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вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна, 54008
тел.: +38(0512) 70-93-54

E-mail: info@bsagriculture.com.ua
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Full Doctor in Biological Sciences, Professor, Leading Research Fellow, NSC "Institute of Biology and Medicine", Taras Shevchenko National University of Kyiv, Ukraine

Boris Boincean

Full Doctor in Agricultural Sciences, Professor, Director of the State Institution Scientific Research Institute of Field Crops "Selektsia", Republic of Moldova

Valentina Gamayunova

Full Doctor in Agricultural Sciences, Professor, Head of the Department of Agriculture, Geodesy and Land Management, Mykolaiv National Agrarian University, Ukraine

Lidia Antipova

Full Doctor in Agricultural Sciences, Professor of the Department of Plant Breeding and Horticulture, Mykolaiv National Agrarian University, Ukraine

Mykola Samoilenko

Full Doctor in Agricultural Sciences, Professor of Viticulture and Horticulture, Mykolaiv National Agrarian University, Ukraine

Vyacheslav Sichkar	Full Doctor in Biological Sciences, Professor, Acting head of the Department of Genetics, Selection and Seed Production of Legumes, Breeding and Genetics Institute – National Center for Seed Science and Variety Research of NAAS, Ukraine
Serhiy Chornyy	Full Doctor in Agricultural Sciences, Professor Head of the Department of Soil Science and Agrochemistry, Mykolaiv National Agrarian University, Ukraine
Viktor Shcherbakov	Full Doctor in Agricultural Sciences, Professor of the Department of Field and Vegetable Crops, Odessa State Agrarian University, Ukraine
Raisa Vozhehova	Full Doctor in Agricultural Sciences, Professor, Director of the Institute of Irrigated Agriculture NAAS, Ukraine
Serhiy Kramarenko	Full Doctor in Biological Sciences, Professor, Professor of Genetics, Animal Feeding and Biotechnology, Mykolaiv National Agrarian University, Ukraine
Serhiy Ruban	Full Doctor in Agricultural Sciences, Professor, Acting Head of the Department of Genetics, Breeding and Biotechnology of Animals, National University of Life and Environmental Sciences of Ukraine, Ukraine
Olena Fedota	Full Doctor in Biological Sciences, Professor, Professor of Obstetrics and Gynecology, V. N. Karazin Kharkiv National University, Ukraine
Svitlana Kovtun	Full Doctor in Agricultural Sciences, Professor, First deputy director for scientific work, Institute of Animal Breeding and Genetics named after M. V. Zubets of NASU, Ukraine
Viktor Balatsky	Full Doctor in Agricultural Sciences, Senior Researcher, Head of the Laboratory of Genetics, Institute of Pig Breeding and Agroindustrial Production NAAS, Ukraine
Bogdan Gutyj	Full Doctor in Veterinary Sciences, Professor, Professor of Pharmacology and Toxicology, Stepan Gzhytskyi National University of Veterinary Medicine and Biotechnologies Lviv, Ukraine
Tetyana Dyman	Full Doctor in Agricultural Sciences, Professor, Vice-rector for educational, educational and international activities, Bila Tserkva National Agrarian University, Ukraine
Isaak Rashal	Full Doctor in Biological Sciences, Professor, Institute of Biology, Latvia
Mykhailo Gil	Full Doctor in Agricultural Sciences, Professor, Dean of the Faculty of TVPPTS, Mykolaiv National Agrarian University, Ukraine
Igor Gorbatenko	Full Doctor in Biological Sciences, Professor, Professor of the Department of Genetics, Animal Feeding and Biotechnology, Mykolaiv National Agrarian University, Ukraine
Valentyn Rybalko	Full Doctor in Agricultural Sciences, Professor, Chief Researcher, Institute of Pig Breeding and AP NAAS of Ukraine, Ukraine
Lyudmila Patreva	Full Doctor in Agricultural Sciences, Professor, Head of the Department of Poultry, Quality and Product Safety, Mykolaiv National Agrarian University, Ukraine
Tetiana Pidpala	Full Doctor in Agricultural Sciences, Professor, Head of the Department of Technology of Processing, Standardization and Certification of Livestock Products, Mykolaiv National Agrarian University, Ukraine
Serhiy Luhovyy	Full Doctor in Agricultural Sciences, Associate Professor, Acting Head of the Department of Genetics, Animal Feeding and Biotechnology, Mykolaiv National Agrarian University, Ukraine
Antonina Panfilova	Full Doctor in Agricultural Sciences, Associate Professor, Head of the Department of Plant Breeding and Horticulture, Mykolaiv National Agrarian University, Ukraine
Ihor Atamanyuk	Full Doctor in Technical Sciences, Professor, Professor of the Department of Applied Mathematics, Warsaw University of Life Sciences, Republic of Poland
Valerii Budak	Full Doctor in Technical Sciences, Professor, Rector, V. O. Sukhomlynskyi National University of Mykolaiv, Ukraine
Andriy Stavynsky	Full Doctor in Technical Sciences, Professor, Head of the Department of Power Engineering, Electrical Engineering and Electromechanics, Mykolaiv National Agrarian University, Ukraine
Viacheslav Prus	Full Doctor in Technical Sciences, Associate Professor, Head of the Department of Electrical Engineering, Kremenchuk Mykhailo Ostrohradskyi National University, Ukraine
Galyna Kondratenko	PhD in Technical Sciences, Associate Professor, Associate Professor of the Department of Intelligent Information Systems, Petro Mohyla Black Sea National University, Ukraine
Oleksiy Kozlov	PhD in Technical Sciences, Associate Professor of Computer Control Systems, Admiral Makarov National University of Shipbuilding, Ukraine
Antonina Kalinichenko	Full Doctor in Agricultural Sciences, Professor of the Institute of Technical Sciences, Opole University, Republic of Poland
Vijay Virendra	PhD, Professor, Head, Center for Rural Development and Technology, Delhi Indian Institute of Technology, India
Boris Butakov	Full Doctor in Technical Sciences, Professor, Mykolaiv National Agrarian University, Ukraine

