than 1.5%. This technique allows preserving the natural properties of products. As pointed out by C. Conidi *et al*. (2020b), juices with a sugar-acid index below 15 are too acidic, and those with a sugar-acid index above 45 are too sweet. Instead, C. Conidi *et al*. (2020a) and R. Castro-Muñoz (2019) believe that for the average person, juice tastes better if its sugar-acid index is 13. However, the taste is formed not only by the ratio of sugar and acid, but also other organic substances, such as colouring ones, and therefore the assessment of taste may differ in the juices of fruits of different cultivars.

According to organoleptic parameters, the juices obtained by heat treatment of the pomace differed from the juices of the control variants. They had a natural appearance, saturated colouring inherent in black currant, pronounced unique aroma, pleasant taste, the freshness of which is somewhat lost, but boiled tones are not felt. The data in Table 4 indicate a substantial effect of heat treatment of pomace on the preservation of ascorbic acid. The preservation of C-vitamin value, regardless of the variety, was 83-85%. While in similar juices obtained with heat treatment of pomace, the level of preservation is 95-97%.

Table 4. *Ascorbic acid content (mg/100 g) and its preservation (%) in black currant fruits of various varieties and juices from them (three-year data are sufficient to confirm the reliability of the results)*

Pre-processing method	2003			2004			2005		
	Fruits	Juices: Natural	Juices: With sugar	Fruits	Juices: Natural	Juices: With sugar	Fruits	Juices: Natural	Juices: With sugar
Minai Shmyrev									
Fruit grinding to pomace (control)	182.1	151.1* 83.0	88.7 97.8	176.0	149.7 85.1	88.0 98.0	172.0	144.5 84.0	85.0 98.0
Heating the pomace at 65-70°C, 5 min		176.6 97.0	104.1 98.3		167.3 95.1	91.1 98.7		165.9 96.5	98.5 99.0
Belarusian Sweet									
Fruit grinding to pomace (control)	237.5	227.0 83.0	133.2 97.8	308.0	261.4 84.9	153.9 98.1	272.8	229.1 84.0	134.8 98.1
Heating the pomace at 65-70°C, 5 min		230.4 97.0	157.2 98.8		292.5 95.0	172.9 98.5		261.8 96.0	155.8 99.2
Novyna Prykarpattia									
Fruit grinding to pomace (control)	229.3	191.2 83.4	112.4 98.0	180.4	153.3 85.0	90.3 98.2	192.4	162.0 84.2	95.1 97.8
Heating the pomace at 65-70°C, 5 min		222.3 97.0	132.3 99.2		171.5 95.1	101.9 99.0		184.4 95.8	109.5 99.0
HIP$_{05}$, mg/100 g		6.9	6.4		6.9	6.4		6.9	6.4

***Note**: * – above dash – the content of ascorbic acid in juices, mg/100 g, under dash – the preservation of ascorbic acid in juices, %*

Blackcurrant juices with sugar considerably differed in the content of ascorbic acid. Its amount decreased by 1.7 times compared to natural juices. However, ascorbic acid in juices with sugar had a high stability – its preservation was 98-99%. The value of the juices was determined by the initial content of ascorbic acid in the fruit. If in the fruits of the Belarus Sweet variety its content is 1.2-1.8 times higher than in the fruits of other varieties, then a similar trend was observed in juices. Dispersion analysis confirmed the greatest strength of influence of specific features of the variety (80%) on the ascorbic acid content in natural juices. In juices with sugar, the weight of the method of heat treatment of pomace is 66%, and the variety – 28%.

According to Table 5, it was found that the yield of blackcurrant juice under heat treatment at 50-55°C depended on the method of preparation of raw materials.

Table 5. *Juice yield depending on the method of pre-treatment of black currant fruits of different varieties,%*

Pre-processing method	Minai Shmyrev		Belarusian Sweet		Novyna Prykarpattia	
	2006	2007	2006	2007	2006	2007
Mechanical grinding of fruits to pomace (control)	20.6	22.0	20.3	21.3	22.8	24.3
Heating the ground pomace at 50-55°C (5 min)	36.0	36.8	34.6	35.1	37.2	38.4
Heating the pomace of crushed fruits at 50-55°C (5 min)	53.6	54.0	49.4	51.0	54.2	55.8
Heating the whole fruits with 15% water at 50-55°C (5 min), (excluding water)	41.0	42.8	38.2	40.5	43.0	45.2
HIP$_{05}$	4.0					

When the ground pomace was heated at 50-55°C, the juice yield increased to 35-38%, which is 1.6-1.7 times more compared to the control. The result is only 7-8% less compared to heating the pomace at 65-70°C (see Table 2). But the temperature regime of 50-55°C probably had a milder effect on the coagulation of colloids, and denaturation of protein substances.

At 50-55°C, the variant with heating whole fruits with the addition of 15% water was satisfactory. Compared to the control, the juice yield increased by 1.9-2 times and amounted to 38-45%, or was at the level of juice yield when the ground pomace was heated at 65-70°C and 10-18% higher at 50-55°C.

The reason for this, evidently, lies in the preservation of the integrity of the fruit before pressing, the skin of the fruit remained intact from the outside, but from the inside the pulp underwent physical and chemical changes, which caused cell plasmolysis (Osokina *et al.*, 2021). It was enough just to press on the fruit as the peel burst, not finding back pressure from the already boiled pulp. The extraction of juice was also facilitated by the water that was added. It liquefied the pomace and promoted the diffusion of soluble organic substances.

The highest juice yield was obtained by pressing the heated pomace of crushed fruits, depending on the variety and year of research, – 49-56%, which is 2.3-2.6 times more compared to the control. The efficiency of fruit crushing is obvious. When comparing the juice output from ground and crushed pomace, under the same heat treatment conditions, the difference was 15-18%. The juice yield increased by 1.4-1.5 times.

The option of pressing the pomace of crushed fruits had advantages over the option of pressing whole fruits with the addition of 15% water. The difference in juice output is 11-13%, which is 23-30% more.

The high efficiency of crushing black currant fruits during heat treatment to increase the juice yield is associated with the degree of cell damage. It was found that for black currant fruits, the degree of cell damage upon grinding is 31%, while upon crushing – 40% (Deinychenko *et al.*, 2020; Conidi *et al.*, 2020b; Cherevko *et al.*, 2020). The use of the combined effect of fruit crushing and heat treatment increased the juice yield by almost 30%.

Juice production of fruits of the Novyna Prykarpattia variety is the best for any juice extraction variant. The increase in juice yield was from 8-9% to 13-14% compared to Belarus Sweet fruits, and from 3-4% to 10% compared to Minai Shmyrev fruits, depending on the variant.

The quality indicators of freshly pressed juices depended on the chemical composition of the fruit. In the juices of the control variants, the content of dry soluble substances and sugars decreased mainly by 1.5-1.7%; the content of acids – by 3-10%. In juices obtained by pressing whole fruits with 15% water – by 9-15%, 8-14%, 9-17%, respectively, which is associated with the dilution of the juices with water.

Freshly pressed juices from the fruits of the varieties Belarus Sweet and Novyna Prykarpattia did not meet the standard (1.5-3.7%) in terms of acid content. This is due to their low content in raw materials (1.3-1.4%), which is rarely found in black currant fruits. The sugar-acid index of juices did not increase significantly (by 2-4%), which did not affect the taste of freshly pressed juices.

Indicators of the chemical composition of juices with sugar depended entirely on the quality of freshly pressed natural juices. The acid content substantially affected the taste of juices with sugar. The sugar-acid index of juices from fruits of the Minay Shmyrev variety is 13-15. The indicator level is satisfactory. However, the sugar-acid index of juices from fruits of the varieties Belarus Sweet and Novyna Prykarpattia is unjustifiably high – 18-22, as it is rare in practice. Although juices with this index are extremely pleasant, soft, silky, and can satisfy the most capricious consumer. They have a pronounced aroma. The appearance and colour of the juices is typical for black currant fruits.

The results of heat treatment of raw materials had a positive effect on the preservation of ascorbic acid. In freshly pressed juices obtained from heated pomace of ground and crushed fruits at 50-55°C, the preservation of ascorbic acid was usually 95-97%, while in the juices of control variants – only 83-87%. At the control level, the preservation of ascorbic acid in juices pressed from heated whole fruits with 15% water, due to dilution, was also found. The high preservation of C-vitamin content of juices is associated with inactivation of oxidative enzymes, acidic environment and deaeration of raw materials upon heating.

In blackcurrant juices with sugar, the content of ascorbic acid decreased by almost 1.7 times. However, the preservation of C-vitamin content remained high – about 99%, regardless of the variety of fruits and the method of pre-processing.

Influence of fruit blanching on the yield and quality of blackcurrant juices

According to Table 6, blanching the fruit before pressing allows increasing the juice yield by 1.5-2 times. But with different processing options, the output was different. Blanching fruits in water is more efficient. The juice yield increased to 39-44% (at 50-55°C) and 42-45% (at 95-100°C), which is 1.8-2 times more than the control. As the water temperature increased, the efficiency of juice extraction increased by 4-7%.

Table 6*. Juice yield depending on the method of pre-treatment of black currant fruits of different varieties (2007), %*

Pre-processing method	Minai Shmyrev	Belarusian Sweet	Novyna Prykarpattia
Mechanical grinding of fruits to pomace (control)	22.0	21.3	24.3
Blanching fruits in water at 50-55°C (5 min)	41.2	39.3	43.6
Blanching fruits in water at 95-100°C (5 min)	44.0	42.0	45.2
Blanching fruits in juice at 50-55°C (5 min), except the juice taken for blanching	35.0	33.4	35.6
Blanching pomace in juice at 50-55°C (6 h)	34.1	33.0	35.0
HIP_{05}	4.2		

Blanching the fruit in juice (5 min) and pomace (6 h) in its own juice at 50-55°C was inefficient – the juice yield increased to 30-35%, which is only 1.5 times more than in the control. The result of juice output is 20-27% worse than blanching fruits in water.

The difference in the yield of juice from the fruits of the varieties under study is from 3-5% to 6-11%.

According to Table 7, quantitative changes in the chemical composition of freshly pressed juices obtained by blanching fruits and pomace in juice, and in the control version, are not substantial. While blanching fruits in water caused a loss of dry soluble substances (5-8%), sugars (3-6%), acids (13-27%) in the juice, which is associated with their diffusion into water. Changes in the content of sugars and acids considerably increased (by 11-32%) the level of the sugar-acid index in juices.

Table 7. *Indicators of the chemical composition of black currant fruits of various varieties and juices from them, 2007*

Preprocessing method	Dry soluble substance content, %	Total sugar content, %	Acid content (in terms of citric acid), %	Sugar-acid index	Ascorbic acid content, mg/100 g	Preservation of ascorbic acid, %
1	2	3	4	5	6	7
Minai Shmyrev						
Fruits	12.8	7.03	2.06	3.41	186.6	–
Mechanical grinding of fruits to pomace (control)	12.6* 19.6	6.93 16.16	1.90 1.14	3.47 13.36	161.9 94.8	86.8 97.6
Blanching fruits in water at 50-55°C (5 min)	12.2 19.2	6.73 16.06	1.62 0.97	4.15 16.56	166.4 98.6	89.2 98.8
Blanching fruits in water at 95-100°C (5 min)	11.8 19.0	6.63 15.98	1.56 0.94	4.25 17.00	156.6 92.6	83.9 98.6
Blanching fruits in juice at 50-55°C (5 min)	13.0 19.8	7.03 16.22	2.10 1.26	3.35 12.87	167.9 99.2	90.0 98.5
Blanching pomace in the juice of pre-pressed fruits at 50-55°C (6 h)	13.0 19.8	7.03 16.22	2.10 1.26	3.35 12.87	160.5 94.7	86.0 98.3
Belarusian Sweet						
Fruits	11.8	6.43	1.54	4.18	234.9	–
Mechanical grinding of fruits to pomace (control)	11.6 19.0	6.36 15.82	1.40 0.84	4.54 17.58	202.3 118.3	86.1 97.5
Blanching fruits in water at 50-55°C (5 min)	11.2 18.6	6.23 15.75	1.34 0.80	4.65 19.69	209.2 123.8	89.1 98.6
Blanching fruits in water at 95-100°C (5 min)	11.0 18.6	6.10 15.65	1.11 0.67	5.50 23.36	194.7 115.2	82.8 98.6

Table 7, Continued

Preprocessing method	Dry soluble substance content, %	Total sugar content, %	Acid content (in terms of citric acid), %	Sugar-acid index	Ascorbic acid content, mg/100 g	Preservation of ascorbic acid, %
1	2	3	4	5	6	7
Belarusian Sweet						
Blanching fruits in juice at 50-55°C (5 min)	12.0 / 19.4	6.48 / 15.90	1.60 / 0.96	4.05 / 16.56	206.6 / 122.0	87.9 / 98.4
Blanching pomace in the juice of pre-pressed fruits at 50-55°C (6 h)	12.2 / 19.4	6.56 / 15.95	1.65 / 1.00	3.98 / 15.95	204.4 / 120.7	87.0 / 98.4
Novyna Prykarpattia						
Fruits	13.4	7.84	1.36	5.76	189.7	–
Mechanical grinding of fruits to pomace (control)	13.0 / 19.8	7.63 / 16.58	1.19 / 0.71	6.10 / 22.10	158.1 / 93.0	83.3 / 98.0
Blanching fruits in water at 50-55°C (5 min)	12.6 / 19.6	7.48 / 16.51	1.20 / 0.72	6.23 / 22.93	170.0 / 101.3	89.6 / 99.1
Blanching fruits in water at 95-100°C (5 min)	12.4 / 19.4	7.42 / 16.45	1.16 / 0.70	6.40 / 23.50	159.3 / 94.8	84.0 / 99.2
Blanching fruits in juice at 50-55°C (5 min)	13.4 / 20.2	7.80 / 16.68	1.39 / 0.83	5.61 / 20.10	170.4 / 101.0	89.8 / 98.8
Blanching pomace in the juice of pre-pressed fruits at 50-55°C (6 h)	13.6 / 20.20	7.90 / 16.72	1.40 / 0.84	5.64 / 19.91	165.0 / 97.80	87.0 / 98.80
HIP_{05}	0.02 / 0.03	0.30 / 0.52	0.12 / 0.06	0.29 / 1.36	4.19 / 5.33	–

***Note**: * – above dash – natural freshly pressed juice, under dash – juice with sugar*

In terms of taste properties, juices with sugar from the experimental versions were pleasant, extractive. Blanching fruits in water practically did not affect their appearance, colouring, aroma, and taste.

The value of freshly pressed juices depended on the blanching method. In juices obtained by blanching fruits in water at 50-55°C, the preservation of ascorbic acid is the best – 88-90%. In juices extracted from pomace blanched in juice, its preservation was lower – 86-87% (close to control), which is associated with the oxidation of raw materials when infused for 6 hours. The preservation of ascorbic acid in juices obtained by blanching fruits in water was the lowest at 95-100°C, amounting to 83-84%.

High losses of ascorbic acid in freshly pressed juices upon blanching in water – 10-17% and upon blanching in juice – 10-14% (control – 13-15%) are associated with dilution of juice with water. The decrease in the biological value of juices is a considerable lack of the variants under study, which is consistent with the results of research by other scientists (Denisenko *et al.*, 2018; Weishtord & Pritykina, 1992). Blackcurrant juices with sugar were described by high preservation of ascorbic acid – 97-99%.

Influence of technological parameters, storage duration on the content of ascorbic acid in blackcurrant juices with sugar

The preservation of ascorbic acid in blackcurrant juices with sugar is influenced by the conditions of the technological process, preparation methods, and storage duration (Table 8).

***Table 8**. Ascorbic acid content (mg/100 g) and its preservation (%) in juices with sugar from black currant fruits of the Minai Shmyrev variety, 2010*

Duration of storage of juice with sugar, months	Method of final heat treatment of juices			
	Hot-bottling		Pasteurisation	
	Content	Preservation	Content	Preservation
Mechanical grinding of fruits to pomace (control)				
Freshly pressed juice	123.0		123.0	
0.5	71.9	97.4	72.3	98.0
3	67.2	91.0	67.6	91.6

Table 8, Continued

Duration of storage of juice with sugar, months	Method of final heat treatment of juices			
	Hot-bottling		Pasteurisation	
	Content	Preservation	Content	Preservation
Mechanical grinding of fruits to pomace (control)				
6	57.2	77.5	56.1	76.0
9	46.1	62.5	43.9	59.5
12	32.8	44.5	29.5	40.0
Heating the pomace at 50-55°C, 5 min				
Freshly pressed juice	143.5		143.5	
0.5	84.7	98.4	85.2	99.0
3	80.9	94.0	81.7	94.9
6	70.7	82.1	69.3	80.5
9	57.7	67.0	55.1	64.0
12	42.4	49.2	38.3	44.5
Heating the pomace at 65-70°C, 5 min				
Freshly pressed juice	141.7		141.7	
0.5	83.3	98.0	83.9	98.7
3	79.4	93.4	80.2	94.3
6	69.2	81.4	67.9	79.9
9	56.5	66.4	53.9	63.4
12	41.1	48.4	37.4	44.0
$HIP_{0.95}$	5.7	–	5.7	–

***Note**: there was no significant difference between varieties and years*

The greatest influence on the content of ascorbic acid in juice is the duration of storage. With its increase, the preservation of C-vitamin content of juices decreased. In the juice of the control version, the process was faster.

Calculations showed that during the first 3 months of storage, the monthly content of ascorbic acid in juices with sugar decreased, depending on the variety and method of final heat treatment: in the control – by 2.5-3%, in experimental versions – by 1.5-2%. For 6 months of storage, the decrease was 7-8% and 6-7%, respectively, for 9 months – 12-14% and 10-13%, for 12 months – 18-20% and 16-19%, respectively. Almost every month, there was a dynamic decrease in the value of the product. For 12 months of storage, the content of ascorbic acid in juices with sugar decreased by 7-10 times. The preservation of ascorbic acid shows the same trend.

During the first 3 months of storage, there was a tendency for a lower ascorbic acid content in hot-bottled juices. But over the last storage period (4-12 months), the picture changed: hot-bottled juices had slightly higher levels of ascorbic acid due to short-term exposure to elevated temperatures. Upon storing juices, their value was higher.

Depending on all these factors, the content of ascorbic acid in juices with sugar largely depended on the initial content in freshly pressed juice, and the latter on the characteristics of the variety.

CONCLUSIONS

The yield of juice from black currant fruits depends on the combined influence of factors – the type of mechanical processing, the temperature of heat treatment of raw materials, the characteristics of the variety, and weather conditions of the growing season.

1. According to Harrington's desirability index, the efficiency indicators for extracting blackcurrant juice are exceptionally good – over 55%, good – 48-55%, satisfactory – 40-48%, unsatisfactory – 35-40%, very unsatisfactory – under 35%.

2. The juice yield upon pressing ground black currant pomace is 18-24%. Juices with a considerable deviation from the inherent colouring. Juice extraction is economically and technologically impractical.

3. The depth of changes and the speed of their passage during heat treatment of fruits is determined by the temperature and methods of influencing raw materials. Already at 50-55°C, the juice yield increases by 1.5-2.5 times compared to the control. The juice yield during 5-minute heat treatment upon pressing is: 49-56% – from the pomace of crushed fruits, 38-43% – from whole fruits with 15% water – at 50-55°C; 37-42% – from the pomace of ground fruits at 65-70°C.

4. Blanching fruits in water with an increase in temperature from 50-55°C to 95-100°C increases the juice yield from 39-44% to 42-45%, and blanching fruits and pomace in their own juice is inefficient – the yield is up to 33-36%.

5. The chemical composition of freshly pressed juices, regardless of the method of processing raw materials, is close to fresh fruits, their taste and aroma do not change.

6. The content of ascorbic acid in freshly pressed juices depends on the variety. Its preservation in juices upon heat treatment is 95-97%, including blanching – 83-90%. In juices with sugar, it is 1.7 times lower compared to natural ones, but the preservation is 98-99%. However, monthly for the first 3 months – by 1.5-2%, for 6 months – by 5.5-7%, for 9 months – by 10-13%, for 12 months – by 16-19% or 7-10 times.

To increase the juice yield, other methods of processing black currant fruits (enzyme, freezing) can also be used, but they require further study and research.

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Оцінювання способів теплового оброблення плодів чорної смородини для підвищення соковіддачі

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Анотація. Чорна смородина – полівітамінна культура з високими дієтичними та лікувальними властивостями, є джерелом виключно цінної сировини для виробництва соків. Сутність проблеми цієї роботи у науковому обґрунтуванні шляхів і способів ефективного витягування соку зі збереженням природного хімічного складу та біологічно активних речовин. Мета роботи – порівняльне оцінювання способів теплового оброблення плодів чорної смородини для підвищення соковіддачі. Оцінку ефективності виходу соку з плодів чорної смородини варто вести диференційовано за рівнем бажаності Харрінгтона: дуже добра – більше 55 %, добра – 48–55 %, задовільна – 40–48 %, незадовільна – 35–40 %, дуже незадовільна – менше 35 %. З плодів чорної смородини, зазвичай, одержують 18–24 % виходу соку, що позбавлений властивого забарвлення. Теплова обробка сировини збільшує вихід соку в 1,5–2,5 рази, порівняно з подрібненням, й при цьому вже за температури 50–55 °С клітини відмирають протягом 5 хв. Добрі показники виходу соку за пресування м'язги роздавлених плодів (49-55 %), задовільні – за нагрівання цілих плодів з додаванням 15 % води (38–45 %), а також бланшування плодів у воді з температурою 95–100 °С (42–45 %). Витягання соку бланшуванням плодів та вичавок у власному соку не ефективне (33–36 %). За хімічним складом свіжовідпресовані соки, незалежно від способу обробки сировини, близькі до свіжих плодів. Теплова обробка сировини не має негативного впливу на смак та аромат соків. Вміст аскорбінової кислоти у соках (142–225мг/100г) залежить від сорту плодів та погодних умов року. Збереженість її у свіжовідпресованих соках за теплової обробки – 95–97 %, в тому числі, при бланшуванні – 83–90 %. У соках із цукром її вміст в 1,7 рази нижчий, але збереженість – 98–99 %. Під час зберігання соків із цукром, збереженість аскорбінової кислоти знижується протягом перших трьох місяців – на 1,5–2 %, за 6 міс. – на 5,5–7 %, за 9 міс. – на 10–13 %, за 12 місяців – на 16–19 % або в 7–10 разів. Чинниками стабілізації аскорбінової кислоти в соках є цукор, гарячий розлий, нетривале нагрівання за високих температур

Ключові слова: лісова пожежа, гідротермічний коефіцієнт, динаміка поширення пожеж, верхова пожежа, вегетаційний період, сума температур повітря, сума опадів

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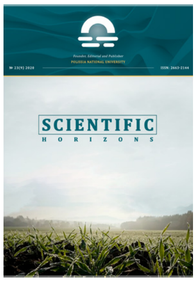

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Influence of Weather Conditions on the Spread of Fires in the Forest Fund of Zhytomyr Polesia

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Abstract. Fires are one of the critical factors in the weakening of forests. Given the high share of pine forests in the Zhytomyr Oblast, the conditions for fires are very favourable. Especially intense fires occurred in 2020, when rapid warming occurred in the spring, which in the absence of snow cover and the presence of intense winds in the February-March 2020 increased the fire danger in forests. The purpose of this study is to identify the features of the dynamics of the spread of fires in the forest stands of the Zhytomyr Oblast Department of Forestry and Hunting and assess the meteorological indicators that may affect their spread. Research methods: statistical – when analysing data on meteorological indicators and materials for accounting for forest fires. The study identified the specific features of the dynamics of fire spread in forest stands of Zhytomyr Oblast in 2014-2021. According to the analysis, there was a considerable increase in the number and area of fires in 2020 compared to the average figures for 2014-2019 and 2021 combined. During 2014-2021, 951 fires occurred on a forested area of 43,807.65 hectares. It was revealed that only 448 fires occurred in 2014-2019 and 2021, and 503 fires were recorded in 2020 on an area of 43,229 hectares. Among others, crown fires were recorded on an area of 6,389 hectares in the same 2020 year and on an area of 35.7 hectares in 2019 alone. The largest areas of crown fires were recorded on the territory of the State Enterprise "Ovrutske SF", State Enterprise "Luhynske forestry", State Enterprise "Ovrutske forestry" and State Enterprise "Slovechanske forestry". The indicators of temperature, precipitation, and hydrothermal coefficient for 2014-2021 are analysed. The values of air temperature and precipitation were determined during the growing season, and the hydrothermal coefficient was calculated according to G.T. Selyaninov. The study established that the sum of air temperatures during the growing season was 3,127.6°C on average for 2014-2021. The highest temperature values were recorded during the growing season of 2018. According to the analysis of the amount of precipitation for the growing season 2014-2021, the indicators were set at 323.8 mm. The lowest precipitation rates were recorded in 2015. According to the ratio of temperature and precipitation indicators, the value of G.T. Selyaninov's hydrothermal coefficient for the growing seasons of 2014-2021 was obtained, the average value of which was 1.04 units

Keywords: forest fire, hydrothermal coefficient, dynamics of fire spread, crown fires, growing season, sum of air temperatures, sum of precipitation

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INTRODUCTION

Forest fires occur periodically in different regions of the world (Boer *et al.*, 2020; Usenya, 2020). The spread of forest fires is facilitated by dry weather conditions, which have become more frequent recently (Shvydenko *et al.*, 2018), as well as an increase in the proportion of coniferous forests weakened by various biotic and anthropogenic factors (Hurzhii *et al.*, 2021). Trees weakened by fire worsen their sanitary condition, sometimes perishing (Chornogor *et al.*, 2021; Voron *et al.*, 2019), and become susceptible to pest infestation and pathogen damage (Davydenko *et al.*, 2021; Meshkova, 2021a; Meshkova, 2021b).

Every year, tens of thousands of cases of wildfires are registered in Ukraine on an area of about 20 thousand hectares. Therewith, in the 1980s, 1,673 cases of fires were registered on an area of 1.2 thousand hectares, in the 1990s – 3,917 cases of fires on an area of 3,962 hectares, in 2000-2010-4,743 cases of fires on an area of 4.4 thousand hectares (Zbitsev *et al*., 2019a). Major fires were recorded in 1993 in the Autonomous Republic of Crimea (600 hectares), in 1995 – in the Luhansk, Kharkiv, and Kherson Oblasts, in 1996 – in the Donetsk, Luhansk, Kyiv, and Chernihiv Oblasts (0.5-8.5 thousand hectares), in 1998 – in the Luhansk Oblast (over 1.7 thousand hectares), in 1999 – in the Kherson and Luhansk Oblast (1-2 thousand hectares), in 2007 – in the Autonomous Republic of Crimea (on an area of more than 1,000 hectares of forests). In August 2007, large forest fires occurred in the Kherson Oblast (8.7 thousand hectares), and in August 2008 – in the Kharkiv region (1.2 thousand hectares) (Voron *et al*., 2021). In 2015, fires covered 14.8 thousand hectares in the Chernobyl Exclusion Zone, 600 hectares – on the territory of the Polesia Nature Reserve, in 2018 – 580 hectares in the forest fund of the State Enterprise "Oleshkivske forest hunting range" (Zbitsev *et al*., 2019b).

Given the high share of pine forest area in Zhytomyr Oblast (Buzum *et al.*, 2018), the conditions for the occurrence of fires are very favourable. The fire danger also increased due to the presence of many areas where pine forests dried up because of bark beetle outbreaks (Borisenko & Meshkova, 2021). Especially intense fires occurred in 2020, when rapid warming occurred in the spring, which in the absence of snow cover and the presence of intense winds in the February-March 2020 increased the fire danger in forests (Kornienko, 2021).

The spread and intensity of fires are characterised by indicators of the average factual burn rate, which are calculated by the number of fire cases per 1 million hectares (average absolute burn rate) and by the area covered by the fire in hectares per thousand hectares (relative burn rate). These indicators are used to assess the regions with the highest risk of fires, which allows determining the strategy for placing monitoring and extinguishing equipment. Thus, it is determined that in the steppe zone of Ukraine the mountain content reaches 27.2-36.9 ha per 1,000 ha of area, and in the Forest-steppe and Polesia this indicator ranges from 1.0 to 4.6 ha/1,000 ha (Voron *et al*., 2021).

In 2007-2017, Polesia identified 763.9 cases of fires per year, an average area of 1,952 ha/year, a relative burn rate of 179 cases of fires per 1,000 ha of area and 4.7 ha per 1,000 ha of area. In particular, in the Zhytomyr Oblast, these figures are 128.5 cases of fires, 204 ha, 128.3 cases per 1,000 ha of area and 2.3 ha per 1,000 ha of area (Zbitsev *et al.*, 2019b; Andreieva *et al.*, 2018; Andreieva & Goychuk, 2020).

These features of varying forest burn rates largely depend on climatic conditions, in particular temperature, precipitation, and its combination, wind strength and direction, as well as on factors that cause a fire (Voron *et al.*, 2016; Sydorenko *et al.*, 2021). The latter include the population, in particular recreants and individuals who set fire to stubble or other plant remains in fields and vegetable gardens (Voron *et al.*, 2021).

Global temperatures have increased by 0.8°C in recent decades (Jain *et al.*, 2022). An increase in air temperature, start and end dates of seasons, an increase in the duration of vegetation and fire-hazardous periods, a decrease in precipitation, and an increase in the frequency and intensity of natural weather events are predicted (Shvydenko *et al.*, 2018), which will lead to an increase in the level of fire hazard (Voron *et al.*, 2021).

The purpose of this study was to identify the features of the dynamics of the spread of fires in the forest stands of the Zhytomyr Oblast Department of Forestry and Hunting and assess the meteorological indicators that may affect their spread.

Although each oblast and natural area is described by certain average values of temperature and precipitation, they vary over the years. Therefore, in some years, the fire danger may increase even in areas where it is not high in terms of long-term average indicators. In this regard, it is important to investigate the dynamics of the spread of fires in the forest stands of the Zhytomyr Oblast Department of Forestry and Hunting and assess the meteorological indicators that may affect the spread of fires.

MATERIALS AND METHODS

The study used materials of statistical reporting of the Zhytomyr Oblast Department of Forestry and Hunting (ODFH) for the last eight years (2014-2021), by implementing analysis and statistical processing of materials on the dynamics of the spread of fires that occurred during the study period in the forest fund of forestry enterprises subordinate to Zhytomyr ODFH.

Based on the results of the data obtained, the average annual number of cases and the average annual area of forest fires for 2014-2019, 2021 were established and compared with the indicators of 2020.

The composition of forest rocks, to determine the class of fire danger, was established using the database of the State Enterprise "UkrDerzhlisProekt" regarding the forest fund of enterprises subordinate to the Zhytomyr ODFH.

Weather conditions for 2014-2021 are analysed. In particular, the dynamics of the sum of air temperatures and the dynamics of the sum of precipitation for the growing seasons of 2014-2021 are determined. Since large-scale fires occurred in April 2020, an analysis of the dynamics of precipitation in April for 2014-2021 was carried out.

In the occurrence of fires, not only elevated temperature and insufficient precipitation are important, but also their correlation, which was calculated using the G.T. Selyaninov's hydrothermal coefficient (HTC) according to the following formula (1):

$$HTC = \frac{10 \sum P}{\sum t} \quad (1)$$

where ΣP is the sum of precipitation in millimetres for a period with an average monthly temperature of more than +10°C; Σt is the sum of the average daily temperatures for the same period, °C [21].

The fire maximum was defined as the months during which the number of fires exceeded their average monthly number, and the fire peak was defined as the months when the highest number of fires was recorded (Voron *et al.*, 2021).

Statistical data analysis and charting were performed using the MS Excel software package.

RESULTS AND DISCUSSION

In the forests of the Zhytomyr Oblast, there is a high fire danger (middle class 2.5), which is mainly associated with a high proportion (about 60%) of coniferous plantations. A considerable part of plantings with a high fire hazard is located in a region with a high level of radiation pollution, where economic activities have been limited for over 30 years, and shrunken plantings have accumulated.

Analysis of the dynamics of the spread of fires in the forests of the Zhytomyr Oblast in recent years shows that in 2014-2019, 2021, the average annual number of fires was 64.0 – from 14 (2014) to 220 (2015), and 503 fires in 2020, i.e., 7.9 times higher than the average value. Therewith, a fairly substantial number of fires (220 cases) were also recorded in 2015 (Table 1).

Table 1. *Dynamics of forest fire spread indicators in Zhytomyr Oblast for 2014-2021*

Indicators	Years								Average for 2014-2019, 2021
	2014	2015	2016	2017	2018	2019	2020	2021	
Number of fires	14	220	36	17	16	94	503	51	64.0
Fire area, ha	2.8	102.4	12.5	237.2	7.4	174.62	43229	41.73	82.67
Crown fires, ha	0	0	0	4	0	35.7	6389	0	5.67
Average area of 1 fire, ha	0.20	0.47	0.35	13.96	0.46	1.86	85.94	0.82	2.60

The average annual area of forest fires in 2014-2019, 2021 was 82.67 hectares – from 2.8 hectares in 2014 to 102.4 hectares in 2015, and in 2020 it reached 43,229 hectares, i.e., 522.9 times higher than the average value.

In 2014-2019, 2021, crown fires were detected only on 4 hectares in 2017 and 35.7 hectares in 2019, while in 2020 they were registered on an area of 6,389 hectares, which accounted for 14.8% of the total area of fires in 2020 (Table 1).

Fires occurred in 2014-2019 in the forest fund of all forestry enterprises of the Zhytomyr Oblast excluding the State Enterprise "Berdychivske forestry" and the State Enterprise "Novohrad-Volynske SFHR", where deciduous stands predominate (Table 2). At the same time, in 2020, forest fires were registered in all forestry enterprises of the oblast.

Table 2. *Dynamics of the number of cases of forest fires in the forest fund of forestry enterprises of Zhytomyr Oblast in 2014-2021*

Forestry Enterprise	Years								Average for 2014-2019, 2021
	2014	2015	2016	2017	2018	2019	2020	2021	
Baranivske FHR	0	3	1	0	1	5	38	1	1.6
Bilokorovytske FHR	3	88	2	2	0	6	39	3	14.9
Berdychivske FHR	0	0	0	0	0	0	7	0	0
Horodnytske FHR	0	2	0	0	0	1	5	4	1
Yemilchynske FHR	0	3	0	0	0	1	1	0	0.6
Zhytomyrske FHR	0	1	1	0	0	5	26	4	1.6
Korostenske FHR	3	11	0	0	7	0	9	0	3
Korostyshivske FHR	0	4	0	1	1	0	21	1	1
Luhynske FHR	2	15	0	0	0	4	19	0	3
Malynske FHR	0	3	1	0	2	0	4	1	1
Narodytske SF	3	19	0	0	0	18	38	12	7.4
N.-Volynske SFHR	0	0	0	0	0	0	14	2	0.29

Table 2, Continued

Forestry Enterprise	Years								Average for 2014-2019, 2021
	2014	2015	2016	2017	2018	2019	2020	2021	
Ovrutske forestry	0	3	3	0	0	5	69	5	2.29
Ovrutske SF	0	2	0	0	0	1	19	1	0.60
Olevske forestry	2	15	0	2	0	24	25	3	6.60
Popilnianske forestry	0	0	1	2	0	6	7	0	1.30
Radomyshlske FHR	0	14	9	6	3	3	26	4	5.60
Slovechanske forestry	0	12	3	0	1	0	64	9	3.60
Poliskyi nature reserve	1	14	10	4	0	2	6	0	4.43
Luhynskyi forestry agro-industrial complex (Luhynske specialised forestry)	0	5	4	0	1	13	48	1	3.43
Zhytomyrskyi MFR (Zarichanske forestry)	0	6	1	0	0	0	18	0	1.0
Total	14	220	36	17	16	94	503	51	64.24

The largest number of cases of fires in 2015 was registered in the State Enterprise "Bilokorovytske forestry" (88 cases). More than 10 cases were reported in state enterprises "Korostenske FHR", "Luhynske forestry", "Narodytske SFR", "Olevske forestry", "Radomyshlske FHR", "Slovechanske forestry" and in Polisia Reserve.

In 2016, fires occurred in 11 forestry enterprises, with the largest number of fires occurring in SEs "Radomyshlske FHR" and in the Polisia nature reserve (9 and 10 cases, respectively).

In 2017, fires occurred in six forestry enterprises, among which the maximum number of cases was also recorded in the State Enterprise "Radomyshlske LMG" and in the Polisia nature reserve (6 and 4 cases, respectively).

In 2018, fires occurred in seven forestry enterprises, among which 7 cases occurred at the State Enterprise "Korostenske FHR" and 3 cases – at the State Enterprise "Radomyshlske FHR" (Table 2).

In 2019, fires were registered on the territory of 14 enterprises, the maximum number of which was recorded in the State Enterprise "Naroditskoe SHR" and State Enterprise "Olevske forestry" (18 and 24 cases).

In 2020, forest fires were registered in all forestry enterprises; in the SE "Ovrutske forestry" and the SE "Slovechanske forestry" – 69 and 64 cases, respectively, in the SE "Baranivske FHR", SE "Bilokorovytske forestry", SE "Narodytske SFR" and SE "Luhynske forestry agro-industrial complex" the number of cases ranged between 38-48. In general, in the Zhytomyr Oblast, the number of fires in 2020 exceeded the average of previous years by 7 times (Table 2).

In 2021, the largest number of fires was recorded in the State Enterprise "Narodytske SFR" – 12 cases.

At the beginning of April 2020, the area of fires amounted to over 8.7 thousand hectares and covered the territory of Narodytske Davydkivske and Klishchivske, Kotovske, and Denysovetske forest districts of the exclusion zone and unconditional (mandatory) resettlement. In April, the entire northern part of the region was also engulfed in fires (SE "Bilokorovytskyi forest farm", SE "Luhynskyi forest farm", SE "Narodytskyi special forest farm", SE "Ovrutskyi forest farm", SE "Ovrutskyi special forest farm", SE "Olevskyi forest farm", SE "Slovechanskyi forest farm"). As of April 21, 2020, the area of fires exceeded 20 thousand hectares. As of January 1, 2021, the forest area of Zhytomyr ODFH covered by fires reached 43,229 hectares in 503 fire centres (Table 3). The largest area of fires was registered in the SE "Ovrutske SHR", SE Enterprise "Narodytske SHR", SE "Slovechanske forestry", SE "Luhynske forestry", SE "Ovrutske forestry", SE "Olevske forestry" and SE "Bilokorovytske forestry", which together accounted for 97.3% of the area of all plantings covered by fire.