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Allelopathic activity of water-soluble and volatile secretions of *Crocus sativus* L. (Iridaceae) flowers in the Northern Black Sea region

Vira Mykolaichuk*

PhD in Biological Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0003-0110-6539>

Antonina Panfilova

Full Doctor in Agrisciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0003-0006-4090>

Margaryta Korkhova

PhD in Agrisciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0001-6713-5098>

Antonina Drobitko

Full Doctor in Agrisciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-6492-4558>

Abstract. The introduction of new crops to agrophytocenoses, to which *Crocus sativus* belongs, should be preceded by research into their ecological safety and place in crop rotation. When harvesting raw materials for obtaining saffron, up to 90% of by-products remain, which during decomposition can have a negative effect on the soil and indirectly on the plants that are grown after saffron. Therefore, the aim of the research was to study the allelopathic activity of water-soluble and volatile secretions of *Crocus sativus* flowers in the agroclimatic conditions of the Northern Black Sea region. The research was conducted in 2021 according to the generally accepted methodology, freshly picked flowers were used, from which individual elements were extracted, and flowers of different stages of flowering. The following research methods were used: field, laboratory, computational and statistical. The results of the research established that the water-soluble secretions of *Crocus sativus* flowers and their parts stimulate the energy of germination and inhibit the growth of one-day seedlings of *Lactuca sativum*. Water-soluble secretions of *Crocus sativus* flowers have a negative allelopathic effect. The index of allelopathic activity under the action of water-soluble secretions of flowers ranges from -0.26 for a flower with all parts to -0.01 for petals. The highest stimulating effect of volatile secretions on the growth of *Lactuca sativum* roots and the allelopathic activity index value is characteristic of the flower that has just bloomed and the stamens, and the lowest - for the pistils. The allelopathic activity of the volatile secretions of *Crocus sativus* flower parts is set at the level of 6.4 (pistil) and 28.8% (stamens). Substances that inhibit the germination of *Lactuca sativum* roots are found mainly in the stamens. It was determined that the volatile secretions of *Crocus sativus* flower parts reduce the energy

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*Corresponding author

of seed germination of the test plant. The practical value of the research is that the results of the research can be used when determining the place of the crop in crop rotation and the duration of its cultivation in one field

Keywords: allelopathy; flowering; flower elements; inhibition; stimulation

INTRODUCTION

In connection with climate change in Ukraine, by the end of the century, an increase in the number of days with high temperatures, more than 100 tropical nights and up to 135 summer days per year, and a decrease in precipitation in the summer period are predicted for the Southern Steppe of Ukraine (World Bank..., 2021). This will lead to a decrease in the yield of certain crops (barley, corn, sunflower). For the stability of the country's agricultural production, it is important to study and attract new crops that would be adapted to rising temperatures in summer, increased aridity in the south and east of Ukraine, and other consequences of climate change. One of these crops is saffron (*Crocus sativus* L.), which belongs to the *Crocus* genus of the *Crocoideae* subfamily of the *Iridaceae* family (Cardone *et al.*, 2020).

Crocus sativus L. is a herbaceous perennial monocotyledonous plant that reaches a height of 20-25 cm. Underground, it forms a tuber with a diameter of 2.5-3.0 cm, covered with mesh and fibrous scales and dark brown fibers from destroyed old scales. The leaves are linear 15-20 cm long and 2-3 mm wide with a longitudinal white stripe. Plants bloom for 7-10 days in October-November. The flowers are large, light purple with a strong aroma (Cardone *et al.*, 2020). *Crocus sativus* is a sterile triploid ($2n=3x=24$), so it does not form fruits and seeds (Cardone *et al.*, 2021). Cultivated mainly in Iran, Afghanistan, Morocco, India, Spain, Greece and Italy (Cardone *et al.*, 2019). Today, Iran supplies about 90% of raw materials to the world market (Kheirabadi *et al.*, 2020).

C. sativus was introduced into culture around 3000-2300 BC., does not occur in the wild (Nemati *et al.*, 2020). Saffron is the most expensive spice, which is called "red gold", has beneficial properties for human health. Saffron is grown on different types of well-drained soils with a pH range from neutral to slightly alkaline (Ghanbari *et al.*, 2019). According to the results of research (Mzabri *et al.*, 2022), the productivity of the receptacles is affected by illumination: the highest productivity is observed at 30% shading. The culture is resistant to low and high temperatures and withstands their range from -22 to 40°C (Siney *et al.*, 2020). According to O.O. Mykhaylenko (2019), to collect 1 kg of dry saffron, it is necessary to collect receptacles from about 167,000 flowers.

During the last time, *Crocus sativus* culture arouses the interest of Ukrainian farmers, but some elements of its agrotechnics of cultivation remain poorly studied. That is why the aim of the research was to establish the peculiarities of the allocation of generative organs

of *Crocus sativus* in the climatic and soil conditions of the Northern Black Sea region in order to establish the safety of growing a new crop for the agrophytocenoses of Southern Ukraine. The peculiarity of the cultivation and processing of plant raw materials of the crop is that when harvesting *Crocus sativus*, other elements of flowers (petals, stamens) or blossomed flowers remain as a by-product, which can be found in the fields or disposed of (Mykolaichuk *et al.*, 2021). Therefore, it became necessary to determine the allelopathic activity of water-soluble and volatile secretions of elements of flowers and flowers of different flowering periods.

LITERATURE REVIEW

In Ukraine, commercial plantings of *C. sativus* for food purposes were established in 2015 in the Kherson region (Mykhaylenko, 2019). After that, cultivation of this crop was also started in other regions.