Table 3. *Area of forest fires in the forest fund of forestry enterprises of Zhytomyr Oblast in 2014-2021*

Forestry Enterprise	Years								Average for 2014–2019, 2021
	2014	2015	2016	2017	2018	2019	2020	2021	
Baranivske FHR	0	3	1	0	1	5	38	1	1.6
Bilokorovytske FHR	3	88	2	2	0	6	39	3	14.9
Berdychivske FHR	0	0	0	0	0	0	7	0	0
Horodnytske FHR	0	2	0	0	0	1	5	4	1
Yemilchynske FHR	0	3	0	0	0	1	1	0	0.6

Table 3, Continued

Forestry Enterprise	Years								Average for 2014–2019, 2021
	2014	2015	2016	2017	2018	2019	2020	2021	
Zhytomyrske FHR	0	1	1	0	0	5	26	4	1.6
Korostenske FHR	3	11	0	0	7	0	9	0	3
Korostyshivske FHR	0	4	0	1	1	0	21	1	1
Luhynske FHR	2	15	0	0	0	4	19	0	3
Malynske FHR	0	3	1	0	2	0	4	1	1
Narodytske SF	3	19	0	0	0	18	38	12	7.4
N.-Volynske SFHR	0	0	0	0	0	0	14	2	0.29
Ovrutske forestry	0	3	3	0	0	5	69	5	2.29
Ovrutske SF	0	2	0	0	0	1	19	1	0.60
Olevske forestry	2	15	0	2	0	24	25	3	6.60
Popilnianske forestry	0	0	1	2	0	6	7	0	1.30
Radomyshlske FHR	0	14	9	6	3	3	26	4	5.60
Slovechanske forestry	0	12	3	0	1	0	64	9	3.60
Poliskyi nature reserve	1	14	10	4	0	2	6	0	4.43
Luhynskyi forestry agro-industrial complex (Luhynske specialised forestry)	0	5	4	0	1	13	48	1	3.43
Zhytomyrskyi MFR (Zarichanske forestry)	0	6	1	0	0	0	18	0	1.0
Total	14	220	36	17	16	94	503	51	64.24

If in previous years only grassroots fires were registered in the forests of the Zhytomyr Oblast, then in 2020, crown fires broke out in the forest background of 10 forestry enterprises, which accounted for a total area of 6,389.3 hectares, or 14.8% of the total area covered by fires.

Crown fires are the most dangerous because sparks from burning needles and branches spread in space, and heat flows damage both coniferous and deciduous trees in the thin bark area. The increase in the area of crown fires could be associated with both strong winds and the spread of plantings with low-lying crowns, since tending cutting was not carried out everywhere on time due to the location of plantings in radiation-hazardous areas and insufficient funding for these activities. In terms of the area of crown fires, the leading place belongs to the SE "Ovrutske SFR" (5,000 ha), large areas of crown fires were recorded in the SE "Luhynske forestry" (404 ha), "Ovrutske forestry" (402 ha), the SE "Slovechanske forestry" (275 ha), the Polisia nature reserve (150 ha) and the SE "Bilokorovytske forestry" (99 ha). The area of crown fires exceeded a third of the total area of forest fires in the SE "Ovrutske SFR" and SE "Popilnianske forestry", approached a third in the Polisia nature reserve and amounted to about 10% in the forests of the SE "Ovrutske forestry", SE "Luhynske forestry" and SE "N.-Volynske SFHR" (Fig. 1).

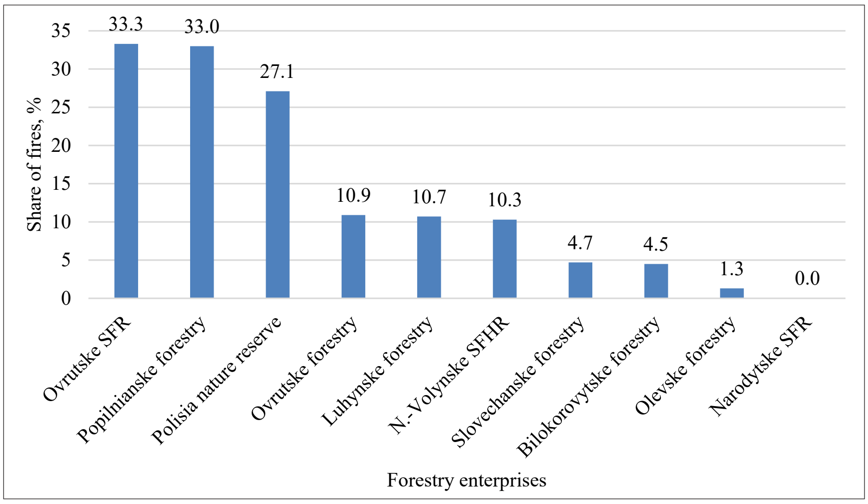

***Figure 1**. Share of the area of crown fires from the total area of forest fires in forestry enterprises of Zhytomyr ODFH*

Analysis of weather conditions according to the Zhytomyr weather station revealed that the sum of air temperatures during the growing season was 3,127.6°C on average for 2014-2021. This indicator exceeded the indicated average data in 2015-2016 and 2018-2020, to the greatest extent – in 2018 – by 211.3°C, or by 6.8% (Fig. 2).

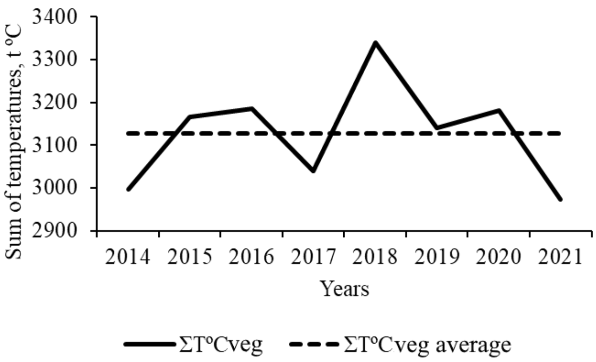

***Figure 2**. Dynamics of the sum of air temperatures for the growing seasons 2014-2021*

The amount of precipitation during the growing season averaged 323.8 mm for 2014-2021, and was the lowest in 2015 (118.4 mm, or 36.6% less than the average value) (Fig. 3). In 2016 and 2017, the amount of precipitation during the growing season was lower than the average data for the period by 67.4 and 74.8 mm (i.e., by 20.85 and 23.1%). In 2020, this indicator was lower than the average data by 9.2 mm, or 2.8% (Fig. 3).

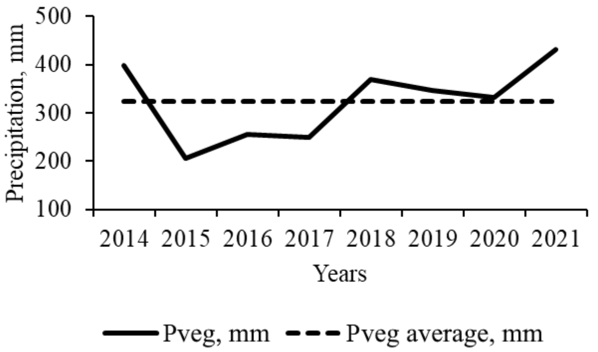

***Figure 3**. Dynamics of the amount of precipitation for the growing seasons 2014-2021*

Since major fires occurred in April 2020, the dynamics of precipitation in April 2014-2021 was analysed (Fig. 4).

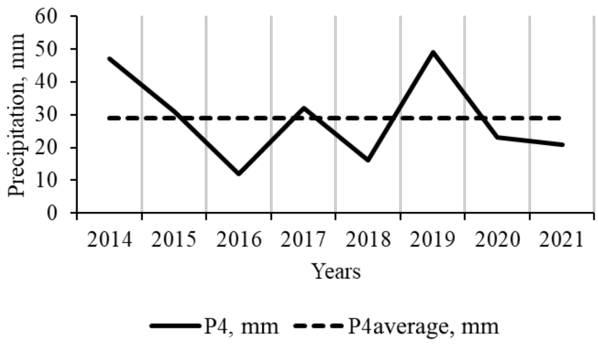

***Figure 4**. Precipitation dynamics for April 2014-2021*

In 2014-2021, the average amount of precipitation in April was 28.9 mm. This indicator was lower than the long-term average in 2016, 2018, 2020, and 2021, with the difference in 2016 and 2018 being 16.9 and 12.9 mm, or 58.5 and 44.6%, respectively, and in 2020 and 2021 – 5.9 and 7.9 mm, or 20.4 and 27.3%, respectively (Fig. 4).

Not only high temperature and insufficient precipitation play a role in the occurrence of a fire hazard, but also their correlation, which is estimated using the hydrothermal coefficient of G.T. Selyaninov (Selyaninov, 1937).

Analysis of the values of G.T. Selyaninov's hydrothermal coefficient for the growing seasons of 2014-2021 shows that the average value of the indicator for this period was 1.04 units (Fig. 5). This indicator was lower than the average values in 2015-2017 by 0.2-0.4 units, or by 21.2-37.6%. It was in those years that foci of stem pests spread in the pine plantations of the region (Shvydenko *et al.*, 2018; Andreieva *et al.*, 2018; Meshkova, 2021b).

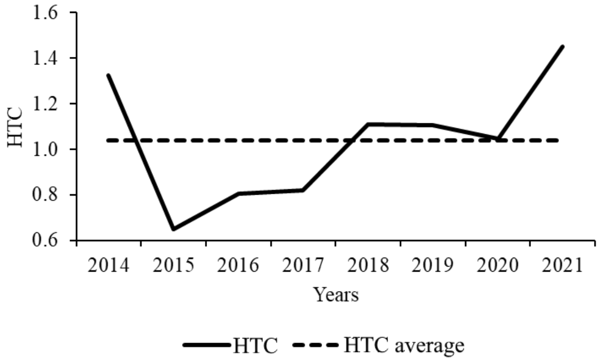

***Figure 5**. Dynamics of the hydrothermal coefficient for the growing seasons 2014-2021*

In 2020, the hydrothermal coefficient of G.T. Selyaninov during the growing season did not considerably exceed the average values (by 0.01 units, or 0.7%) (Fig. 5).

Thus, weather conditions themselves were not the main causes of large forest fires.

CONCLUSIONS

1. In the forests of Zhytomyr Oblast Department of Forestry and Hunting, forest fires were registered in the forest fund of all forestry enterprises of the oblast (in total, on an area of more than 20 thousand hectares). The average annual number of fires is 7.9 times higher, and the average annual area of forest fires is 522.9 times higher than the average values in 2020. The area of crown fires in 2020 was 14.8% of the total area of fires.

2. The sum of air temperatures during the growing season exceeded the average data by 6.8%. The amount of precipitation in April 2020 was lower than the long-term average of 5.9 mm, or 20.4%. G.T. Selyaninov's hydrothermal coefficient was 21.2-37.6% lower than the average values in 2015-2017, and in 2020 it exceeded them by 0.7%.

3. According to reports on forest fires and their consequences in Zhytomyr Oblast Department of Forestry and Hunting, it is established that the causes of fires are the activity of the population. At the same time, the fire spread under favourable weather and climatic conditions (high air temperature, low precipitation, etc.).

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Вплив погодних умов на поширення пожеж у лісовому фонді Житомирського Полісся

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Анотація. Пожежі є одним із важливих чинників ослаблення лісів. Зважаючи на високу частку площі соснових лісів у Житомирській області, умови для виникнення пожеж є дуже сприятливими. Особливо інтенсивні пожежі відбулися у 2020 році, коли навесні відбулося швидке потепління, що за відсутності снігового покриву та наявності сильних вітрів у лютому-березні 2020 року підвищило пожежну небезпеку в лісах. Мета дослідження – виявити особливості динаміки поширення пожеж у лісових насадженнях Житомирського ОУЛМГ та оцінити метеорологічні показники, що можуть вплинути на їх поширення. Методи дослідження: статистичні – під час аналізу даних метеорологічних показників і матеріалів щодо обліку лісових пожеж. Визначено особливості динаміки поширення пожеж у лісових насадженнях Житомирської області у 2014–2021 рр. Згідно проведеного аналізу встановлено значне збільшення кількості та площ пожеж у 2020 році порівняно з середніми показниками за 2014–2019 та 2021 роки разом. За період 2014–2021 років виникла 951 пожежа на вкритій лісом площі 43807,65 га. Виявлено, що лише 448 пожеж виникли за 2014–2019 та 2021 роки, а у 2020 році зафіксовано 503 пожежі на площі 43229 га. У тому числі верхові пожежі було зафіксовано на площі 6389 га у тому ж 2020 році та на площі 35,7 га лише у 2019 році. Найбільші площі верхових пожеж зафіксовано на території ДП «Овруцьке СЛГ», ДП «Лугинське ЛГ», ДП «Овруцьке ЛГ» та ДП «Словечанське ЛГ». Проаналізовано показники температури, опадів і гідротермічного коефіцієнта за 2014–2021 роки. Було визначено за вегетаційний період значення температури повітря, кількості опадів, та розраховано гідротермічний коефіцієнт за Г.Т. Селяніновим. Встановлено, що сума температур повітря протягом вегетаційного періоду становила 3127,6 °С в середньому за 2014–2021 рр. Найвищі температурні показники були зафіксовані протягом вегетаційного періоду 2018 року. Згідно аналізу суми атмосферних опадів за вегетаційний період 2014–2021 рр. встановлено показники на рівні 323,8 мм. Найнижчі показники атмосферних опадів було зафіксовано у 2015 році. За співвідношенням показників температури та опадів отримано значення гідротермічного коефіцієнта Г.Т. Селянінова за вегетаційні періоди 2014–2021 рр., середнє значення якого становило 1,04 одиниці

Ключові слова: лісова пожежа, гідротермічний коефіцієнт, динаміка поширення пожеж, верхова пожежа, вегетаційний період, сума температур повітря, сума опадів

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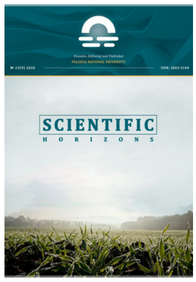

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Key Drivers of Urban Digital Economy Sustainable Development: The China Case

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Abstract. Digitalisation is a modern social and economic reality. The search for efficient pathways to move towards high-quality digital communities' sustainable development constitutes the scope of current urban research worldwide. Given the need to move towards sustainable urban digitalisation, investigation of its critical influencing factors deserves special attention. However, quantitative empirical studies that avoid subjective judgement on the drivers of sustainable urban digitalisation are lacking. The purpose of this study is to fill this knowledge gap by outlining and quantifying the key factors affecting the sustainable development of the urban digital economy through entropy-TOPSIS modelling. The study takes China's provinces and cities as an example due to China's success in digital economy development. It is proposed to use the complex four-dimensional (scientific and technological innovation, economic growth, social development, information infrastructure) system involving 16 sub-indices to measure urban digital economy sustainability. Applying data from 31 Chinese provinces and cities for 2016-2019 and the entropy-TOPSIS model, the development of the technological innovations was found to be the most impacting factor on the urban digital economy sustainability path. The R&D staff engagement and expenditures, goods export and import, and e-commerce sales fuel the urban digital economy sustainability the most, while the number of students, public financial expenditures, and unemployment are the least significant. Results show that the urban digital economy is more a business-driven process than pushed by authorities. The gap between Chinese regions' digital economy development was identified. This could be explained by the prevalence of conventional industries in several areas and the low level of their digitalisation and indicates the need to enhance interregional cooperation and partnership to promote sustainable development of the country under the digital economy paradigm. Despite China's context, this research contributes to further science and policy development in this field globally, covering the role of talents, innovations, business R&D investments, interregional cooperation, and multiscale partnership in the promotion of urban digitalisation conducive to sustainability ideas

Keywords: digitalisation, entropy method, sustainability, TOPSIS model, urban development

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INTRODUCTION

The digital economy is a more advanced economic stage following the agricultural and industrial economies. It takes digital information and knowledge as the key production factors, modern information networks as the primary carrier, the integration and application of information and communication technology, the digital transformation of all aspects as important driving forces to promote a new economic form that is inclusive, innovative, efficient, and sustainable (Chen *et al.*, 2020; Purnomo *et al.*, 2022). The digital economy comprehensively utilises information technology such as the Internet, computer, space technology, and communication – the comprehensive integration of contemporary high-tech reflecting the most advanced productive forces in the 21st century – and is conducive to the sustainable development of the urban economy and society (Gautier & Lamesh, 2021). To this end, the Chinese government attaches foremost importance to the sustainable development of an urban digital economy. It puts forward "implementing the national big data strategy, building a digital economy with data as the key element, accelerating the construction of "digital China" to promote the high-quality and sustainable development of digital economy from the aspects of technical support, market supply and demand, industrial development, and policy guarantee (Yin *et al.*, 2019). China's digital economy has achieved remarkable results in recent years. By 2020, the scale of China's digital economy has reached 5.4 trillion US dollars accounting for 34.8% of GDP and ranking second only to the US (13.6 trillion US dollars) (Chen *et al.*, 2020), which has become a driver for high-quality economic development and enhanced international digital competitiveness.

The rapid development of the Chinese digital economy has also revealed the following problems: the insufficient digital-driven innovation capability, the backward core innovation field of the digital economic basis, and weak R&D investments. Secondly, the construction of digital economic infrastructure is biased towards the construction of network communication resources. In contrast, the infrastructure development for new generation artificial intelligence and high-end equipment manufacturing is insufficient. Thirdly, a small proportion of knowledge-based talents engagement in a digital economy causes an imbalanced structure of the supply and demand for knowledge-based labour. Despite the achieved results, China's digital economy is still far from the sustainable path, especially in urban systems (Cao *et al.*, 2021). This is due to a lack of understanding of the entire digital economy development system and its drivers and a lack of measurement models to evaluate the performance and sustainability of digital economic development (Sturgeon, 2021). Elaboration of policy and promotion of sustainable conducive development of digital economy in urban agglomerations need drivers and incentives to be clearly defined through comprehensive studies and explorations. Therefore, the purpose of this paper is to outline the key factors affecting the sustainable development of the urban digital economy: build a scientific evaluation index system and quantitatively describe the impact of each key factor, supporting the science-based and justified decisions concerning the promotion of a sustainable path of urban digitalisation.

LITERATURE REVIEW

In recent years, different institutions have constructed various index systems to assess various aspects of digital economy development. The EU Digital Economy and Society Index measures the development of the digital economy in EU countries concerning five main elements: broadband access, human capital, Internet application, digital technology application, and digital public services (Curran, 2018). The International Telecommunication Union has set up 11 indicators to evaluate access, use, and skills concerning information and communication technologies (ICT). "White Paper on China's Digital Economy Development (2017)", issued by the China Academy of Information and Communications, suggests a direct method to estimate the digital economy expansion (includes seven leading indicators, ten consistent indicators, and four lagging indicators) (Yin *et al.*, 2019). Saidi Research Institute divides the digital economy into primary, resource-based, technology-based, integrated, and service-oriented and designs 34 secondary indicators like the scale of the information transmission industry and the number of data trading centres (Shaikh *et al.*, 2020; Zhao & Zhou, 2022).