Recently, the demand for saffron has been increasing, and this is due to the discovery of biologically active substances in various plant organs that have pharmacological properties (Jadouali *et al.*, 2019; Chen *et al.*, 2020). Extracts and pure substances from *C. sativus* have been shown to have antioxidant, antiparasitic, hypolipidemic, hypotensive, immunomodulatory, antimicrobial, antitumor, and antidepressant effects. The range of actions is determined by the composition of biologically active substances contained in the capsules (Chen *et al.*, 2020; Soukrat *et al.*, 2019). Among the volatile aromatic substances, monoterpene aldehydes (isophorone, safranal and their isomers), as well as non-volatile compounds of various nature, are the main ones. Among which: crocetin, crocin, lycopene, zeaxanthin, α , β , γ -carotene; p-coumaric, vanillic, 3-hydroxy-4-methoxybenzoic acids, pyrogallol, gallic acid, mangi-crocin, emodin, 2-hydroxyemodin, safranal, β -pinene, 1,8-cineole, picrocrocin; crocuses; 3-hydroxy- β -ionone, sugars, calcium, potassium, phosphorus, etc. The composition of saffron essential oil includes pinnen, prineol, fatty oils, B vitamins, flavonoids, sugars, gums, etc. Freshly collected flowers of *C. sativus* contain the glycoside protocrocin, which, when dried, splits into crocin and picrocrocin. According to M.A. Shajari & P.R. Moghaddam (2022), crocin predominates in the receptacles, (Ghanbari *et al.*, 2019) found mainly flavonoids in the petals and leaves. As a result of research (Ghanbari *et al.*, 2019) it was established that the volatile organic compounds of the *C. sativus* flower, in addition to safranal, include 11 compounds, including acetic acid, 2(5H)-furanone,

isobutanal, a fragment of biogenic aldehyde, 4-ketoisoforon, acetaldehyde, butyrolactone.

During the last decade, intensive studies of the biochemical composition of *C. sativus* organs and their allelopathic activity have been conducted. It is known that *C. sativus* can grow in one place for up to 12 years, but after 5-6 years the plantations thin out, the yield of the receptacles decreases (Ghanbari et al., 2019). Releases of *C. sativus* have an inhibitory effect on seedlings and tested plants. The main volatile substances of saffron that have an inhibitory effect are safranal, D-limonene and isophorone (Mardani et al., 2019). Safranal (2,6,6-trimethyl-1,3-cyclohexadiene-1-carboxaldehyde), which is the main component of saffron volatile compounds, is known for its inhibitory effect on cell division (Mardani et al., 2019). The stimulating effect of the water extract of the petals on the growth of eggplant seedlings was revealed (Khoulati et al., 2020). The prospect of using saffron by-products has been studied by a number of scientists (Lahmass et al., 2018; Shadmehri et al., 2019). Saffron leaf and tuber extract has an allelopathic effect on germination and shoot and root length of *Datura stramonium* and depends on saffron phenological phases (Barkhordari et al., 2018).

During the production of saffron, for each kilogram of spices produced, about 53 kg of perianth leaves remain, which is up to 90% of the by-products that end up in waste (Menghini et al., 2018). Scientific studies have proven that some water-soluble metabolites of perianth leaves have a positive effect on plant growth, influencing the activity of photosynthesis (Lahmass et al., 2018).

A study of the biochemical composition of saffron grown in Ukraine showed that in terms of the content of the main compounds (crocin, picrocrocin, saffron), the raw material meets the international standards of ISO 3632 and belongs to category I (Mykhaylenko, 2019). Research on the allelopathic activity of saffron flowers in Ukraine was conducted on the basis of Mykolaiv National Agrarian University. The stimulating effect of water-soluble secretions of individual parts of *C. sativus* flowers of different concentrations on the germination energy of *L. sativum* seeds was established. The highest indicators of allelopathic activity of water-soluble secretions of flowers were found at a concentration of 0.02% (Mykolaichuk et al., 2021).

MATERIALS AND METHODS

To establish the allelopathic activity of water-soluble and volatile secretions of *C. sativus* flower parts of flowers of different flowering periods, laboratory studies were carried out in the laboratories of the department of plant breeding and horticulture of the Mykolaiv National Agrarian University in 2021. *C. sativus* was grown in accordance with recommendations, the plot was planted in 2019 on at the base of the branch of the

department with coordinates 46°58'31" north latitude 31°59'37" east longitude, at an altitude of 42 m above sea level. The material for research was collected in the third decade of October 2021.

To study the allelopathic activity of flower parts, freshly picked flowers were used, from which the generative organs (stamens and pistil) were removed in accordance with the recommendations for the collection of saffron raw materials.

Determination of the allelopathic activity of water-soluble and volatile secretions of individual parts of the flower of *C. sativus*, the energy of germination and growth of the roots of seedlings of the biotester plant was carried out by the bioassay method of A.M. Grodzinsky (1991). The test object was *L. sativum* seeds, which were sown in sterile Petri dishes on filter paper moistened with distilled water and placed for 24 hours in a thermostat at a temperature of +23-24°C. Seedlings of *L. sativum* whose root length reaches 2 mm are considered suitable for research.

To detect the allelopathic activity of the generative organs of *C. sativus* flowers, fertile and sterile elements were separated (variants of the experiment: "petals", "flower", "petals+stamens", "petals+pistil"). The mass of stamens was 0.025±0.003 g, pistils – 0.035±0.002 g, petals – 0.376±0.013, and flowers – 0.435±0.016 g. They were placed in distilled water in the ratio of 1 g of the studied material per 100 ml (0.01%) of water and kept for 24 hours at a temperature of +23-24°C in a thermostat (Fig. 1). The solution was filtered through filter paper No. 2. After a day, 100 seedlings of *L. sativum* were transferred to filter paper in Petri dishes and 3-4 ml of filtrate was added.