Scholars continue to explore the development of the digital economy and evaluate it from different perspectives. X. Wan *et al.* (2019) propose a system of 71 four-level indicators assessing a digital economy's inputs and outputs. Zhang and Chen (2018) develop a system of 20 indicators to measure economic efficiency, social progress, structural optimisation, and resource environment for the digital economy by applying the analytic hierarchy process (AHP). Existing research also focuses on concrete geographical areas. Q. Lin and H. Lv (2019) suggest eight indicators, such as key applications, government affairs platform investment, and scientific research platform investment, to evaluate the digital economy industrial integration in Hefei through a fuzzy comprehensive evaluation method. J. Xin *et al.* (2019) propose the evaluation index system of digital economy development for Zhejiang province based on the complete index method. X. Ning (2018) designs the evaluation indices for Hubei Province based on the technological and economic paradigms.

The available literature provides a good reference for further research and can guide the urban digital economy sustainable development measurement process in general. However, the following issues are questionable: 1) the available approaches to measure the sustainability of urban digital economic development rarely include scientific (and technological) innovation capacity and digital infrastructure construction in the index system; 2) the most common methods used (a fuzzy comprehensive evaluation method, AHP, comprehensive index method) utilise expert scoring, which is too subjective; 3) there are few quantitative empirical studies on the macro-level factors affecting the sustainable development of the urban digital economy. To fill this knowledge gap, this study explores the core elements intertwined in the urban digital sustainable development and constructs the evaluation index system integrating four dimensions: information infrastructure, innovation, economic growth, and social development.

MATERIALS AND METHODS

The sustainable development of the urban digital economy is a complex system problem affected by many factors (Pan *et al.*, 2022). The multi-index comprehensive evaluation method could be more beneficial in assessing the urban digital economy sustainability. In this regard, an entropy weights-TOPSIS model (Technique for Order Preference by Similarity to an Ideal Solution) fits well to quantify a complex of impacts and ensure the factual accuracy of evaluation results.

The entropy method is an objective method to determine the weights. It deals with the original data variability: the smaller the degree of index variation, the lower will be the corresponding weight. This weighting method effectively avoids the interference of human factors, better reflects the evaluation index's objectivity and authenticity, and is widely used in social and economic sciences (Ding *et al.*, 2016). TOPSIS model is a common approach for multiple attribute decision making. It evaluates the existing object's attributes (Yang *et al.*, 2018). Evaluated things are not restricted to time, space, and sample size; the TOPSIS approach follows a simple calculation procedure, making it desirable. This study applies a combination of entropy-weight and TOPSIS to quantify factors affecting the urban digital economy of China regions' sustainable development. The entropy weight method is used the first to identify the weights of each indicator. Then the impact of each factor on the regional sustainable development is measured through the TOPSIS approach. The following steps specify the procedure of entropy weight-TOPSIS model application:

1. *Construction of the original data matrix*. To evaluate the sustainable development of m cities via n indicators, the initial X matrix of $m \times n$ is composed of the original data characterising cities' parameters (Eq. 1):

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ \dots & \dots & \dots & .. \\ \dots & \dots & \dots & .. \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \quad (1)$$

where m is the number of objects to be evaluated; n is the number of assessment criteria; x_{ij} is the element of matrix X, the value of the j ($j = 1, 2, \dots, n$) indicator of the i ($i = 1, 2, \dots, m$) object.

2. *Data normalisation*. To make the original data of different dimensions and different data sources comparable, this study follows the normalisation procedures. Evaluation results are classified according to the index content: in the case of a higher index value causing higher evaluation results, the impact will be judged positive (and negative – otherwise). For the positive effects of indicator x_{ij}, the normalised value S_{ij} can be calculated as follows (2):

$$S_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (2)$$

For the negative impact of x_{ij}, the normalised value S_{ij} is calculated in the following way (3):

$$S_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (3)$$

where S_{ij} is the normalised value; $max x_{ij}$ is the maximum value of the j^{th} indicator of the i^{th} object;
$min\ x_{ij}$ is the minimum value of the j^{th} indicator of the i^{th} object.

3. *Use of the entropy method* to quantify indicators' weights presupposes calculation of the standardised value p_{ij} of indicator j for object i following the Eq. 4 and an entropy value of the indicator – e_j (Eq. 5) used then to assess an information utility d_j value of the indicator (Eq. 6). Finally, the weighting value – w_j – of the j indicator is quantified in line with Eq. 7:

$$P_{ij} = \frac{S_{ij}}{\sum_{i=1}^{m} S_{ij}} \quad (4)$$

$$e_j = -\frac{1}{Inm} \sum_{i=1}^{m} p_{ij} Inp_{ij} \quad (5)$$

$$d_j = 1 - e_j \quad (6)$$

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (7)$$

where P_{ij} is the standardised value of indicator j for object i; e_j is the entropy value for j indicator; d_j is the information utility value of indicator j; w_j= is the weighting value for j indicator.

4. Use of TOPSIS model to quantify factors' impact. The first step is to compose the weighted assessment matrix (Eq. 8). The matrix elements are then classified as the best A^+ and the worst A^- solutions (Eq. 9, Eq. 10).

$$a_{ij} = w_j p_{ij} (i = 1,2, \dots, m; j = 1,2, \dots, n) \quad (8)$$

$$A^+ \{\max A_{ij} | i = 1,2, \dots, m\} = \{A_1^+ A_2^+, \dots, A_n^+\} \quad (9)$$

$$A^- \{\max A_{ij} | i = 1,2, \dots, m\} = \{A_1^- A_2^-, \dots, A_n^-\} \quad (10)$$

where a_{ij}=the weighted standardised matrix element; A^+=the positive ideal solution; A^-=the negative ideal solution.

The next step is to calculate the Euclidean distance $D_i^{+/-}$ between the evaluation value and the best solution A_j^+ (Eq. 11), the evaluation value and the worst solution A_j^- (Eq. 12):

$$D_i^+ \sqrt{\sum_{j=1}^{n} (A_j^+ - A_{ij})^2} (i = 1,2, \dots, m) \quad (11)$$

$$D_i^- \sqrt{\sum_{j=1}^{n}(A_j^- - A_{ij})^2}(i = 1,2, \dots, m) \quad (12)$$

The relative proximity C_i of the object i allows quantifying the distance between the evaluation value and two ideal solutions:

$$C_i = \frac{D_i^-}{D_i^+ - D_i^-}(i = 1,2, \dots, m) \quad (13)$$

where D_i^+ is the Euclidean distance between the evaluation value and the best solution; D_i^- is the Euclidean distance between the evaluation value and the worst solution; C_i is the relative closeness of the object i.

Finally, schemes are sorted according to the relative proximity: the larger the relative proximity is, the better the system is.

This research utilises the entropy-TOPSIS model to select and quantify the key factors influencing urban digital sustainable development and its performance among Chinese cities. This study utilises the data of 16 essential indicators of 31 provinces and cities in China for 2016-2019 from "China Statistical Yearbook", "China Urban Statistical Yearbook", and "China Regional Economic Statistical Yearbook". Provinces serve as primary statistical units in China – this determined the data selection approach. To grasp the overall state of China's digital economy sustainable development, this study explored regions under China's Central Government control (except for Hong Kong, Macao, and Taiwan). The vigorous growth of China's digital economy began with the "G20 Digital Economy Development and Cooperation Initiative" released at the G20 Hangzhou Summit in 2016. In this regard, the earlier data (before 2016) was judged as of little significance to this study. Following principles of data representativeness, regularity, and availability (the last complete statistical records are available only for 2020), 2016-2019 were selected to do this research.

RESULTS AND DISCUSSION

Construction of an urban digital economy sustainable development complex evaluation system

Accounting for the role of technology and innovations for digital transformation and based on the connotation of the sustainable development of the urban digital economy (Hongyue & Koblianska, 2022; Hongyue *et al.*, 2022), this study proposes the four-criteria complex system of indicators to measure the sustainability of urban digital economy development (Table 1). The proposed system embraces 16 sub-indices selected due to principles of scientificity, systematicity, practical significance, and data availability. Some comments on the proposed measurement system are given below.

Table 1. *System of factors influencing sustainable development of urban digital economy*

Criterion Layer	Index Layer	Index Unit	Index attribute
Information Infrastructure(A)	Mobile phone penetration (A1)	%	Positive
	Internet broadband access users (A2)	Thousands of families	Positive
	Length of optical cable line per unit area (A3)	Km/sq.	Positive
	Number of computers used per 100 population (A4)	Pieces	Positive
Science and Technology Innovation(B)	R&D project expenditure (B1)	Ten thousand yuan	Positive
	R&D personnel full-time equivalent (B2)	Man-year	Positive
	Number of patents granted (B3)	Item	Positive
	Number of students enrolled in institutions of higher learning (B4)	Ten thousand people	Positive
Economic growth(C)	E-Commerce Sales (C1)	Billion yuan	Positive
	Added value of tertiary industry (C2)	Billion yuan	Positive
	Industrial added value (C3)	Billion yuan	Positive
	Revenue from software business (C4)	Ten thousand yuan	Positive
Social development(D)	Urban registered unemployment rate (D1)	%	Negative
	Expenditure of urban public finance (D2)	Billion yuan	Positive
	Total imports and exports of goods (D3)	Thousands of US dollars	Negative
	Employed persons in software and information technology services (D4)	Ten thousand people	Positive

Source*: authors' development*

Information infrastructure (A) is the foundation for urban digital economy development and drives sustainability (Demestichas & Daskalakis, 2020; Wahome & Graham, 2020). Based on the digital economy networking nature, infrastructure mainly refers to Internet facilities and broadband networks: the penetration rate of mobile phones (A1), the number of Internet broadband access users (A2), the length of optical cable lines per unit area (A3), and the number of computers used per 100 people (A4). The mobile phone penetration rate (A1) reflects the potential driving force for developing a digital economy, while Internet broadband access users (A2) reflect the communication network quality in a particular area. The length of the optical cable line per unit area (A3) reflects the region's completeness of the Internet infrastructure. The number of computers per 100 people (A4) measures the degree of digital development.

The scientific and technological innovation development reflects the potential of a region's digital economy development and sustainability (Yi *et al*., 2021). R&D project expenditure (B1) measures enterprises' innovation, and digital investment activity, the full-time equivalent of R&D personnel (B2) reflects the current labour potential for innovations. Patent authorisation (B3) indicates the region's leadership in scientific and technological innovations, while the number of college students (B4) reflects the region's long-term potential to innovate. Economic growth is closely related to the development of the digital economy (Li *et al*., 2020). Given this, urban digital economy sustainability can be measured via proper economic growth indicators, namely: e-commerce sales (C1), the tertiary industry added value (C2), industrial added value (C3), and software business income (C4). Commenting on these sub-indices, one should mention the sales volume of e-commerce (C1) significance in measuring the scale of economic activities carried out by digital and network region's assets. Value-added of the tertiary industry (C2) reflects the degree of the region's economic transformations. Industrial added value (C3) reflects the contribution of the secondary sector to economic development. Software business income (C4) measures the digital industry development. Social development (D) affects the urban digital economy's sustainable development in a multifaceted way. A higher social development level better promotes the development of the digital economy (Sutherland & Jarrahi, 2018). In particular, the total import and export of goods (D3), indicating the level of the economy's openness, directly affects the urban digital economy caused by globalisation. The number of employees in the software and information service industry (D4) reflects the potential to drive the development of the urban digital economy and society.

Identification of factors' influence on urban digital economy sustainability via entropy method

Following the proposed measurement system (Table 1), the original data was collected and processed. Table 2 summarises the results of initial data normalisation and weighting (via entropy-weight method) for 31 Chinese cities.

Table 2*. Factors influencing the urban digital economy sustainability in China: Weights' dynamics for 2016-2019*

Primary index	Primary weight, %				Average weight of primary index, %	Secondary weight, %				Average weight of secondary index, %	Secondary index
	2016	2017	2018	2019		2016	2017	2018	2019		
A	14.02	13.71	13.01	14.05	13.7	2.20	1.94	2.36	2.63	2.28	A1
						4.49	4.67	3.96	4.18	4.33	A2
						4.65	4.64	4.02	4.21	4.38	A3
						2.68	2.46	2.67	3.03	2.71	A4
B	31.28	34.12	33.35	36.9	33.91	9.21	9.99	9.30	10.05	9.64	B1
						9.64	10.55	11.22	12.62	11.01	B2
						9.40	10.37	9.85	10.96	10.15	B3
						3.03	3.21	2.98	3.27	3.12	B4
C	28.22	30.43	27.7	30.95	29.33	9.66	10.81	9.68	11.00	10.29	C1
						5.01	5.27	4.82	5.42	5.13	C2
						5.80	6.13	5.64	6.23	5.95	C3
						7.75	8.22	7.56	8.30	7.96	C4
D	26.48	21.75	25.92	18.1	23.06	2.30	1.90	1.85	1.13	1.80	D1
						1.91	2.18	2.06	2.55	2.18	D2
						14.12	8.53	13.08	8.20	10.98	D3
						8.15	9.13	8.95	6.22	8.11	D4

Source*: authors' development*

Table 2 shows the highest average weight (33.91%) of scientific and technological innovation (B) among selected groups of factors influencing the urban digital economy's sustainable development. This is due to the policies issued at different scales to support the digital economy development via investments in scientific and technological innovation. Economic growth (C), accounting for 29.33% of significance, fuels the sustainable development of a digital economy and its rapid expansion. Social development (D) creates a favourable urban digitalisation and sustainability environment. Information infrastructure (A) has the lowest weight (13.7%), but it is no less vital for urban digital economy sustainability.

Scientific and technological innovation (B) significance increases year by year, reaching 36.9% in 2019. This aligns with earlier research on the crucial role of technological innovation and infrastructure construction in promoting sustainable urban development (Zhu & Chen, 2022). Among the group's secondary indicators, the weight of R&D personnel full-time equivalent (B2) is the highest, indicating the high relevance of the number of research and innovation personnel for sustainable urban digital economy development. The amount of patent authorisation (B3) and R&D project expenditure (B1) have minor difference in the influence on technological innovation, with an average weight of 10.15% and 9.64%, respectively. The average number of students in colleges and universities (B4) is the least impacting urban digital economy sustainability among the scientific and technological factors (3.12%).

The weight of e-commerce sales (C1) is the highest (10.29%) among the economic growth group of factors. Although the added value of tertiary industry (C2) has the lowest weight among economic factors, it is upward.

Although the overall weight of social development (D) has not changed much, it is declining. The most weighting index — the total import and export of goods (D3) — decreases significantly. The registered urban unemployment rate (D1) and urban public financial expenditure (D2) weights (1.80% and 2.18%, respectively) impact urban digital sustainability the least among all secondary indices. The impact of unemployment marks further "dis-embeddedness" of the digital employment sector from conventional social regulations that was found by B. Chen *et al.* (2020), and the need of transforming social institutions to support sustainable urban digitalisation (Curran, 2018).

Information infrastructure (A) weight is the most stable among all groups. The length of optical cable lines per unit area (A3) and the number of computers used per 100 people (A4) weights are slightly larger than those of mobile phone penetration (A1) and Internet broadband access users (A2). However, impacts of the mobile phone penetration rate (A1) and the number of computers per 100 people (A4) have a clear upward trend, indicating their high significance for urban digital economy sustainability.

To summarise, the following factors influence the urban digital economy sustainability the most (by average weights, top-five): the R&D personnel full-time equivalent; the total import and export of goods; the e-commerce sales; the amount of patent authorisation; the R&D project expenditure. The least significant are as follows: registered urban unemployment rate; public financial expenditure; mobile phone penetration; the number of computers per 100 people; the number of students in colleges and universities. This shows the fundamental driving forces of urban digital economy sustainability: talents, research, and economic activity. The urban digital economy is more a business-driven process than pushed by authorities.

Assessment of digital economy sustainable development performance in Chinese provinces and cities

The entropy-TOPSIS calculation results (Table 3) allow comparing the sustainable development of the digital economy in 31 Chinese provinces and cities. The relative proximity Ci [0; 1] serves the evaluation standard: Ci value closer to one attests to the better digital economy sustainability performance in the city and opposite. Figure 1 visualises obtained results.

Table 3. *Digital economy sustainable development performance in Chinese provinces and cities in 2019*

Region	Relative proximity Ci	Ranking	Province	Relative proximity Ci	Ranking
The eastern coastal region	0.333	1	Guangdong	0.733	1
			Beijing	0.534	2
			Jiangsu	0.522	3
			Zhejiang	0.421	4
			Shanghai	0.358	5
			Shandong	0.305	6
			Fujian	0.166	10
			Hebei	0.119	14
			Tianjin	0.118	15
			Hainan	0.049	26
The central region	0.132	2	Hubei	0.192	7
			Henan	0.168	9
			Anhui	0.147	12
			Hunan	0.133	13
			Jiangxi	0.096	17
			Shanxi	0.055	24
The north-eastern region	0.079	3	Liaoning	0.117	16
			Heilongjiang	0.062	21
			Jilin	0.059	22

Table 3, Continued

Region	Relative proximity ***Ci***	Ranking	Province	Relative proximity ***Ci***	Ranking
The western region	0.071	4	Sichuan	0.185	8
			Shaanxi	0.152	11
			Chongqing	0.094	18
			Yunnan	0.066	19
			Guangxi	0.065	20
			Inner Mongolia	0.055	23
			Guizhou	0.054	25
			Xinjiang	0.042	27
			Qinghai	0.042	28
			Gansu	0.037	29
			Ningxia	0.031	30
			Tibet	0.026	31

Source: *authors' development*

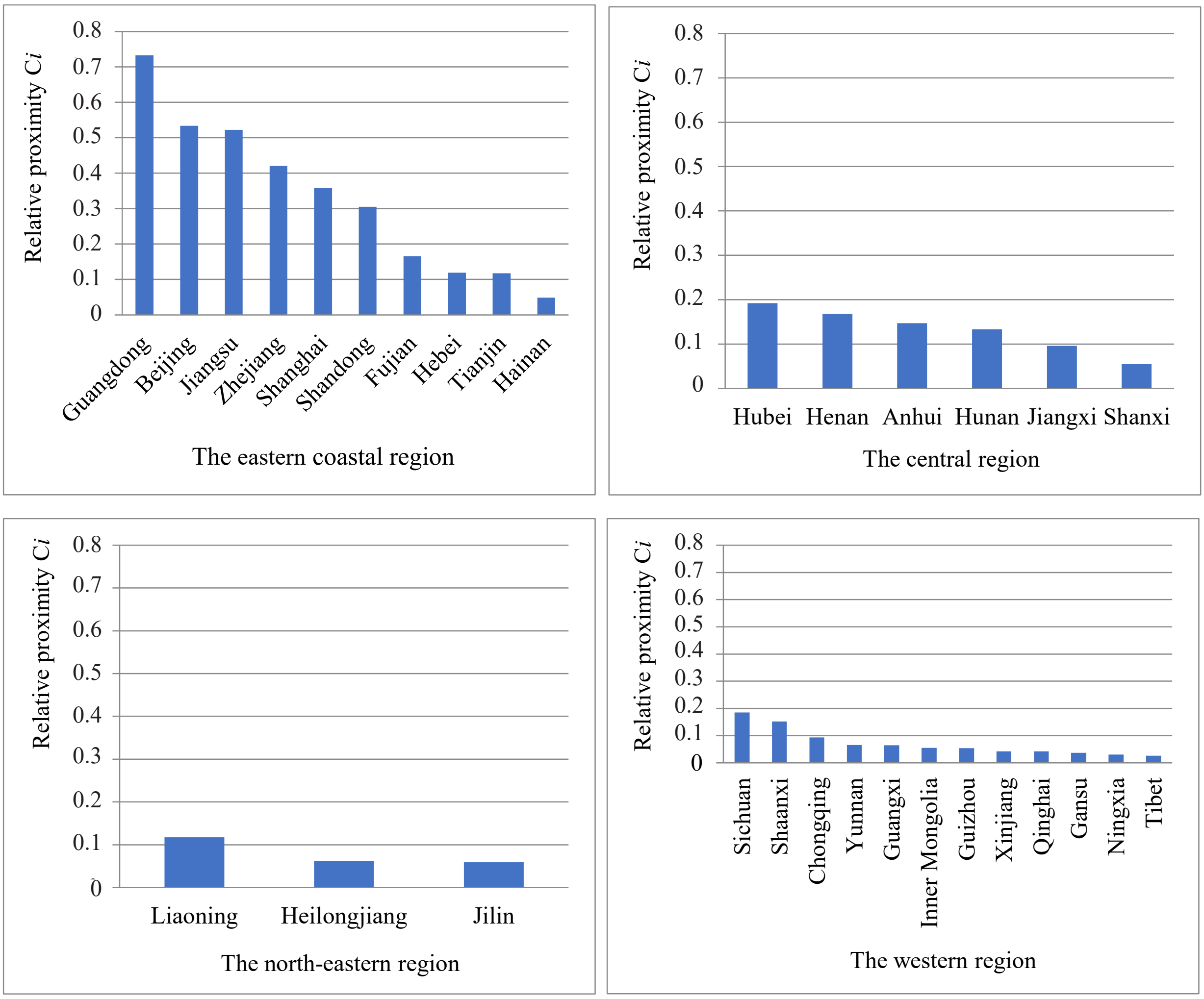

Figure 1*. Range of Chinese provinces and cities' digital economy sustainable development performance in 2019*

Source: *authors' development*

Chinese regions differ in the urban digital economy sustainability performance. Guangdong, Beijing, Jiangsu, Zhejiang, and Shanghai have the highest performance values and represent the eastern coastal region. Cities with the lowest performance value are concentrated mainly in the western part (Tibet, Ningxia, Gansu, Qinghai, Xinjiang). This is due to the weak development of digital industries like digital literary and content creation and lagging traditional industries' digital transformation. Many central and western provinces are still dominated by conventional industries: tourism in Tibet and Hainan, heavy industry in Heilongjiang and Liaoning, etc. Urban digitalisation in the central, western, and north-eastern regions is still in its infancy, resulting in a gap between the east and these regions. Complementing results of the available studies (Li *et al.*, 2020; Xin *et al.*, 2019; Zhu & Chen, 2022), the use of the entropy-TOPSIS model allows quantifying the level of urban digital economy performance in Chinese regions to identify leaders and prominent strategies.