Figure 1. Setting up an experiment with water-soluble secretions of *C. sativus* flowers

Source: developed by the authors

To determine the allelopathic activity of volatile secretions of the flower and its separate parts, they were removed from the flower and placed on a plastic rise in a Petri dish. At the same time, the flower and its parts did not touch the surface of the filter paper, which was moistened with 3-4 ml of distilled water and where 100 seedlings of *L. sativum* were transferred (Fig. 2). Petri dishes were placed for 24 hours in a thermostat at a temperature of +23-24°C. The experiment was carried out in five repetitions.

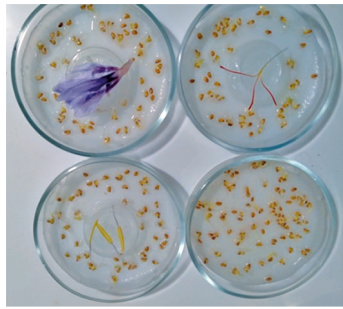


Figure 2. Setting up an experiment with volatile secretions of *C. sativus* flower parts

Source: developed by the authors

To determine the allelopathic activity of volatile secretions of flowers of different ages, buds, a blooming flower,

and a faded flower that bloomed 1 day ago were used. The experiment was carried out in five repetitions (Fig. 3).



Figure 3. Setting up an experiment with volatile secretions of *C. sativus* flowers of different ages (a – wilted, b – blossomed flower, c – faded flower)

Source: developed by the authors

During the day, the growth length of the roots of the seedlings was measured with the help of a caliper. To determine the energy of germination, the percentage of *L. sativum* seeds with developed roots was calculated after one day of exposure to volatile extracts of *C. sativus*.

Germination energy was determined as the ratio between the number of germinated seeds and their total number in percentage. The statistical analysis of the obtained results (the length of the roots of the seedlings of the biotester plant) was performed using Microsoft Excel and Statistica 7.0 programs. The average, minimum and maximum length of the roots were determined. The degree of trait variability was determined according to the method of S.A. Mamaev (1972): very low at <7%, low 8-12%, medium 13-20%, elevated 21-30%, high 31-40% and very high >40%. Graphs were constructed using Excel 7.0 software.

Allelopathic activity was determined according to the method of A.M. Grodzinsky (1991) as the ratio between the length of the roots in the experiment to the length of the roots of *L. sativum* in the control (on distilled water), expressed as a percentage.

The allelopathic activity index (RI) was used to quantify the allelopathic effect, which was determined by the formula: $RI=1-C/T$,

where C are control indicators, T are indicators obtained in the experiment. If $RI>0$, then there is a stimulation effect, $RI<0$ indicates inhibition.

RESULTS AND DISCUSSION

As a result of the research, it was established that the water-soluble and volatile secretions of *C. sativus* flowers are allelopathically active. Taking into account that during the collection of *C. sativus* receptacles, other morphological elements of flowers (petals, stamens) remain as a by-product, it became necessary to determine the allelopathic activity of water-soluble secretions of flowers and their elements, which in the future can be washed by water into the soil and affect other types of plants and crops in crop rotation. Considering the results of research by O. Mykhalenko (2019) regarding the quality of saffron plant raw materials obtained in Ukraine, it meets international standards ISO 3632 and belongs to category 1, the content of safranal, crocin and picrocrocin does not differ from the standards.

According to the research results, it was found that the water-soluble secretions of *C. sativus* flowers inhibit the growth of *L. sativum* root length, compared to the control (Table 1).

Among the variants of the experiment, the largest indicators of root length were registered in the "petal" variant, and the smallest – in the "flower". Statistically significant differences are typical for the variants "flower" with control, "petals+pistil" and "petals" ($p<0.05$). The coefficients of variation in the length of roots of *L. sativum* range from high ("petals+pistil") (38.9%) to very high (>40%), which is characteristic of other variants.

Water-soluble secretions of the flower of *C. sativus* and their parts do not affect the energy of seed germination of the biotestor plant. The germination energy is slightly lower in the “petals+pistil” variant compared to other variants.

Table 1. The effect of water-soluble secretions of the flower of *C. sativus* on root growth (mm) and germination energy (%) of *L. sativum* (N=100)

Option	M±m	min-max	Cv, %	The energy of germination	RI
Control (distilled water)	8.18±0.49	2.0-18.0	52.5	100	-
Flower	6.48±0.36	2.0-13.0	49.5	100	-0.26
Petals + pistil	7.75±0.37	2.0-18.0	38.9	99	-0.06
Petals + stamens	7.29±0.41	2.0-15.0	45.8	100	-0.12
Petals	8.10±0.42	2.0-15.0	45.7	100	-0.01

Source: developed by the authors

The index of allelopathic activity indicates that the water-soluble secretions of *C. sativus* flowers have negative indicators ranging from -0.26 for the flower with all elements to -0.01 for the petals. It was established that the allelopathic activity of the water-soluble secretions of the *C. sativus* flower and its elements is in the range from -21.4% (“flower”) to -1.0%, which is typical for the petals (Fig. 4). Comparison of allelopathic activity

indicators with the index of allelopathic activity of the elements of the *C. sativus* flower confirms that, with different approaches to their determination, which we used, the water-soluble secretions of the flower and its individual elements are allelopathically active. Analyzing the obtained results, it can be assumed that the substances that cause inhibition of the growth of the roots of *L. sativum* seedlings are found mainly in the stamens.