CONCLUSIONS

This study constructs the four-level evaluation index system with 16 secondary indicators to quantify the influence of varied factors on the sustainability performance of the digital economy in Chinese regions. The results obtained via the entropy weighting method show the highest relevance of technological innovations followed by economic growth, social development, and urban information infrastructure development to promote sustainable urban digitalisation. Staff R&D engagement and R&D project expenditure, together with economic transparency and e-commerce development, were the most significant for the sustainable development of the urban digital economy. It was unexpected that the number of college and university students is a minor principal factor for urban digital sustainability. In this context, a new problem arises regarding the content of training programmes and the need to adapt it for society's digitalisation and innovation needs. The low significance of public financial expenditure attests to the small role of authorities' investments in digital economy growth. However, the legal and institutional environment favouring science and innovative business activity should not be underestimated. The same is true for the "physical foundation" of the digital economy — an information infrastructure.

This study uses the entropy-TOPSIS approach to evaluate the performance of Chinese provinces and cities in digital economy sustainable development. The eastern coastal areas of China demonstrate the highest level of sustainable digital development, followed by central and north-eastern towns, while the digital economy in western territories is underdeveloped. The gap in provinces' performance could be explained by the prevalence of conventional industries, their slow digitalisation, and the weak development of digital initiatives in China's west. The need to intensify regional opening-up and cooperation is prominent to avoid the marginalisation in the regions and ensure China's sustainable development path.

Although this study addresses China's practices, it is undoubtedly relevant in a broader context, covering the role of talents, innovations, business R&D investments, interregional cooperation, and multiscale partnership in promoting digitalisation conducive to the idea of sustainability. Whereas a lot of factors are difficult to quantify directly (for instance, public perception of a digital economy, responsibility, and enthusiasm) and thus were left out of this paper, further studies in this area could take obtained results as a starting point to measure the sustainable development of urban digital economy comprehensively and world-wide.

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Основні фактори сталого розвитку цифрової економіки в містах: приклад Китаю

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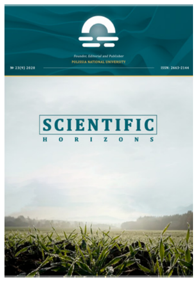
Анотація. Цифровізація є сучасною соціальною та економічною реальністю, і пошук ефективних шляхів для забезпечення високоякісного сталого розвитку, побудованих на цифрових рішеннях спільнот, є предметом сучасних досліджень щодо розвитку міст у всьому світі. На шляху до забезпечення сталості цифрової економіки міст на особливу увагу заслуговує вивчення ключових факторів, що впливають на ці процеси. Водночас, сьогодні бракує кількісних емпіричних досліджень, які б дозволяли уникнути суб'єктивних суджень щодо рушіїв сталої цифровізації міських поселень. Це дослідження має на меті заповнити цю прогалину шляхом визначення та кількісної оцінки ключових факторів, які впливають на сталий розвиток міської цифрової економіки, через застосування моделі ентропії-TOPSIS. Дане дослідження проведено на прикладі провінцій і міст Китаю, зважаючи на успіхи Китаю в питаннях розвитку цифрової економіки. У цьому дослідженні запропоновано використовувати комплексну чотиривимірну (науково-технічні інновації, економічне зростання, соціальний розвиток, інформаційна інфраструктура) систему показників, що містить 16 суб-індексів для вимірювання сталого розвитку цифрової економіки міських поселень. Використовуючи дані щодо 31 китайської провінції та міст за 2016-2019 роки та модель ентропії-TOPSIS, було встановлено, що розвиток науково-технічних інновацій має найбільший вплив на забезпечення сталості міської цифрової економіки. Залучений до досліджень персонал та витрати на дослідження та розробки, експорт та імпорт товарів, продажі через електронну комерцію найбільшою мірою сприяють сталому розвитку міської цифрової економіки, тоді як кількість студентів, публічні фінансові витрати та безробіття мають найменший вплив на цей процес. Отримані результати свідчать про те, що міська цифрова економіка, більшою мірою, є процесом, який стимулюється з боку бізнесу, а не влади. Визначений розрив у розвитку цифрової економіки регіонів Китаю пояснюється поширеністю традиційних галузей і низьким рівнем їх цифровізації. Останнє свідчить про необхідність посилення міжрегіонального співробітництва та розвитку партнерств для сприяння сталому розвитку країни в умовах парадигми цифрової економіки. Незважаючи на те, що дослідження побудоване на даних провінцій Китаю, отримані результати сприяють подальшому розвитку науки та політики у цій галузі в усьому світі, розкриваючи значення розвитку талантів, інновацій, бізнес-інвестицій у дослідження та розробки, міжрегіонального співробітництва та різносторонніх партнерств у сприянні процесам цифровізації урбанізованих територій відповідно до ідеї сталого розвитку

Ключові слова: цифровізація, метод ентропії, сталість, модель TOPSIS, міський розвиток

REVIEW ARTICLE



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Solar Energetics in Ukraine and the Experience of the Visegrad Group Countries

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Abstract. The urgency of investigating the improvement of solar energy industry efficiency in Ukraine is conditioned upon the exhaustive nature of conventional energy sources and their polluting effect, the availability of the potential for efficient use of solar energy and lower than possible level of its implementation, and by the opportunities of applying the practices of V-4-countries, which are connected with Ukraine geographically, economically, and naturally. The purpose of this study was to identify the main positive elements of the said practices and devise possible development vectors for solar energy industry in Ukraine. The main methods employed in this study are general methods (analysis and synthesis combined with scientific abstraction and generalisation, induction) and special economic and statistical methods (analysis of dynamic series, indexes, comparison). The main results of this study: the author identified the methods for obtaining and using solar energy, established its advantages and disadvantages, trends, rates, and potential of branch development; identified the share of solar energy in the structure of renewable energy on the level of 10 %; outlined the importance, state, and trends of solar energy development in Ukraine, its leading role in greening the entire economy using the available favourable conditions, and how this development is relatively low and hampered by the lack of national support, energy accumulation and storage systems, clear and understandable national strategy of its development, outdated practices of green tariffs, instability of public investment policy in the industry, high level of wear of electric networks. In this regard, the aforementioned practices concern the consolidation of the solar energy market to increase its level of regulation; the normalisation of national energy policy and investment climate; the development of the practice of creating solar parks and systems of cogeneration of different types of energy and energy storage systems; replacement of green tariffs by the mechanism of green auctions and other schemes

Keywords: solar power, practices of V-4 countries, green tariff, green auction, solar energy market

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INTRODUCTION

The period of carefree interaction between humankind and the environment is long gone, and the ignorance of this fact has led to a rising tendency for the quality of this environment to deteriorate. One of the main factors in this is the pollution of the environment with waste from the production and use of energy from conventional sources.

It will be difficult or even impossible to obtain energy from non-renewable sources in the foreseeable future, as explored fossil fuels will only last for another 30-50 years (Semena, 2009). Therefore, the only way out is to diversify energy sources towards maximising the share of renewable sources – heat, wind, tides, biogas, solar radiation, etc. Nuclear energy provides almost 7% of the world's energy and 16% of the world's electricity. The total number of operating nuclear reactors in the world (in more than 30 countries) exceeds 440 units. Most nuclear energy in the structure of domestic production is produced in the United States – 20%, while in France nuclear energy has the largest share in electricity production – 80%. In Europe as a whole, the index of the latter is 30% (Mikhailov, 2008). But the rapid development of nuclear energy that humanity had hoped for was not as halcyon as it seemed because of a series of catastrophes at nuclear power plants. The most promising of possible renewable sources of energy is currently the solar energy. Solar power is the source of all energy sources used by man (renewable and non-renewable) (Golashevski, 2011) and can be produced while the Sun is shining. The amount of energy consumption by humankind today is 6 thousand times less than the magnitude of the potential of solar energy, which is 200 times greater than the potential of the wind energy (Mikhailov, 2008). The rate of development of solar energy in the world is one of the highest, comparing to other types of green energy, but differs region from region (Sadik-Zada, 2021).

The features and effects of solar energy use are quite fully described in the studies of some Ukrainian and foreign researchers. According to A. Dolinskii, from the standpoint of physical economy, the use of solar energy in technological processes is the most effective vector of energy industry due to the simultaneous solution of environmental, economic, energy, and social issues (Dolinskii, 2006). In this context there is an interesting idea about the large potential of solar energy in North Africa, which theoretically meets the world's energy demand manifold (May, 2005). Researchers also note that the highest conversion coefficient of solar energy can be provided in its conversion into heat using solar collectors without concentration of light flux in the temperature range from 50 to 2,000°C directly in the technological processes of drying, steaming, space heating and water heating (Savchenko, 2013). A special place in the use of solar energy is occupied by cold formation from radiant solar energy using photovoltaic panels based on the Peltier effect (Science Direct, 2016). To date, even S2P (Solar To Petrol) technology has been developed, which can use the heat from the sun to split carbon dioxide from the air into oxygen and carbon monoxide, and the latter component – to produce artificial gasoline (Mikhailov, 2008). The method developed by E. Savchenko to quantify the prevention of damage to health and the development of environmental effects from the sale quotas by reducing CO_2 emissions is also noteworthy due to the introduction of solar power in technological processes (Cherevko & Savchenko, 2016).

In Ukraine, solar energy industry is a relatively new vector, but its development is rapid, which, however, could be even more rapid. For Ukraine, solar energy industry is, on the one hand, a forced step due to the extremely low level of efficiency of the available energy system, and, on the other hand, there are conditions for its development in the country, which are not worse, than, for instance, in Germany. Thus, the study and application of the practices of developing this industry by Ukrainian neighbours – the V-4 countries – can positively affect the development of solar energy industry in Ukraine, as can be seen from the results of relevant studies (Sadik-Zada, & Gatto, 2021).

Effective development of solar energy in Ukraine can be important for V-4 countries too, as Ukraine is geographically the nearest neighbour to this region and will then be capable of constructively fitting into the possible energy market. The development of mutually beneficial approach to shaping relations between Ukraine and the V-4 countries is necessary to improve and strengthen regional cooperation, as well as to prevent differences between them in the future, which is a necessary prerequisite for facilitating the regional stability and unity, and for promotion of the Visegrad Four values given the existing security threats and challenges in the region.

Thus, the relevance of investigating the efficiency improvement of solar energy industry in Ukraine is conditioned upon the exhaustive nature of conventional energy sources and their polluting effect, the potential for efficient use of solar energy and lower than possible level of its implementation and the opportunities of applying the practices of the V-4-countries, which are connected with Ukraine geographically, economically, and naturally. Accordingly, the *purpose of this study* was to identify the main positive elements of the solar energy industry development practices of V-4 countries and devise possible vectors of implementing these practices for the effective development of solar energy industry in Ukraine.

MATERIALS AND METHODS

The general methodological approach to this study was based on the understanding of the economic importance of solar energy development through its positive impact on the environment and, the social aspect of population welfare, as environmental impacts are ultimately expressed in social effects, but the economy remains the basis of its achievement. Methodological aspects of this study also relate to the main reasons for choosing V-4 countries to identify elements of positive practices in solar energy industry related to the geographical proximity of these countries to Ukraine, to the same level of surface insolation, to economic and cultural relations, and to some extent – to close mentality due to a fairly similar "socialist" past.

The methodological approach to this study was based on the perception of the economic importance of solar energy through its basic positive impact on the environment and the social sphere. The main research methods were applied based on the known dialectical approach to the study of economic phenomena: general methods (analysis and synthesis combined with scientific abstraction and generalisation – to investigate the development of solar energy and to generalise the results; induction – to predict possible prospects based on the facts) and special economic and statistical methods (analysis of dynamic series – to examine the available trends and determine the pace of their changes; indexes – to determine the values of relevant indicators; comparison – to identify positive practices of solar energy industry in different countries).

The materials used for this study were obtained mainly from information sources relevant to the subject under study, namely the State Agency for Energy Efficiency and Energy Saving of Ukraine – DerzhEnerhoEfektyvnist, Solar Energy Association of Ukraine – SEAU, Avenston Group; Energy Watch Group; OECD Statistics; International Renewable Energy Agency – IRENA, Bloomberg NEF, McKinsey&Company, Mordor Intelligence, Proper Power Supply company, Global Solar Atlas, Green System Company, Global Renewable Energy Community REN21, Solar Power Europe Association, Energy Watch Group.

The study used information sources that contain data mainly for the period from 2010, as feed-in tariff (FIT) for renewable energy support schemes has been introduced in Ukraine since 2010, although most intensive solar energy development in Ukraine began only in 2018-2019. The development of solar energy in Ukraine in this period took place against the background of no less intensive development of this energy sector around the world, specifically in European countries, including Visegrad Four. Some aspects of the problem were investigated based on the widest possible period, as well as more recent available data.

RESULTS AND DISCUSSION

Solar energy industry: Types and advantages and disadvantages

The Sun emits 881,024 calories of heat every second, which is equivalent to 1.25.1016 t.o.eq. or 1.02.1020 kWh. Only a part of this energy reaches the Earth – about 1.1018 kWh (123.1012 t.o.eq.) per year, which is about 100 times more than the energy resources of all explored combustible minerals on Earth (Cudria, 2020). Solar energy can be generated in two main ways (Fig. 1): by direct conversion of solar radiation into electricity using photovoltaic cells (PV), which, firstly, is most convenient for the consumers, and secondly, is considered an environmentally friendly means of obtaining electricity; by solar power concentration (SPC) method, using special mirrors. Figure 1 shows that the shares of electricity produced by two different methods are vastly different due to the presence of certain advantages and disadvantages in these two methods.

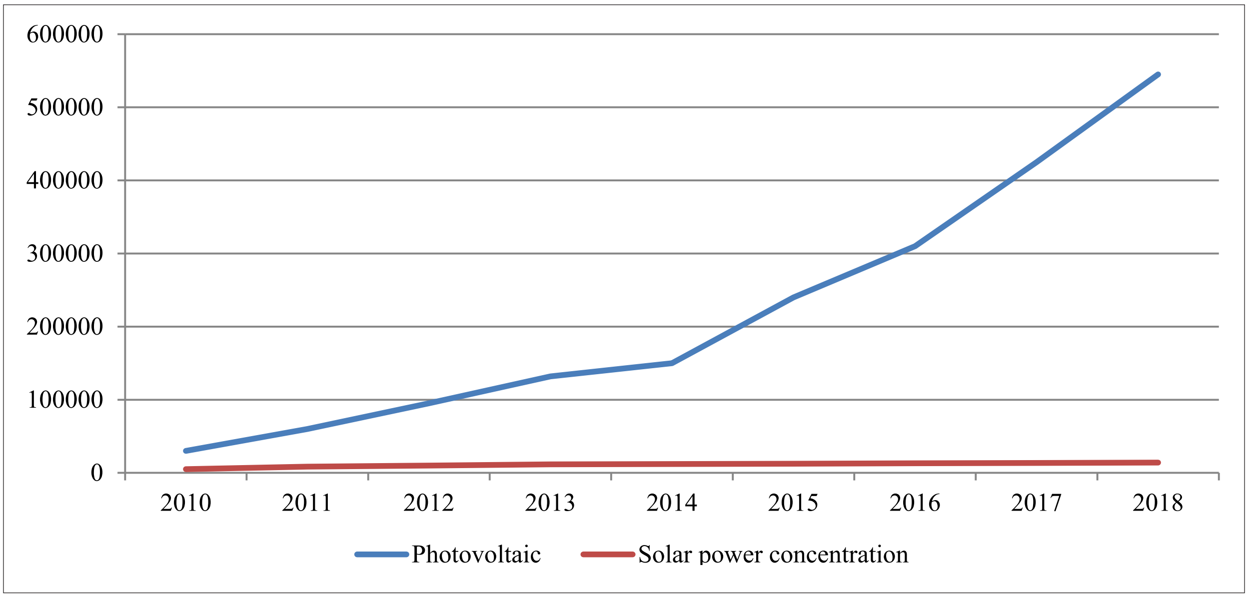

***Figure 1**. Production of solar electricity in the world in terms of technology, GWh/year*
***Source**: constructed by authors according to IRENA (2019)*

One of the main advantages of the SPC over a solar power plant is that it can be supplemented with tanks with molten salts, which can store heat. Concentration SES (Solar Energy Stations) are mainly spread in the United States and Spain due to their high cost (Weiss & Spörk-Dür, 2020). About 2.3 GW of concentrated solar power has been installed in the EU since 2013, but most new projects take place in Africa and the Middle East (European Commission, 2019). The world's largest SPC power plant, Noor Energy, built in Dubai, combines

100 MW of SPC tower, 200 MW of three parabolic systems that concentrate solar energy and create a heating effect, 250 MW of photovoltaic power and a capacity of molten salt for 15-hour storage of accumulated heat (Reve, 2020).

Solar energy, like any other method of obtaining energy, has its advantages and disadvantages. The advantages include practical inexhaustibility (the solar energy may remain unchanged for another 5 million years), fast return of investment, environmental friendliness, quietness, possibility of installing SES utilities anywhere, safety, ease of operation, independence, durability of the equipment, the minimum care and service, fast modernisation of branch and the corresponding reduction in price of the equipment, no need for expensive power lines and fuel storage, no need for fuel delivery, rapid reduction in price – since 2009, the price of solar energy has dropped by almost 90%. During the life cycle, the solar panel produces 30 times more energy than it needs for its manufacture (Lazard, 2019).

One of the positive effects of solar energy is the generation of employment (Sadik-Zada, 2021). Each TWh of electricity generated by SES allows creating 1,100 jobs – much more than in other energy industry sectors, resulting in, for example, 3.4 million jobs created in the world in 2017, all thanks to solar energy industry, and the global solar-related industry may employ over 18 million people until 2050 (IRENA, 2019). The number of jobs in photovoltaic solar energy in the world in 2020 is about 3.97 million – 33% of renewable energy sector worldwide (IRENA, 2020). Most jobs in solar energy industry are provided by small solar utilities – three times more than the large ones, as most small utilities (2/3) are roof-type utilities, the installation of which requires more workforce. About a third of all jobs in the sector are needed in maintenance and operation of such utilities. The technological features of solar energy industry require maintenance for the entire lifetime of solar power utilities, and therefore fluctuations in the labour market do not directly affect employment in this sector (Solar Power Europe, 2019).

The relative disadvantages of solar energy are quite easy to solve: the instability of equipment productivity, dependence on weather conditions, time of day and year, excessive cost of batteries, impossibility of precise forecasting. Solar energy industry is scattered – the power, removed from 1 m^2 of sunlit surface does not exceed 100 W on average (Bliznyuchenko & Smerdov, 2010). It means that 1 MW of SES capacity requires the allocation of at least 1.5 hectares of land (State Agency for Energy Efficiency..., 2018). These disadvantages are more than offset by such an effect of solar energy as the environmental friendliness of the energy obtained. Moreover, according to the report by the IRENA, in 2019 alone, the cost of solar electricity dropped by 13%, and since 2010 the cost of equipment for solar power plants in the world has dropped by 82% (IRENA, 2019) due to innovations in the solar energy sector. Further innovative development of this sector will ensure the introduction of innovative technologies for the production, accumulation, and storage of energy and reduce its value in all links of the chain of its formation. Solar energy is becoming inexpensive in comparison to other conventional energy sources due to innovations in the solar sector that have reduced the global average selling prices of solar power. With the predicted technological advance and increased supply of panels from China/Europe, the capital costs are expected to stabilise at lower levels. As a result, investors/developers are expected to focus on the commercial viability of solar projects.

Solar energy: The dynamics of development in the world and in Europe

The clear plenitude of the advantages of solar energy over its disadvantages is a factor of its rapid development – the annual increase in solar energy capacities put into operation, is about 40-50% (IRENA, 2019). Accelerated growth of solar power combined with deep electrification can yield 21%-reduction of CO_2 emissions (almost 4.9 gigatons per year) by 2050. Solar electricity could cover a quarter of the world's electricity needs. Global capacity could exceed the current one by 18 times, reaching over 8,000 GW by 2050. The share of solar energy in the total amount of renewable energy is also growing and amounts to one tenth of all renewable energy already (REN21, 2020) (Fig. 2).

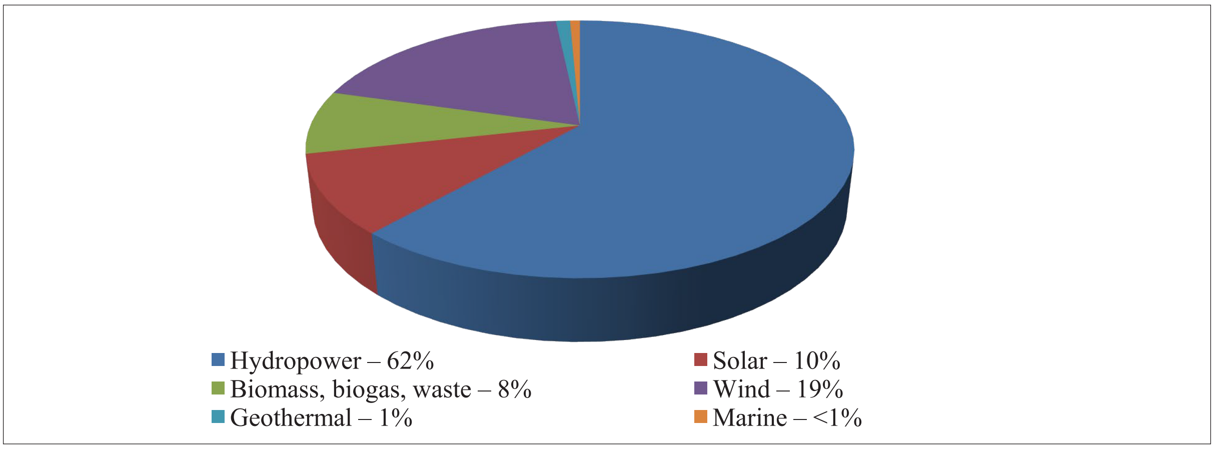

***Figure 2**. Structure of electricity production from RES in the world, 2018*

***Source**: constructed by authors according to IRENA (2019)*

To a considerable extent, the rapid growth of solar energy industry is explained by the elevated dynamics of the proper investments because of the high investment attractiveness of this sector (Fig. 3), which have amounted to about $300 billion over the past 10 years.

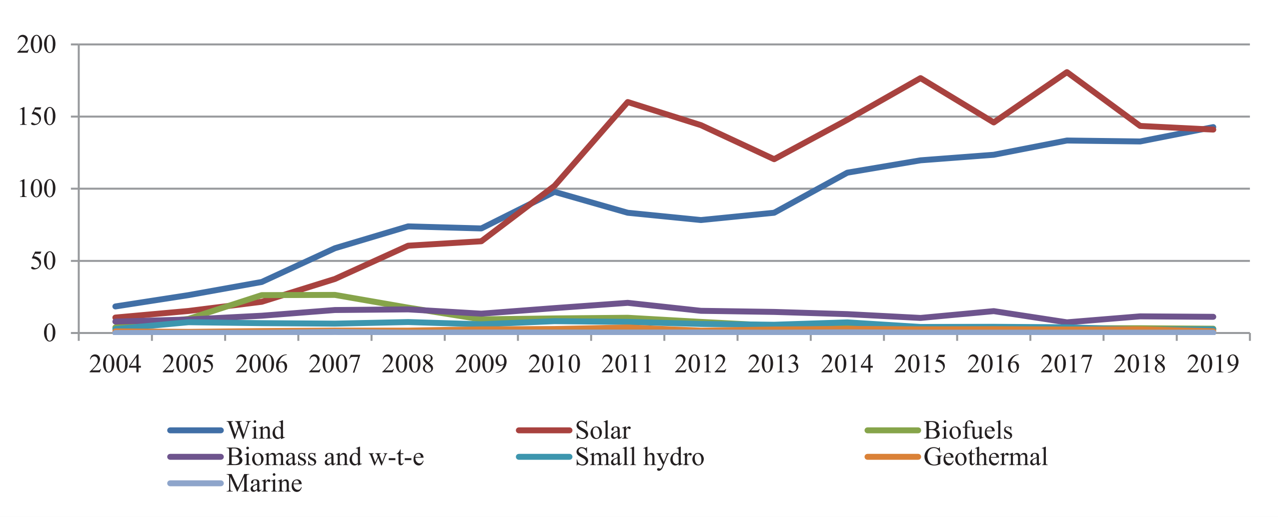

Figure 3*. New annual investments in electricity generation from RES in the world, $ billion*
Source*: constructed by authors according to Bloomberg (2021)*

In Europe, the installed capacity of solar power generation reaches 121.5 GW (2018); 140.9 GW (2019) and SES electricity production – 131.753 GWh (2018). Therewith, the share of solar energy in renewable energy in the EU is the same as in the world – 10% (IRENA, 2019) (Fig. 4).

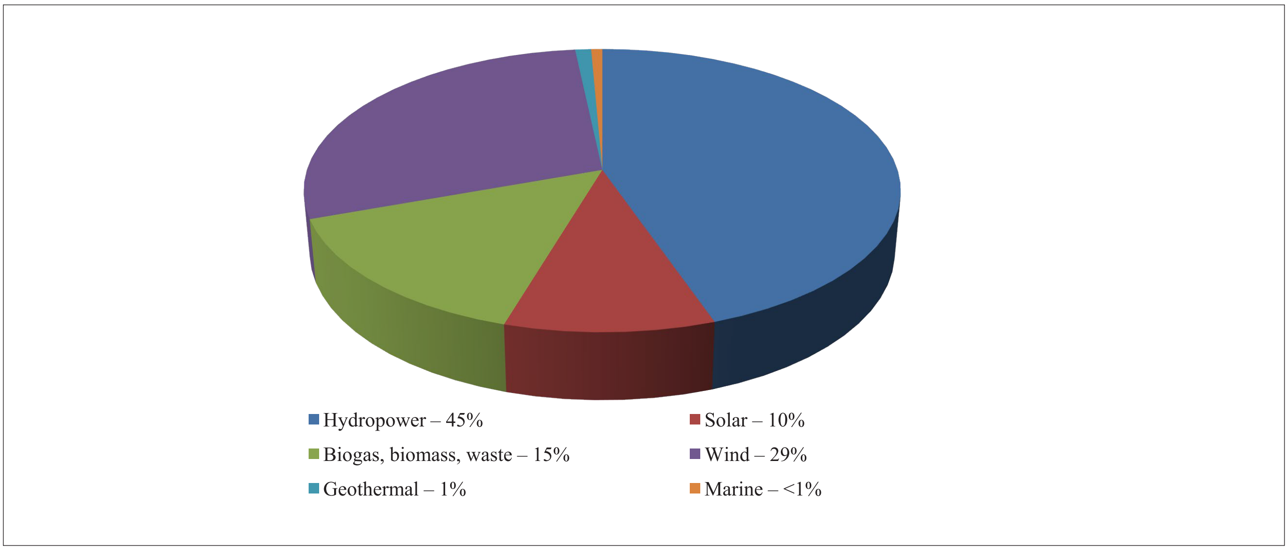

Figure 4*. Structure of electricity production from RES in Europe, 2018*
Source*: constructed by authors according to IRENA (2019)*

The potential of solar energy is impressive. An area of 254 kmx254 km (1% of the Sahara Desert) would be enough to meet the total electricity demand of the world. The amount of electricity needed by the EU-25 states could be produced on an area of 110 kmx110 km. For Germany, with a demand of 500 TWh/year, an area of 45 kmx45 km is required, which amounts to 0.03% of all suited areas in North Africa (May, 2005).

According to nearest prospects for the development of solar energy in the EU, to keep the growth of the average temperature on Earth not more than 2°C from the level of the pre-industrial period, in contrast to the scenario of continuation of the current practices, by 2050, the greenhouse gas emissions should reduce by 70%, which will affect all sectors of economy, and 75% of this reduction should be ensured by the use of RES (IRENA, 2019). Thus, in December 2019, the European Commission introduced an ambitious proposal to make the bloc climate-neutral by 2050 (McKinsey & Company, 2020). According to McKinsey & Company (2020), the most cost-effective decarbonisation pathway in Europe illustrates the technical feasibility of reducing the European Union's emissions by 55% by 2030 from 1990 levels and reaching zero by 2050, providing broad economic benefits, including GDP growth, lower cost of living and generation of employment.

In 2020, 132 GW of SES capacities in the world were added. According to the conservative scenario, another 160 GW will be added in 2021, according to the optimistic scenario – 209 GW (Bloomberg NEF, 2021).

Solar energy: Development and its problems in Ukraine

For Ukraine, diversification of energy sources is a particularly pressing issue. In 2018, Ukraine topped the list of countries with the most inefficient and most expensive heat generation in the world. Most thermal power plants in Ukraine were built 60-70 years ago, and some – in the 1930s. They are obsolete morally and technically, which affects not only the cost of the electricity they generate, but also their environmental friendliness. 68 out of 75 thermal power plants in Ukraine operate beyond their designated service life (Accounting Chamber, 2021). And the most promising of renewable sources in terms of the availability of proper conditions in Ukraine is solar energy, which is developing quite dynamically in this country (Table 1).

Table 1. *Dynamics of solar energy development in Ukraine*

Year	Installed (MW)	Growth rates compared to the previous year, %	Generation (million kWh)
2010	3	–	n/a
2011	196	653	n/a
2012	326	166	n/a
2013	616	189	563
2014	411	67	485
2015	432	105	475
2016	531	123	492
2017	742	140	715
2018	1,388	187	1,101
2019	4,925	355	2,412
2020	6,320	128	4,740

Source: *calculated by authors according to Global Market Outlook for Photovoltaics (2015), State Agency on Energy Efficiency (2017) (2019a)(2019b)(2020), Radio Liberty (2021), Ovcharenko (2018), National Commission for State Regulation…(2019)*

As calculation results above show (Table 1), the dynamics of solar energy development in Ukraine is very uneven, but the general trend is quite understandable. Preferential ("green") tariff for renewable energy in Ukraine was introduced in 2010 as an incentive for its development, but it has been developing most dynamically in 2018-2019 – in 2019 alone, the solar energy sector increased by 1,169 MW of commercial and 226 MW of household photovoltaic capacities. As a result, the total capacity of SES in Ukraine amounted to 6,873 MW, of which 11% were formed by household photovoltaic power utilities (Aventson Group, 2021).

The main producer of solar electricity in Ukraine is DTEK VDE, which is currently operating the Trifanivska SES – its pilot project in the solar energy industry sector equipped with 37,000 solar panels (DTEK, 2018). In addition, in March 2019, DTEK VDE launched the Nikopol SES, which has 750,000 solar panels with a total capacity of 200 MW and is the largest solar power plant in Ukraine (DTEK, 2019). Focusing on the "green" tariff, the Ukrainian solar energy market also includes such foreign companies as "China National Building Material Company" (n.d.), "TIU Canada Ltd." (2019), Recom LLC (2019) and Scatec Solar (n.d.).

However, the current development of solar energy in Ukraine is at a stage that Europe passed 7-10 years ago. Therewith, favourable conditions for the development of solar energy have been created in Ukraine: the availability of resources and land plots, preferential tariffs, even insufficient national support aimed at achieving 25% of clean energy production by 2035. As a result, interest in renewable energetics in Ukraine continues to grow. As of the end of 2020, SES with a total nominal capacity of 6,320 MW has been installed, generating 1,265 billion kWh of electricity. The share of SES for the first quarter of 2021 of the total power generation of Ukraine was about 6%. Such active development of the industry has allowed Ukraine to rise from 34th to 23rd place in the world ranking of solar energy industry.

About 30,000 families in Ukraine have already switched to solar power stations. € 600 million has already been invested in domestic solar power stations in Ukraine (State Agency for Energy Efficiency…, 2022). At the beginning of 2014, when there were only 20 households with connected solar power stations, it was quite difficult to predict such a rapid development. But presently such a mechanism as the "green tariffs" has been successfully integrated into the economy of Ukraine.

Ukraine already has the Solar Energy Association of Ukraine, which unites 45 companies and 43 solar stations, whose capacity exceeds 400 MW. Additionally, according to DerzhEnerhoEfektyvnist (State Energy Efficiency) and Solar Energy Association of Ukraine, over the past three years, the dynamics of the development of SES in Ukraine is fully consistent with the nature of the dynamics of SES in Europe; in 2050 there will be at least 17 GW of solar stations; in 2019, Ukraine got into the top 10 countries with high added capacity in the SES – 8th after Australia and Germany (Avenston Group, 2015). According to Global Solar Atlas, potential of solar energy in Ukraine as solar radiation potential is similar to V-4 countries (Global Solar Atlas, 2020).

According to Solar Power Europe and Solar Energy Association of Ukraine, installed capacities of SES per capita (Watts/capita) in 2019 are as follows: in Ukraine – 164; in Germany – 651 (maximum from top-10), in Spain – 283 (minimum from top-10) (Solar Industry Reports, 2019).

Ukraine's climate and geographical location, even its northern regions are favourable for the development of solar energy and the construction of SES, which is not inferior to conditions in most European regions. The average annual amount of total solar radiation energy that enters the territory of Ukraine annually is in the range from 1,070 kWh/m^2 in the northern part of Ukraine up to 1,400 kWh/m^2 and higher in the Crimea (State Agency for Energy Efficiency, 2018). The theoretical potential, or the total annual inflow of solar radiation into the territory of Ukraine is estimated at 720·1012 kW·h, which is equivalent to 88.4 billion tons o.eq. (State programme..., 1997). Term of effective operation of solar energy equipment in the southern regions of Ukraine – 7 months (from April to October), in the northern regions – 5 months (from May to September) (Cudria, 2020). The level of intensity of sunlight per unit of land area in Ukraine exceeds such index of the flagship of solar energy – Germany. According to scientific research, considering not only the value of solar radiation, but also the area available for the construction of stations and power factor of SES, which depends on the type and location of photovoltaic panels, distance between rows of panels, etc., the estimated capacity of SES in Ukraine and the annual potential of SES electricity generation is about 100 billion kWh/year (Cudria, 2020).

The available stocks of raw materials in Ukraine, sufficient human capital, technical and technological receptivity and the legal framework are sufficiently favourable for strong investments in the alternative energy sector of the country in general. In addition, production capacity of such giants of microelectronics as production associations "KVAZAR", "IRVA" (Kyiv), "Graviton" (Chernivtsi), "Hartron" (Kharkiv), "Gamma" and "Elektroavtomatika" (Zaporizhzhya), Dnipro (Kherson) allow for a full technological cycle of solar elements creation. Ukraine also has a highly qualified scientific potential in this field (Institute of Physics of Semiconductors and Institute of Electrodynamics of NASU, Taras Shevchenko National University of Kyiv, Yu. Fedkovych National University of Chernivtsi, "KPI" National Technical University).

There is enough reason to expect an accelerated development of the solar energy industry capacity in Ukraine in the nearest future because of plenty of examples of efficient functioning of solar energy equipment and stations, which forms foreign investors' interest in investing into this branch (Avenston rou, 2015). It remains to wait for real state support for solar energy. Otherwise, in the near future, along with foreign cars, appliances and household waste, Ukraine will start intensively receiving foreign solar panels.

Feed-in tariffs (FITs), which have been in force in Ukraine since 2008, are prevalent support policies for scaling up renewable electricity capacity. They are market-based economic instruments, which typically offer long-term contracts that guarantee a price to be paid to producers of a pre-determined source of electricity per kWh fed into the electricity grid, which is no longer extremely popular in other countries. From the 47 countries that had a Feed-in Tariff since 2000, only 9 countries kept the opportunity to receive it in 2019 (including Ukraine) (OECD Stat, 2020).