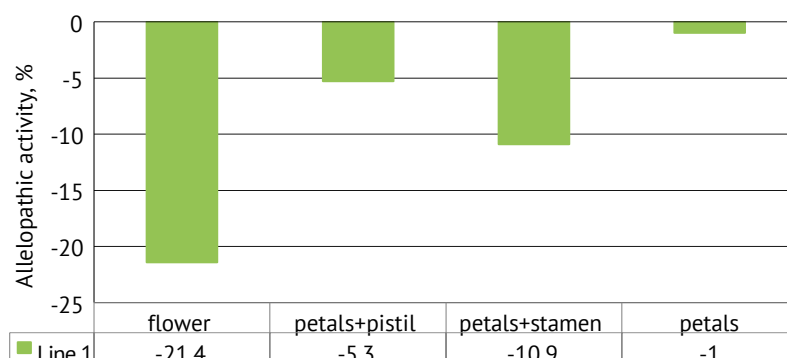


Figure 4. Allelopathic activity of water-soluble extracts of *C. sativus* flower, %

Source: developed by the authors

According to the research results, it was established that the volatile secretions of individual parts of the flower of *C. sativus* have a stimulating effect, and their allelopathic activity ranges from 6.4% for the volatile secretions of the pistil to 28.8% for the volatile secretions of the stamens compared to the control.

Volatile secretions of individual parts of the *C. sativus* flower have a slight stimulating effect on the growth of *L. sativum* roots compared to the control. The length of seedling roots exceeded the control in all variants, but the highest values were observed under the influence of volatile secretions of stamens and flowers (28 and 37%, respectively). The smallest increase in length is characteristic under the influence of volatile

secretions of the pistil (6%). Statistically significant differences are characteristic of the “stamen” and “flower” options with the control ($p < 0.05$), there is no significant difference between the other options. The length of the roots in all variants has high variability, it is characterized by a coefficient of variation that is $> 40\%$.

Volatile secretions of individual parts negatively affect the germination energy of *L. sativum* seeds, which is in the range from 57.6% (stamens) to 72.2% (pistil) and is less than the control by 42.4 and 27.8%, respectively (Table 2). The results obtained by us coincide with the results (Mardani *et al.*, 2019) regarding the inhibitory effect of volatile extracts of *C. sativus* on the growth of root length of seedlings.

Table 2. Effect of volatile secretions of flower parts of *C. sativus* on root growth (mm) and germination energy (%) of *L. sativum* (N=100)

Option	M±m	min-max	Cv, %	The energy of germination	RI
Control (distilled water)	5.66±0.31	2,0-13.0	42.7	100	-
Stamens	7.29±0.67	2,0-15.0	53.5	57.6	0.22
Pistil	6.02±0.54	2.0-14.0	58.5	72.2	0.06
Petals	6.51±0.54	2.0-13.0	51.3	66.1	0.13
Flower	7.75±0.37	2.0-18.0	58.0	62.3	0.24

Source: developed by the authors

The index of allelopathic activity of volatile secretions of individual parts of the flower indicates that they have a stimulating effect and range from 0.06 (pistil) to 0.24 (flower).

According to the results of research, it was established that the volatile secretions of individual parts of the flower of *C. sativus* plants grown in the Northern Black

Sea region have a stimulating effect, which ranges from insignificant – 6.4% (pistil) to medium – 37.0% (flower) (Fig. 5). The low allelopathic activity of the volatile secretions of the uterus is due to the fact that it contains the largest amount of physiologically active substances (saffron, D-limonene and isophorone (Mardani *et al.*, 2019; Shadmehri *et al.*, 2019), which have an inhibitory effect.

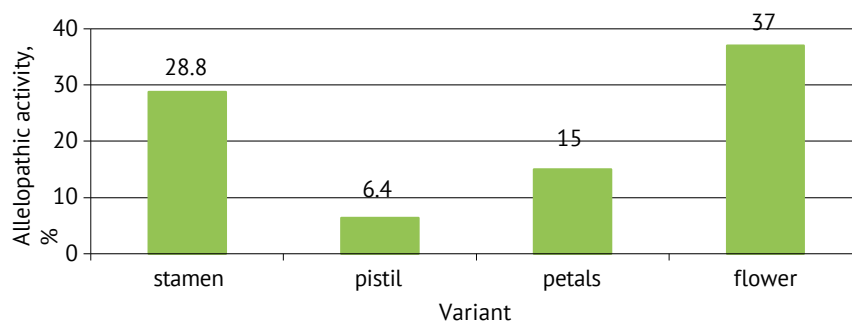


Figure 5. Allelopathic activity of volatile secretions of flower parts *C. sativus*, %

Source: developed by the authors

The analysis of the effect of volatile secretions of flowers at different stages of flowering (from the bud to the flower that has bloomed) shows their stimulating effect on the growth of the roots of biotester plants, compared to the control. The increase in seedling root length ranged from 46.2% (open flower) to 65.9% (bud) compared to the control. Statistically significant differences are characteristic of the options

“blossomed flower” and “bloomed flower” with control and “bud” with “bloomed flower” ($p < 0.05$), there is no significant difference between other options. The volatile secretions of the *C. sativus* flower bud have a greater stimulating effect on root growth, compared to the control and other variants (Table 3). The coefficients of variation of root length for all variants are very high (>40 %).

Table 3. Effect of volatile secretions of *C. sativus* flowers at different stages of flowering on root growth (mm) and germination energy (%) of *L. sativum* (N=100)

Option	M±m	min-max	Cv, %	The energy of germination	RI
Control	5.64±0.43	2.0-20.0	81.3	100	-
Bud	6.43±0.36	2.0-19.0	55.1	58.8	0.33
A blossomed flower	7.75±0.37	2.0-18.0	58.0	62.3	0.24
A bloomed flower	7.29±0.41	2.0-17.0	56.4	57.0	0.27

Source: developed by the authors

Volatile secretions of *C. sativus* flowers of different stages of flowering negatively affect the energy of seed germination, which was lower than the control and ranged from 43% (bloomed flower) to 36.7% (bloomed flower) compared to the control (Table 3). The results obtained coincide with the results of research by H. Mardani (2019), regarding the inhibitory effect of volatile secretions of *C. sativus* flowers on certain processes in *L. sativum*. At the same time, the index of allelopathic

activity of volatile secretions of flowers, which was determined by the increase in the length of the roots of the seedlings of the test plant, has positive indicators and ranges from 0.24 (blooming flower) to 0.33 (bud).

Volatile secretions of flowers of different degrees of flowering are allelopathically active, their effect is stimulating, and the values are in the range from 30.7% (bloomed flower) to 48.2% (bud), compared to the control (Fig. 6).

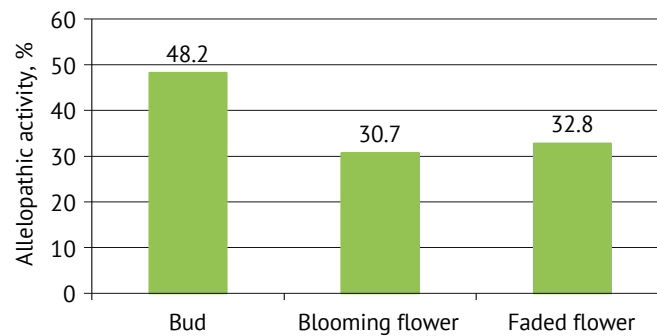


Figure 6. Allelopathic activity of volatile secretions of *C. sativus* flowers at different stages of flowering, %

Source: developed by the authors

It is known that the main factors causing the allelopathic effect are the content of volatile substances in the flowers of *C. sativus*, among which safronal and other compounds are isolated. We assume that the content of these compounds is the lowest in flower buds, compared to blooming and faded flowers, therefore the indicators of allelopathic activity of volatile secretions of buds prevail over the control and other variants of the experiment.

Research results confirm the presence of biologically active substances in *C. sativus* flowers that have allelopathic properties, this is also confirmed by the research of other scientists (Mardani et al., 2019).

According to the results of research (Khoulati et al., 2020) it was established that the water-soluble secretions of the perianth of *C. sativus* plants grown in Morocco, the activity of water-soluble secretions also depends on the concentration of biologically active substances: at a dilution of 2 mg/ml, it stimulates plant height and chlorophyll content, but reduces the antioxidant property and content of malondialdehyde. When the concentration is increased to 3 mg/ml, the opposite effect is observed: inhibition of plant growth and an increase in the concentration of ascorbic acid. Based on this, the authors suggest taking these phenomena into account and using aqueous extracts at a dilution of 2 mg/ml of perianth (petals) as biostimulants. The water-soluble secretions of the petals of *C. sativus*, which were grown in the Northern Black Sea region of Ukraine, when diluted to 1 g/100 ml of distilled water, have a slight inhibitory effect on the seedlings of biotester plants. At the same time, they do not affect the energy of seed germination of the biotester plant. This indicator is slightly lower in the "petals+pistil" variant compared

to other variants. The obtained results coincide with the results of studies (Abbasi-Alikamar et al., 2007), which established that the petals of *C. sativus* flowers do not significantly affect the germination of plants.

According to (Serrano-Díaz et al., 2013), inhibition or stimulation of plant growth by water-soluble secretions of parts of the flower of *C. sativus* depends on the content of various compounds (amino acids, fibers and necessary minerals) that stimulate growth.

Research (Feizi et al., 2018) showed that the allelopathic activity of *C. sativus* plants is determined not only by the concentration of solutions, but also by plant organs (flower, bulb, leaves). The research results showed that the leaves and bulbs of *C. sativus* had an inhibitory effect on the germination and vital activity indicators of safflower and sugar beet seeds. Increasing the concentration of the extract reduced all germination characteristics, including the percentage and rate of germination, hypocotyl, seedling and root length, seedling and root weight, as well as seed viability index of the studied crops. Therefore, there is a possibility of allelopathic action of all plant organs of *C. sativus* on plants cultivated in crop rotation with it.

(Barkhordari et al., 2018) determined that aqueous and alcoholic extracts of flavonoids of various organs of saffron, regardless of the phase of plant growth and development, have allelopathic potential, influencing the germination characteristics of *Datura stramonium* seeds. Thus, saffron concentration and phenological stage had a significant effect on *Datura stramonium* germination percentage, but the main effect of organ type on this trait was insignificant. The aqueous extract of saffron had no significant effect on the germination

of *Datura stramonium* at the stage of formation of new bulbs at a concentration of 2 g/l, but at a concentration of 4 g it significantly reduced seed germination.

Research results (Kheirabadi *et al.*, 2020) established that *C. sativus* bulbs also have substances that cause allelopathic effects. Thus, the allelopathic activity of bulb residues and soil water extracts on the germination of lettuce seeds showed that the highest inhibition was associated with bulb extract. The minimum germination percentage (82.0% and 86.5%) was obtained in extracts with a concentration of 75% and 100%, respectively. The average time of germination of lettuce seeds was significantly increased with respect to different concentrations of aqueous bulb extract. The combination of activated carbon and tuber bulb residues reduced the average germination time. However, there were no significant differences in the average seed germination time. The length of the root and hypocotyl did not show significant fluctuations according to different concentrations of the solutions. The allelopathic effect of saffron tuber residues caused growth imbalance between the lettuce shoot and roots. According to biochemical analyses, the use of adsorbents increased the content of carotenoids and the chlorophyll index of lettuce by 23.33% and 5.25%, respectively.

The obtained results indicate that in the conditions of the Northern Black Sea region of Ukraine, water-soluble and volatile secretions of *C. sativus* plants have allelopathic properties. Further research should establish the influence of the introduction's secretions on crops common in the agrocenoses of Ukraine, the possibility of reducing the negative impact on them, and the study of the phenomenon of soil fatigue on perennial plantations of *C. sativus*.