The green tariff, at which the state buys all the electricity produced by SES, is one of the highest in Europe in Ukraine, but not as high as one might expect, especially since it is steadily declining over the years. As of January 1, 2021, 8,516 MW of RES have been installed in Ukraine, which operate at a "green tariff" and capacity structure of RES facilities operating at the green tariff (01/01/2021) is as follows: SES – 6,094 MW – 71.6%; SES (roof) – 779 MW – 9.1%; WPS – 1,314 MW – 15.4%; biomass – 109 MW – 1.3%; biogas – 103 MW – 1.2%; MHPS – 117%; MW – 1.4%. The unpredictable actions of the government to reduce the green tariff due to the lack of funds to pay for it have had a considerable negative impact on the development of solar energy industry in Ukraine, because it has shaken the confidence of foreign investors in the government.

One of the most vulnerable factors in Ukraine that reduces the efficiency of any type of energy production, including the solar power, is aging power lines. 95% of electrical distribution networks in Ukraine are in poor condition (90%). Therefore, due to changes in climatic conditions in recent decades, a sizeable number of lines built in the 1970-80s are vulnerable to increased climatic loads. The designated service life (40 years) of most of them has already expired, which causes considerable losses of electricity in the grid. Depreciation on distribution networks is about 60%, of which 36.7% transformer substations have exhausted their resources, on main and interstate networks – 45%, of which about a third have been in operation for over 40 years, 260 thousand km of overhead power lines require replacement, with switchgear equipment being obsolete (Sadik-Zada & Gatto, 2021).

Considering the practices of introducing solar power plants in EU countries with levels of solar radiation similar to Ukraine, as well as given the global trends of constant reduction of SES construction costs due to technological development, due to technology improvement and commissioning of new capacities, production of solar energy in Ukraine can be significantly increased. The presence of favourable climatic conditions, significant reserves of raw materials, industrial and technological base for the manufacture of photovoltaic devices can fully meet not only the needs of domestic consumers, but also allow exporting more than two-thirds of the energy produced (State Agency for Energy Efficiency..., 2018).

Solar energy: The practices of V-4 countries and the possibilities of its application

Ukraine is also in the European space and the general course of its development is officially recognised as European integration. Thus, the development of solar energy in Ukraine is necessarily associated with the development of the SE of the world and specifically of Europe. For Ukraine, when it comes to the possibility of using foreign practices in the development of solar energy, the experience of countries around the world is important – especially the V-4 countries as the closest neighbours to Ukraine geographically, which have natural conditions similar to those in Ukraine.

Notably, that the V-4 countries, like all EU Member States, are developing their energy sector, including renewable energy sources, according to NECPs (National Energy and Climate Plans), which were introduced by the Regulation on the governance of the energy union and climate action (EU) 2018/1999, agreed as part of the Clean energy for all Europeans package which was adopted in 2019 (Energy and Climate Plans, 2020). Solar energy industry in Poland is growing rapidly, with a current 3.9 GW capacity. Poland on an EU level currently has a 12% solar market share. Increasing solar photovoltaic (PV) deployment is likely to drive the Poland renewable energy market in the forecast period. The country is planning to increase its solar power share, to meet its target of 15% renewable energy in its energy mix by 2020 (Mordor Intelligence, 2020c). The country is well on track to reach its NECP goal of 7.8 GW of solar energy industry by 2025. The Institute of Renewable Energy has reported that by December 2020, 10 GW worth of preliminary grid project permits were acquired, marking the sustained growth of solar energy sector in Poland. It is predicted that by 2024, Poland's annual solar capacity will increase by 46% as renewable energy prices continue to drop and newer innovations take over the market (Solar Industry Reports, 2019).

However, there is the potential for a 300% increase in Poland's solar capacity by 2024. Solar capacity here is expected to reach 7.3 GW by 2030 with about half installed by 2025. Poland's renewable energy market is expected to grow at a CAGR (Compound annual growth rate (CAGR) is the rate of return that would be required for an investment to grow from its beginning balance to its ending balance, assuming the profits were reinvested at the end of each year of the investment's life span (Gartner Glossary, 2021)) of more than 8% (Mordor Intelligence, 2020c). Poland has a large potential to install solar utilities on former coal sites. There is an interest from Polish grid operators in large photovoltaic projects to fill in the summer peak demand, partly resulting from the higher capacity of air-conditioning systems. To foster the deployment of solar energy, the government announced a corresponding policy in November 2019. The VAT applied to residential PV in Poland was reduced from 23% to 8%. The programme is open to residential PV projects with a generation capacity of 2-10 kW and grants rebates of up to PLN 5,000 per project. The Polish government is currently supporting solar through net metering (up to 40 kW) and the auction mechanism for large-scale projects over 40 kW – two schemes, which replaced the green certificate mechanism. The Polish renewable energy market is moderately fragmented. Some of the key players in the market include PGE Polska Grupa Energetyczna SA, Akuo Energy SAS, Engie SA, Dalkia Polska, and SGS SA Mordor Intelligence, 2020b).

Solar power generation continues to be the most popular technology in Hungary. Solar energy grew here significantly in 2018, and it is likely to increase during the forecast period. Hungary, due to its number of sunny days in the country, has good solar potential, so renewable energy market is expected to grow at a CAGR of over 4% during the forecasting period. Very good practice of solar energy industry in Hungary is Solar Parks, which are something like clusters. One can mention Dunai Solar Park, Felsőzsolca Solar Park, Solar Park near Parks Nuclear Power Plant. In 2018, MET Group completed its Dunai Solar Park project with a total capacity of 17.6 MW and ability to provide electricity to 9,000 houses. In In addition, MVM Group built the Felsőzsolca Solar Park, which has the capacity of 20 MW and can generate up to 21 GWh of electricity per year. In 2019, a new Solar Park near Parks Nuclear Power Plant was opened. The facility has a capacity of 20.6 MW and can generate electricity for 8,500 households. The Hungarian renewable energy market is moderately consolidated. Some of the key actors in this market include E.ON SE Sponsored ADR (Germany), China National Machinery Import and Export Corporation, MVM Group, MET Holding AG, and Solarpro Holding AD (Mordor Intelligence, 2020b).

Slovakia plans to support renewables that can replace fossil fuels in a way ensuring the safety of electricity and heat production without any great added costs. After replacing solid fossil fuels with renewable energy sources, Slovakia is expected to become one of the cleanest countries in the entire EU. Solar energy in Slovakia provides an essential contribution to meet energy needs in the electricity sector. According to the latest statistics published by the International Renewable Energy Agency, Slovakia had around 472 MW of installed solar power generation capacities in 2019. Solar power is expected to claim 44% of the clean energy capacity required to generate 2.4 TWh of electricity by 2021. The electricity generated by solar power has reached 585 GWh in 2018. In addition, the quantity of installed solar power capacity is expected to reach 600 MW by 2020 and 750 MW by 2030. Slovakia solar energy market is expected to grow at a CAGR of more than 1% during the forecasting period. Slovakian solar photovoltaic is mainly driven by the residential sector. Since March 2010, Slovenské elektrárne has been operating two photovoltaic power plants: Mochovce photovoltaic power plant and Vojany photovoltaic power plant. The Slovakian renewable energy market is consolidated.

Some of the major companies include Slovenské elektrárne AS, Axpo Holding AG, CONTOURGLOBAL PLC, VP Solar, and Acrosun SRO (Mordor Intelligence, 2020d).

Czech Republic's renewable energy shares around 12% of the total electricity generation in the country. The primary driver for the market includes the government initiatives that involve the use of clean and alternative sources of energy to protect the environment from the growing carbon emission. With increasing carbon emission, the government of the Czech Republic is expected to increase its renewable energy share in total electricity production. With 15% share of renewable sources in electricity generation in 2019, the country is estimated to increase this share to nearly 22% by 2030. Solar energy has considerably grown from negligible levels in 2009 to around 0.5% in 2015, primarily due to generous subsidies. In December 2016, the Czech Republic reached a cumulative installed solar power capacity of about 2.08 GW. During 2010-2014, the growth of renewable energy sources was supported by several different mechanisms, including feed-in tariff (FIT) system (guaranteed price), feed-in premiums (an amount paid on top of the market price for electricity, or green bonuses), investment subsidies, and fiscal measures. Two-third of the subsidies for RES were allocated to solar power, which produces only 5% of renewable energy. In 2019, Czech Republic had installed a solar power capacity of around 2,071 MW, with an electricity generation capacity of around 2.3TWh. The Czech Republic solar energy market is expected to grow at a CAGR of around 2.5% during the forecasting period (Mordor Intelligence, 2020a). Solar energy is becoming inexpensive in comparison to other conventional energy sources due to innovations in the solar sector that have reduced the global average selling prices of solar power. With the expected improvements in technology and increased supply of panels from China/Europe, the capital costs are expected to stabilise at lower levels. As a result, investors/developers are expected to focus on the commercial viability of solar projects. The Czech Republic solar energy market is moderately consolidated. The key players in the market include CEZ Group, Senvion S.A., EP Energy, Scatec Solar, Solar Global AS Burke, M.J., & Stephens.

Common to the V-4 countries is the presence of the same factors inhibiting the development of solar energy, the main of which is the resistance of conventional fossil energy companies. "In a time of climate emergency, weak forms of democracy may also delay the transition or elicit centralisation, and thus persistent local resistance to renewable energy sources may reflect a missed opportunity to redistribute political and economic power" (Burke & Stephens, 2018).

A positive experience that deserves attention is the creation of combined energy systems, which allows for a more stable balance of energy production with needs and provides a cogeneration and synergy effect. An example is the Matra Power Plant in northern Hungary: 100 MW are obtained by biomass + 60 MW are obtained by SES + 50 MW are obtained by ESS. This practically confirmed the conclusion of scientists at the Centre of Alternative Technologies in the mountains of Wales made 20 years ago, that a mixed system of renewable energy sources is the most optimal and reliable for environmental and economic reasons (Konechenkov, 2004).

The practice of the V-4 countries also confirmed the results of the research that energy storage systems (ESS) increase the efficiency of solar (and wind) power plants by 30-50% (Avenston Group, 2021). In 2019, such capacities in Poland were already producing 1 MWh; in the Czech Republic — 3 MWh; in Hungary — 7 MWh; even small Slovenia — 13 MWh (UK – 570 MWh, Germany — 406). This answers the question why Germany managed to develop solar energy industry so quickly — because 406 MWh work primarily on balancing the conventional network and RES.

In the future, Ukraine may also adopt a few more elements of successful practices of foreign colleagues to expand the prospects of solar energy. In V-4 countries, photocells are placed on the roofs of trains, thereby providing them with electricity during operation. This technology can be used on ships and planes. Thermal energy is a way to convert solar energy by heating water in containers made of heat-conducting materials (Avenston Group, 2015).

Thus, the results of the practices of the V-4 countries under study, where the natural conditions for the development of solar energy are similar to the Ukrainian ones, give grounds for identifying certain possible ways to improve the solution of solar energy development in Ukraine: consolidation of the solar energy market — in each of the V-4 countries the solar energy market has only about 5 key operators, which makes this market more regulated; creation of the favourable government regulatory and supporting policies and improvement of investment attractiveness; development of the practice of cogeneration of different types of energy; development of the practice of building energy storage systems; creation of solar parks; auction mechanism and other effective schemes (feed-in premium, simplified taxation, direct subsidies, etc.) replacing the green certificate mechanism. These solutions outline the immediate tasks for Ukraine: updating of Ukraine's Energy Strategy with more ambitious SES development targets; elaboration of new goals of the National Action Plan on RES Climate 2020-2025 at least at the medium level for EU countries; development of the concept of "green" energy transition and "Ukrainian Green Deal; construction of additional 25 GW SES, considering the growing share of roof and hydrogen SES.

Some elements of the European practices, including experience of V-4 countries are already implied in Ukraine. Thus, in April 2019, the "Law on Green Auctions" was adopted (State Agency for Energy Efficiency, 2019). According to that, the implementation of projects with a capacity of more than 1 MW in the solar energy sector from 2020 makes provision for mandatory prior participation in "green" auctions, which should prevent the emergence of monopolies in the RES market in Ukraine. An inherent feature of such auctions is their transparency, and they are expected to be held twice a year through the ProZorro electronic trading system. The level of the "green" tariff was clearly prescribed in the Law, and in the case of auctions, the amount of support for each project will be determined at the auction, and this will considerably reduce the cost of such energy. The adoption of this law preceded the conclusion of a memorandum with RES producers on June 10, 2020 (National Commission for State Regulation..., 2020). Under the terms of this memorandum, it is planned to reduce tariffs by 15% for SES and shift to an auction model of tariff setting from July 1, 2020. "Green" auctions were supposed to be introduced in 2019-2020, but this was not done due to problems with the mentioned payments under the "green" tariff. Provision of national support to economic entities in renewable energy sector exclusively through auctions for the distribution of quotas will ensure the development of alternative energy sources, including solar power, in a more controlled and efficient way and reduce the financial burden on consumers and the threat of violating the operational security of the United Energy System of Ukraine in the future.

The Verkhovna Rada of Ukraine also adopted the Draft Law of Ukraine No. 5436-d "On Amendments to Certain Laws of Ukraine on the Development of Energy Storage Facilities" (Draft Law on Amendments..., 2020). The drafting of the document considered the fundamental principles of legal regulation of energy storage systems in EU countries, including V-4 countries. Its adoption will ensure the use of energy storage systems, balance the operation of the energy system, facilitate the synchronisation of the Ukrainian energy system with the European ENTSO-E, as well as increase the stability of electricity supply to consumers. However, these measures are only the first individual steps.

Countries, combined with geographical proximity, common history, and long-term prospects, have traditionally focused on active multifaceted cooperation. Various similarities, related interests and aspirations form the basis that eventually determines the mutually beneficial coexistence and interaction (Chorna, 2012). In the field of renewable energy, such cooperation is objectively possible by integrating the United Energy System of Ukraine into ENTSOE (European Network of Transmission System Operators for Electricity), which will allow for more efficient use of the solar energy capacity of Ukraine and V-4 countries, organically balancing local needs for clean solar energy within the region.

CONCLUSIONS

Solar energy resources can be used to produce energy both by directly converting solar energy into electricity, which is user-friendly and environmentally friendly, and by concentrating solar energy (SPC) with special mirrors, what has its advantages but is much more expensive.

Advantages of solar energy industry are practical inexhaustibility, fast return on investment, environmental friendliness, quietness, the ability to install SES everywhere, safety, ease of management, independence, durability of equipment, minimal care and maintenance, rapid modernisation of technology and cheaper equipment and energy, intensive generation of employment; disadvantages include instability, high cost of batteries, difficult forecasting, spatial scattering. Due to the considerable advantages of positive features of solar energy over its drawbacks, it is developing at a fairly high rate, but so far, its share in the structure of renewable energy in the world and in Europe is only 10%, although the potential of solar energy industry in terms of clean energy is impressive.

Ukraine's energy industry is currently one of the least efficient and the most environmentally harmful and dangerous. Thus, for Ukraine, solar energy industry is, on the one hand, a forced step due to the extremely low level of efficiency of the available energy system, and on the other hand, there are favourable conditions for its development in the country. In this regard, the study and application of the development practices for this industry by Ukraine's neighbours – the V-4 countries – can positively affect the development of solar energy industry in Ukraine.

The general trend and motives for the intensive development of solar energy in Ukraine in 2018-2020 are quite clear, although the legal and economic conditions for this have been created as early as 2010, and natural conditions have always been favourable and are not worse than in countries that are leading solar energy producers. The available human capital, production capacities, and investment attractiveness also contribute to this. But the current level of solar energy development in Ukraine was surpassed by Europe 7-10 years ago, because of numerous negative aspects holding Ukraine back. The main problems are a lack of support from state institutions; high level of wear of electric networks; delay in the development of systems for accumulation and storage of energy received by SES; delay in the introduction and dissemination of the practice of "green" auctions in the renewable energy sector, instability of national policy towards investors in solar energy industry; lack of clear and understandable governmental strategy of solar energy industry development.

Therefore, the practices of developing the solar energy industry in the V-4 countries can be practically useful for Ukraine due to the similarity of conditions and the geographical proximity of these countries to Ukraine. The most valuable elements of these practices for Ukraine are the consolidation of the solar energy market, which makes this market more regulated; creation of a favourable state regulation and proper investment climate; development of practices of cogeneration of different types of energy and construction of energy storage systems; creation of solar parks; development of an auction mechanism and other effective schemes instead of a green tariff mechanism. Therefore, the immediate tasks for Ukraine include the updating of Ukraine's Energy Strategy; development of new goals for the National Action Plan on Climate Resistance and the concept of transition to green energy and the Ukrainian Green Course; construction of additional SES utilities; integration with ENTSOE, which together will positively affect both Ukraine and the V-4 countries through the development of mutual electricity exchange. Prospects for further research relate to creating proper conditions for the implementation of specified elements of the V-4 countries' practices in solar energy industry development.

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Сонячна енергетика в Україні та досвід країн Вишеградської групи

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Анотація. Актуальність дослідження шляхів підвищення ефективності розвитку сонячної енергетики в Україні зумовлюється вичерпністю конвенційних джерел енергії та їх забруднюючим ефектом, наявністю потенціалу ефективного використання енергії Сонця і нижчим від можливого рівнем його реалізації та можливостями використання досвіду країн V-4, які пов'язані з Україною географічно, економічно та природно-екологічно. Метою дослідження було визначення основних позитивних елементів названого досвіду та на цій основі – можливих напрямів подальшого розвитку сонячної енергетики в Україні. Основні методи дослідження застосовуються на основі діалектичного підходу до вивчення економічних явищ: загальні методи (аналіз і синтез у поєднанні з науковою абстракцією та узагальненням, індукцією) та специфічні економіко-статистичні методи (аналіз динамічних рядів, індексів, аналізу, порівняння). Основні результати дослідження: визначено методи отримання та використання сонячної енергії, її переваги та недоліки, тенденції, темпи та потенціал розвитку галузі; визначено частку сонячної енергії в структурі відновлюваної на рівні 10 %; окреслено значення, стан і тенденції розвитку сонячної енергетики в Україні, її провідну роль в екологізації всієї економіки, використовуючи існуючі сприятливі умови, але зараз цей розвиток є відносно низьким і гальмується відсутністю державної підтримки, систем накопичення та зберігання енергії, чіткої та зрозумілої державної стратегії її розвитку, застарілими практиками зелених тарифів, нестабільністю державної інвестиційної політики у галузі, високим рівнем зношеності електричних мереж. У зв'язку з цим згаданий вище досвід стосується консолідації ринку сонячної енергії з метою підвищення рівня його регульованості; адекватизація державної енергетичної політики та інвестиційного клімату; розвиток практики створення сонячних парків та систем когенерації різних видів енергії та систем зберігання енергії; заміна зелених тарифів механізмом зелених аукціонів та іншими схемами

Ключові слова: слова: енергія Сонця, практика країн V-4, зелений тариф, зелений аукціон, ринок сонячної енергетики

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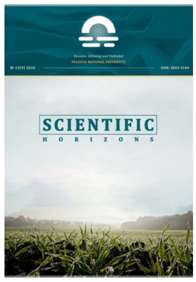

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Development of a System for Recycling Used Batteries and Lead-Containing Batteries: Assessment of the Economic Effect with Minimising Damage to the Environment

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Abstract. The relevance of the subject under study is determined by the issues of practical application of charging batteries and accumulators after the completion of the declared technical lifetime, in connection with the pollution problems due to lack of potential for normal disposal. The purpose of this study is to investigate the prospects of development and practical implementation of a system of recycling used batteries and lead-containing batteries, in the context of assessing the potential economic impact of minimising environmental damage while fully implementing the objective. The methodological framework of this study comprises a combination of quantitative and qualitative methods. The application of methods of analysis, synthesis, induction, and deduction in this paper provides sufficient information about the existing principles of recovery of lead-containing batteries and accumulators. The method of generalisation involves the implementation of a qualitative assessment of the data obtained in this study. The method of modelling provides the display of the results obtained using appropriate schemes and diagrams. The available publications of several researchers engaged in scientific development of the issues of disposal of spent lead batteries and accumulators were analysed. The factors of the economic effect that can be achieved by the high-quality recycling of lead-containing batteries were investigated. An approximate assessment of the economic effect with a given direction to minimise damage to the environment was formed. The results obtained in this paper and the conclusions formulated on their basis have practical significance in terms of the prospects of increasing the volume of production of secondary lead by recycling of used batteries and reducing damage to the environment, when it is uncontrollably contaminated by secondary products of their use

Keywords: recycling of used batteries, industrial recycling, minimisation of environmental damage, economic efficiency of battery recycling, recycling of lead-containing batteries

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INTRODUCTION

Lead is among the metals that are repeatedly included in material production and are relatively little wasted in industrial use (Morachevsky, 2014; Gupta *et al.*, 2022). The environmental pollution by lead and its degradation products poses a considerable risk to all human activities. Low-melting, practical, and convenient to recycle, lead is widely used today. Lead is used to make ammunition; it is used in the finishing of bullets (Akhmadova *et al.*, 2018). It is a component of numerous alloys, in particular, used for heavy loads, such as metal. It is used to produce tetraethyl lead and its different compounds. A large amount of lead dust is emitted into the atmosphere during the production of lead and its alloys. Such dust is involved in the biological cycle, adversely affecting all life (Xu *et al.*, 2021).