CONCLUSIONS

Research on the allelopathic activity of water-soluble and volatile secretions of flowers of *C. sativus* plants grown in the agroclimatic conditions of the Northern Black Sea region of Ukraine was conducted for the first time, so the results obtained are original. It was established that the water-soluble secretions of flowers and their elements do not have a negative effect on the germination energy of *L. sativum* seeds, but it was

found that they inhibit the growth of the roots of seedlings of the biotester plant. The highest inhibition rates are characteristic of water-soluble secretions of a flower with all morphological elements, the lowest – for petals (-21.4 and -1.0%, respectively).

Volatile secretions of *C. sativus* flowers inhibit the energy of germination of *L. sativum* seeds by 42.4 and 27.8% compared to the control in variants of exposure to stamen and pistil secretions. However, the volatile secretions of individual elements of the flower have a stimulating effect on the growth of roots, which are in the range of 6-28.8%. The index of allelopathic activity of volatile secretions of individual parts of the flower indicates their stimulating effect and is in the range of 0.06-0.24.

Water-soluble secretions of flowers have a stimulating effect on the germination energy of *L. sativum* seedlings, but an inhibitory effect on the growth of the roots of test plants and have a negative allelopathic effect and index of allelopathic activity.

It was established that the volatile secretions of *C. sativus* flowers of different stages of flowering inhibit the energy of seed germination, the blossomed flower and bud have a greater inhibitory effect compared to the control, the indicators of which are 43.0 and 36.7% less than the control. However, they stimulate the growth of seedling roots compared to the control from 46.2% (open flower) to 65.9% (bud). The index of allelopathic activity ranges from 0.24 (blossomed flower) to 0.33 (bud).

Water-soluble and volatile extracts of *C. sativus* flowers grown in the Northern Black Sea region are allelopathically active. Their effect is stimulating and inhibiting on the germination energy and root growth of *L. sativum* seedlings.

Further studies of the allelopathic activity of *C. sativus* plants should establish their influence on common field crops of Southern Ukraine, primarily winter wheat.

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CONFLICT OF INTEREST

The authors declare that the study was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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Алелопатична активність водорозчинних та летких виділень квіток *Crocus sativus* L. (Iridaceae) в Північному Причорномор'ї

Віра Георгіївна Миколайчук

Кандидат біологічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0003-0110-6539>

Антоніна Вікторівна Панфілова

Доктор сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0003-0006-4090>

Маргарита Михайлівна Корхова

Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0001-6713-5098>

Антоніна Вікторівна Дробітько

Доктор сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-6492-4558>

Анотація. Введенню в агрофітоценози нових культур, до яких належить *Crocus sativus*, повинні передувати дослідження їх екологічної безпечності та місця в сівозміні. При збиранні сировини для отримання шафрану залишається до 90% побічних продуктів, які при розкладанні можуть негативно впливати на ґрунт і опосередковано на рослини, які вирощуються після шафрану. Тому метою досліджень було вивчення алелопатичної активності водорозчинних та летких виділень квіток *Crocus sativus* в агрокліматичних умовах Північного Причорномор'я. Дослідження проводили у 2021 р. за загальноприйнятою методикою, використовували свіжозібрані квітки, з яких вилучали окремі елементи, та квітки різного ступеню квітування. Використовували такі методи досліджень: польовий, лабораторний, розрахунковий та статистичний. Результатами досліджень встановлено, що водорозчинні виділення квіток *Crocus sativus* та їх частин стимулюють енергію проростання та пригнічують приріст однодобових проростків *Lactuca sativum*. Водорозчинні виділення квіток *Crocus sativus* мають негативну алелопатичну дію. Індекс алелопатичної активності за дії водорозчинних виділень квіток знаходиться в межах від -0,26 для квітки з усіма частинами до -0,01 для пелюсток. Найвища стимулююча дія летких виділень на приріст коренів *Lactuca sativum* та значення індексу алелопатичної активності характерна для квітки, яка щойно розквітла, та тичинок, а найменша – для маточок. Алелопатична активність летких виділень частин квітки *Crocus sativus* встановлена на рівні 6,4 (маточка) та 28,8% (тичинки). Речовини, які інгібують проростання коренів *Lactuca sativum* знаходяться переважно в тичинках. Визначено, що леткі виділення частин квітки *Crocus sativus* знижують енергію проростання насіння тест-рослини. Практична цінність досліджень, полягає в тому, що результати досліджень можуть бути використані під час визначення місця культури в сівозміні і тривалості вирощування її на одному полі

Ключові слова: алелопатія; квітування; елементи квітки; інгібування; стимулювання

Allelopathic activity of plants *Hyssopus officinalis* L.

Yevgenia Tkachova

Graduate Student
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-4265-2934>

Mikhail Fedorchuk*

Full Doctor in Agrisciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0001-7028-0915>

Oleg Kovalenko

Full Doctor in Agrisciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-2724-3614>

Abstract. The need for phytoremediation prompts the introduction of plants into the culture, which will not only have several directions of use of the obtained raw materials, but also contribute to the improvement of the soil and be a good precursor for the further successful cultivation of the following agricultural crops. It is known that essential oil crops activate the development of beneficial microbiota and prevent soil fatigue. The article presents the results of research on the allelopathic activity of plant parts of medicinal hyssop (*Hyssopus officinalis* L.) of the Marquis variety, taking into account age characteristics under conditions of climate change in Southern Ukraine. The aim of the work was to reveal the influence of allelopathic activity of aqueous extracts of leaves, stems and flowers of hyssop, soil in the rhizosphere zone and plant age on the growth of watercress roots. In the research process, empirical methods were used, in particular, an experiment. As a result of research carried out with the medicinal hyssop culture of the first, second and third years of vegetation on the basis of the experimental field of the Mykolaiv National Agrarian University during 2019-2021, the optimal concentration of water extracts of the culture with a stimulating effect was found. The dependence of the allelopathic activity of water-soluble biologically active substances of aerial organs of medicinal hyssop plants is shown, and the concentration of the solution, which causes an inhibitory effect, is revealed. Thus, the highest allelopathic activity was noted on the variant using hyssop flowers of medicinal plants of the second year of vegetation in a concentration of 1:10. Aqueous solutions of the soil layer of the root system where medicinal hyssop plants grew in the third year of vegetation have an inhibitory effect on the linear growth of watercress roots. It was the largest in the leaf + stem variant at a concentration of the aqueous solution of 1:10. This suggests that it is necessary to use the culture of medicinal hyssop in crop rotation carefully taking into account its ontogenesis features. The obtained results will have practical application in enterprises of various forms of ownership that will have the desire to grow medicinal hyssop and use it in the structure of crop rotation