Modern disposal systems for lead-containing batteries and accumulators have essentially served to protect the environment by preventing alkali and lead from penetrating into water and soil (Jin *et al.*, 2021). The economic effect of the practical application of such systems is closely related to the prospects of further use of the environment, if there is no need to carry out cleaning of the pollution, caused by violations of regulations for the storage of lead-containing batteries and end-of-life batteries. The practical use of such aggregates is a costly process, which can result in considerable profits (Prasad & Vithanage, 2019). Today, lead-containing batteries account for about 1% of solid domestic waste on the scale of the whole segment (Denisova, 2019). Thus, the development of an efficient disposal system of used batteries and lead-containing batteries is an urgent and relevant task.

The recycling of lead is a critical environmental issue that requires professional solutions (Rovin & Ohremchuk, 2013). Both the state of the environment and the prospects for the development of industrial waste processing, which includes elements that can severely damage the environment and pollute it, depend on the quality of the solutions introduced (Nowroozi *et al*., 2021). The development of a system for recycling used batteries and lead-containing batteries should contribute both to the achievement of a tangible economic benefit from minimising environmental damage and to the development of the entire system for processing harmful industrial waste (Liu *et al*., 2019). The disposal of old, used batteries has an incredibly positive impact on the environmental and economic situation. More recently, however, the need for integrated reuse of battery components has become evident. To date, many countries in Europe have legislated the ban on disposal from used batteries in garbage bins because of the adverse environmental damage.

The purpose of this paper is to investigate the principles of developing a system of recycling used batteries and lead-containing batteries in the context of assessing potential economic effect within a given area to minimise environmental damage.

FEATURES OF RECYCLING USED BATTERIES AND LEAD-CONTAINING BATTERIES

The development of a system for recycling used batteries and lead-containing batteries implies the need to determine the priority areas of this process, considering the types of recyclable battery devices and the characteristics of the disposal of each particular battery type. In this context, L. Ma *et al.* (2019) classified the batteries according to the type of active substance used in the chemical reaction, where the batteries are grouped as follows:

– alkaline (including zinc anode, manganese dioxide cathode, and a conductive liquid based on a solution of potassium dioxide aqueous);

– lithium-manganese (including lithium anode, manganese dioxide based powdered cathode and organic electrolyte);

– zinc-carbon (including zinc anode, carbon cathode with manganese dioxide, and zinc/ammonium chloride-based electrolytic solution);

– cylindrical (including powder zinc anode, oxygen cathode, and KOH type electrolyte solution);

– mercury (including zinc anode, mercury cathode, and KOH type electrolyte solution);

– silver (including zinc anode, silver oxide-based cathode, and potassium hydroxide-based electrolyte).

All parts of lead-containing batteries and used batteries are to be recycled, and this process necessarily includes the collection of batteries that have used their allotted service life, transportation to the enterprise performing such processing, as well as separation of battery components, followed by melting of lead cells and cleaning. According to A. Manthiram (2020), the main steps of recycling used batteries and lead-containing batteries are electrolyte drain, separation of accumulator batteries into components cell, lead component analysis, incineration or disposal of plastic and ebonite waste, transportation of disassembled batteries to the smelting plant, melting and cleaning, collection and transportation of accumulator batteries

In turn, G. Saldaña *et al.* (2019) believe that upon disposal, lead fragments are dispersed in the air, which causes pollution of the environment and considerably damages the health of workers on whose clothing these fragments settle. Furthermore, toxic smoke causes similar damage during incineration, and, in the case of the burying plastic and ebonite wastes, there is significant soil contamination at such burial sites (Jenkins, 2017; Tran *et al.*, 2018). Without the implementation of a set of measures to ensure technological and engineering control over the recycling of used batteries, it is impossible to fully prevent the release of lead into the environment. Furthermore, it is mandatory to observe occupational health measures to prevent workers from becoming infected and harming their health.

Table 1 presents the main steps in establishing an environmentally safe and effective recycling system for used batteries and lead-containing batteries, as well as the characteristics of each step (Liu *et al.*, 2021; Li *et al.*, 2021).

***Table 1**. Establishment of an efficient system for recycling used batteries and lead-containing batteries*

Centralised monitoring and collection of used batteries and lead batteries	Ensure high quality control and accounting of waste components to prevent loss during collection
Organisation of transportation of waste elements to recycling sites	Control of transport process coherence to avoid loss and pollution
Monitoring the separation of batteries and lead batteries into components	Implementation of measures to prevent harmful substances from entering soil and water at separation sites of batteries and lead batteries
Ensuring the delivery of separated components to the enterprises of their subsequent recycling	Provision of qualitative accounting of volumes of delivery of separated components and measures to prevent their losses during transportation
Monitoring the progress of the recycling of separated components at end points	Ensure that all process and process conditions are met to prevent environmental pollution during process operations
Ensure that recycled components are shipped to their place of use	Tracking accuracy and delivery times of recycled components

Figure 1 presents a graphical display of the global capacity of used batteries and lead-containing batteries from 2016 to 2025 (Smyrnov *et al*., 2020). As can be seen from the data presented in Figure 1, the total global battery capacity has been steadily increasing since 2016 and is expected to reach 170 GW per year by 2025 (Smyrnov *et al*., 2020). Consequently, without the development and implementation of comprehensive measures for the disposal of used batteries, the threat of environmental pollution on a global scale is increasing significantly.

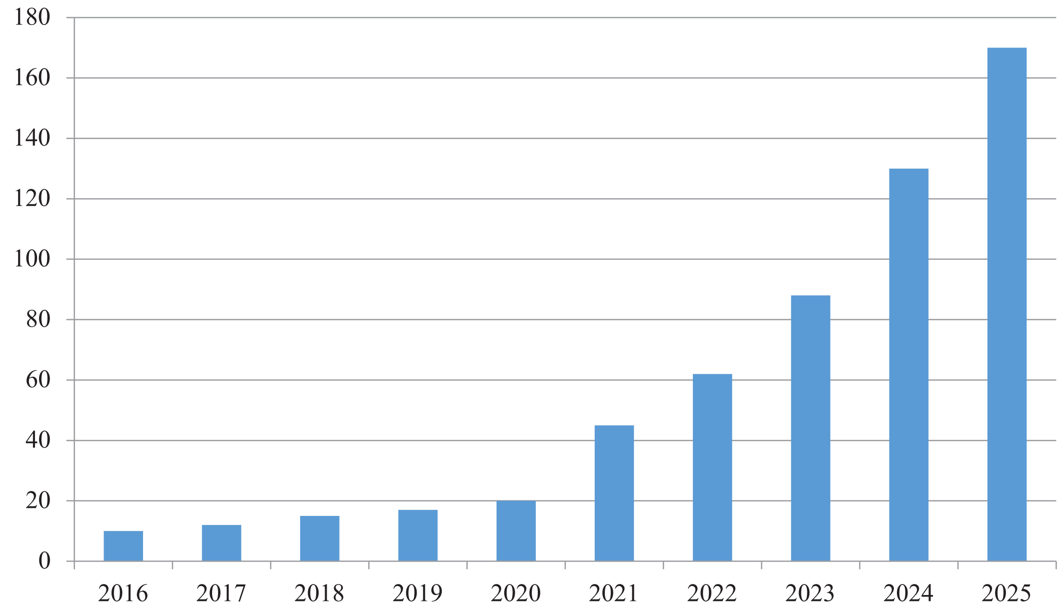

***Figure 1**. Total global capacity of used batteries as of 2016 and in the context of the 2025 forecast*

ASSESSMENT OF THE ECONOMIC EFFECT WITH A GIVEN DIRECTION TO MINIMISE DAMAGE TO THE ENVIRONMENT

J. Shea & C. Luo (2020) are convinced that the economic impact achievable by the high-quality recycling of lead-containing batteries is conditioned upon the following factors: recycled lead can be used to produce a variety of consumer goods; natural reserves of ore are preserved as lead from battery recycling is diverted to industrial use; soil and water are protected against harmful chemical elements and are therefore suitable for further beneficial use; there is no need to use storage facilities to stockpile used batteries. However, V. Kumaravel *et al.* (2021) is convinced that assessment of the economic effect towards minimising the damage to the environment should be formed considering the estimated savings of funds allocated for the restoration of the environment from the effects of its pollution, as well as the cost of recycling used batteries and lead-containing batteries over a specified period of time. In general, the following equation (1) can be used for calculating the economic effect achieved within one calendar year:

$$E_{EF} = E_E - E_{KE} \times Z_Y \tag{1}$$

where EEF is the economic effect that can be achieved during a calendar year in the implementation of a set of measures for the recovery of used allotted life of batteries and lead-containing batteries; EE is the annual savings which can be achieved without the need to spend money on cleaning the environment of lead and its compounds; EKE is the efficiency factor, constant value, depending on the organisation of activities for recycling of batteries and lead-containing batteries; ZY is the costs of disposal of the specified elements.

Thus, the assessment of the economic effect in the chosen area of activity to minimise environmental damage upon recycling used batteries and lead-containing batteries can be made considering the amount of money spent on recycling, as well as making a preliminary estimate of the costs of environmental clean-up if there is actual pollution. In addition, A. Molina *et al.* (2020) believe that the final value of the economic effect achieved per unit of time can serve as a qualitative assessment of the efficiency of measures to recycle a certain number of used batteries and lead-containing batteries in a specified time.

NECESSARY CONDITIONS FOR THE HIGH-QUALITY RECYCLING OF USED BATTERIES AND LEAD-CONTAINING BATTERIES

The qualitative resolution of the problems of recycling used batteries and lead-containing batteries is essential for the prospects of improving environmental safety and increasing the real potential for recycling hazardous industrial waste in general. The risk of environmental contamination by lead and its various compounds is clear when used batteries are not stored properly and if there is no well-designed system for their subsequent disposal. Spent batteries contaminate the soil; lead compounds penetrate the water, causing considerable contamination and their rapid spread (Tabelinet *et al.*, 2021). In turn, E. Lizundia & D. Kundu (2021) are convinced that all this necessitates the development of effective measures to create the necessary conditions for the high-quality recycling of used batteries and lead-containing batteries to prevent lead and its compounds from entering the soil and thus worsening the environmental situation.

The general instability of the current environmental situation causes problems of safe use of battery devices and their subsequent disposal (Danilov, 2014). The situation requires a systematic solution, as the removal of such devices to a landfill without proper control may result in severe damage to the overall state of the environment and have extremely negative consequences for the established human living conditions. Therewith, H. Kim *et al.* (2020) think that the correct operation of lead-containing batteries and batteries has a positive impact on the environmental situation, which makes it necessary to find the best combination of innovative development technologies and modern technical solutions, aimed at improving the quality of disposal of used batteries.

According to N. Mittal *et al.* (2021), the orderly disposal of used batteries should be entrusted to specific organisations that specialise in such activities and are authorised to carry out such activities. The organisation of such activities is very strictly controlled around the world. Because carrying out such work without sufficient experience and licenses can entail serious environmental issues (Torabi & Ahmadi, 2019). However, S. Bai *et al.* (2021) believe that this results in continuous improvements in the recycling of used batteries, which has a positive effect on the environment.

Today, the manual method of recycling batteries is often preferred, even though it is quite dangerous in general. According to D. Cao *et al.* (2020), this is because the equipment for the implementation of a full set of such measures is expensive, especially when this refers to the industrial scale of the operations. Efficient performance of such operations requires high qualifications because ignorance of the elementary rules of operation with batteries may further lead to serious health problems (D'Adamo *et al.*, 2019). As a rule, this method is most often abandoned, even though it allows obtaining high-quality raw materials.

The standard car battery holds an average of about 3.5 kg of acid and approximately 6-7 kg of lead. J. Sun *et al.* (2020) are convinced that such substances, as well as their derivatives, can greatly harm the environment and the human body. For this reason, the used batteries must necessarily be recycled by special organizations and using specially developed technologies to prevent the release of alkali elements, metals, and harmful acids into the environment. In several Western European countries, the management and processing of lead-containing batteries is a matter decided by the state. Legislation governs the disposal of batteries in electric vehicles, motorcycles, and automobiles (Levchenko & Britchenko, 2021).

There is an increased global interest in electric vehicles, with governments of many countries supporting this trend by subsidising the sale of electric vehicles and providing tax breaks to electric vehicle manufacturers. Such policies are primarily aimed at supporting environmental protection trends, as electric traction transport is completely environmentally friendly. However, car batteries, which are the key elements of electric vehicles, hold considerable amounts of toxic substances that can severely damage the environment (Farhad *et al.*, 2022). J. Popovic *et al.* (2021) believe that the problem of recycling battery electric vehicles will become acute in European countries by the second half of the 2020s, when a significant amount of such cells will accumulate. Therewith, the battery life of modern electric vehicles, which are produced today in European countries, is at least eight years, which gives Europeans enough time to systematically prepare for the application of battery recycling technologies for active electric vehicles.

All batteries that are currently used in the automotive industry are divided into two large classes: disposable and rechargeable (Garche & Brandt, 2018). N. Meng *et al.* (2021) noted that the first group comprises conventional batteries of many varieties, while the second group includes batteries of all types and technological varieties. Used batteries pose a considerable risk to the environment because they emit heavy metals (Garche *et al.*, 2017). The burial of used batteries at the proper landfills is coupled with percolation of heavy metals, which affect the soil and water by leachate. In a situation where spent batteries are burned in waste incinerators, heavy metals are concentrated in ash and slag, as well as in released gases. According to statistical studies (Denisova & Pirogova, 2020), on average batteries account for about 1% of the total volume of solid household waste, while the level of responsibility for the formation of heavy metals at solid waste landfills is many times higher and reaches approximately 60-70%.

Today, a fundamental problem is the disposal of lithium-ion batteries of modern electric vehicles after the end of their service life. About 150,000 of these batteries will be decommissioned by about 2030 (this number equates to their annual production) (Bicer & Dincer, 2018). According to S. Wang *et al.* (2021), unless effective measures are developed for the safe disposal of lithium-ion batteries in modern electric vehicles, the situation could become alarming and gradually become a serious environmental issue.

In the EU, the number of electric vehicles is steadily increasing, and the total number of electric vehicles is expected to increase to 7-8.5 million by 2030. Accordingly, this will aggravate the issue of recycling used batteries from electric vehicles, which requires the adoption of a set of purely legal measures to organise this process and legislatively consolidate it (Mir & Dhawan, 2022). In general, the measures adopted will contribute to the environment preservation and will provide a considerable economic benefit from minimising soil and water contamination in the storage sites of used batteries, provided that they are managed in a timely and high-quality manner.

CONCLUSIONS

The results of this study showed a strong correlation between the sequential implementation of used batteries and lead-containing batteries recycling processes and the economic effect which can be obtained by minimising environmental pollution. A comprehensive assessment of the possibility of causing damage to the environment, in the case of violations of the order of disposal of devices of the batteries and lead-containing batteries was carried out. It was clarified that the problem of recycling used batteries and lead-containing batteries is of considerable practical importance regarding the potential damage to the environment, where lead and its constituents are introduced into soil and water when storage rules are violated.

It was established that in assessing the economic impact, the decision-makers should consider the cost of disposing of these devices and the cost savings, which could be used to clean the environment from lead and its compounds. In general, it was revealed that well-organised and well-executed measures for the recycling of these accumulator devices contribute not only to the preservation of the environment from lead pollution and lead-containing compounds, but also provide considerable money savings, so very profitable in economic terms. This necessitates further research exploring the rational opportunities for optimising the processes of recycling used batteries and lead-containing batteries, as well as exploring additional cost-saving possibilities, provided that the high quality of industrial processing of this type of devices is ensured within the established time frame.

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Розробка системи утилізації відпрацьованих батарейок та свинцевих акумуляторів: оцінка економічного ефекту з мінімізацією шкоди довкіллю

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Анотація. Актуальність тематики визначається численними питаннями практичного застосування зарядних батарей та акумуляторів після завершення заявленого технічного терміну експлуатації, у зв›язку з проблемами забруднення через відсутність потенціалу для нормального утилізації. Основною метою даного дослідження є вивчення перспектив розробки та практичної реалізації системи утилізації відпрацьованих акумуляторів та свинцевих акумуляторів у контексті оцінки потенційного економічного впливу мінімізації шкоди довкіллю при повній реалізації поставленої мети. Основою методології цього наукового дослідження є поєднання кількісних і якісних методів. Застосування методів аналізу, синтезу, індукції та дедукції в даній дослідницькій роботі дає достатню інформацію про існуючі принципи відновлення свинцевих батарей та акумуляторів. Метод узагальнення передбачає здійснення якісної оцінки даних, отриманих у ході наукової роботи. Метод моделювання забезпечує відображення отриманих результатів за допомогою відповідних схем і діаграм. Проаналізовано наявні публікації низки дослідників, які займалися науковою розробкою питань утилізації відпрацьованих свинцевих батарей та акумуляторів. Досліджено фактори економічного ефекту, якого можна досягти при якісній переробці свинцевих акумуляторів. Сформовано приблизну оцінку економічного ефекту із заданим напрямком мінімізації шкоди навколишньому середовищу. Отримані в цій дослідницькій роботі результати та сформульовані на їх основі висновки мають практичне значення з точки зору перспектив збільшення обсягів виробництва вторинної продукції міді шляхом утилізації використаних батарейок та зменшення шкоди, що наноситься навколишньому середовищу, коли воно безконтрольно забруднено вторинними продуктами їх використання

Ключові слова: переробка відпрацьованих акумуляторів, промислова переробка, зменшення шкоди довкіллю, економічна ефективність утилізації акумуляторів, утилізація свинцевих акумуляторів

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