Keywords: medicinal hyssop; watercress; aqueous extracts; solution concentration; allelopathy; stimulation; inhibitory effect

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*Corresponding author

INTRODUCTION

Such consequences of climate change as an increase in average annual temperatures, frequent and intense droughts, as well as the active, often ill-advised implementation of advanced agricultural technologies lead to deterioration of soil properties and loss of soil fertility. Therefore, there is a need to find effective solutions to restore optimal conditions for growing agricultural crops. One of these solutions can be the use of phytoremediation, which significantly improves the physical properties of the soil, enhancing its biological activity and increasing its humus content, which positively affects the productivity and yield of plants (Aipova *et al.*, 2020).

Recently, research aimed at the use of essential oil medicinal plants as phytomeliorants that synthesize specific secondary metabolites, mainly of phenolic nature, is relevant. For example, L. Mikhalska (2018) experimentally established the possibility of cleaning soils contaminated with metals and improving their ecological condition with the help of such a plant as narrow-leaved lavender. According to A. Shahid (2021), root secretions of white mustard reduce the accumulation of common diseases in the soil, such as late blight, rhizoctoniosis, fusarium rot, etc.

The specificity of medicinal plants is that they contain a variety of biologically active substances that can be released into the environment, and their type, content and proportion can affect the growth and development of plants that are in the same agrophytocenosis. Such phytochemicals include phenolic compounds, alkaloids, flavonoids, tannins, resins and balms, essential oils, etc. But terpenoids deserve special attention – secondary metabolites that affect the taste of fruits, the color of leaves and the smell of flowers and are the main component of plant essential oils. Terpenoids produced by plants protect them from fungal diseases, insects and animals. One of the ways of terpenoids entering the soil is plant root secretions (Kornienko *et al.*, 2021). Essential oils have high volatility in atmospheric air (Grodzinsky, 1992). Phytomelioration significantly improves the agrochemical, agrophysical and biological parameters of the soil. According to scientists' experiments, the essential oil of plants belonging to the *Lamiaceae* family significantly reduces the number of phytoneatodes. The most sensitive are the soil stages of the root nematode (Abd-Elgawad & Omer, 1995). In the conditions of the Mykolaiv region, medicinal hyssop, as an essential oil crop adapted to the extreme soil and climatic conditions of the south of Ukraine, can be grown for the reclamation of degraded soils, on technogenically polluted territories for local greening, on saline soils for the purpose of improving ecosystems (Dobrovolskyi *et al.*, 2021).

Root exudation is an important process that determines the interaction of plants with the soil environment and is the main component of carbon distribution in the soil. Root exudation is a complex phenomenon

that encompasses processes that control carbon transport to roots and exudation from roots to soil. This process optimizes root growth to facilitate efficient foraging for nutrients and possibly detection of competing neighbors. Root exudates include rhizodeposits consisting of sugars, organic acids, amino acids, etc. The peculiarity of perennial plants is that over the years in the process of cultivation, they form a dead mass that forms a specific microbiota, which not only activates the processes in the soil, but also changes its properties. With the constant cultivation of such crops, there is an accumulation of phytopathogens and toxigens, which negatively affect the realization of the biological potential of the plant cultivated after the previous one (Canarini *et al.*, 2019). An experiment by Japanese scientists showed that joint plantations of tomato (*Solanum Lycopersicum*) with plants of the *Lamiaceae* family improve the growth and development of tomato plants, due to changes in secondary metabolites and amino acids of the plant. That is, *Lamiaceae* root exudates change soil properties and have a positive effect on its microbiota (Ahmad *et al.*, 2020).

It is necessary to investigate not only the use of allelopathy of essential oil crops in agriculture, but also to establish determinants that can interfere with its positive effect on the growth and development of plants. A distinctive feature of plants of the *Lamiaceae* family, which includes hyssop, is their aromaticity, which proves the presence of terpenes and their oxygen-containing derivatives. In addition, plants contain glycosides, saponins, resins and alkaloids (Islam Momtinul *et al.*, 2022). Over time, the accumulation of these chemicals can have toxic potential.

Based on the above, the goal was to study the influence of age, parts of plants and their root secretions depending on the concentration of the solution on the allelopathic activity of water-soluble biologically active substances and to establish its stimulating and inhibitory effect.

The tasks that contributed to the realization of the set goal were:

- to investigate the allelopathic activity of the above-ground organs of the hyssop plant and its root-containing soil layer;
- to compare the allelopathic activity of the obtained water extracts in relation to the test object;
- to determine the allelopathic activity of water extracts of aerial parts of the hyssop plant depending on the age and the root layer of the soil in relation to the test object.

LITERATURE REVIEW

In connection with the active cultivation of essential oil crops, including medicinal hyssop, it is important to study their effect on other types of plants, so scientists have started researching their allelopathic properties.

According to M. Shinwari *et al.* (2013), 70 species of Japanese plants were examined for allelopathy using the aqueous extraction method. The scientists concluded that before large-scale cultivation of any medicinal plant in an established agricultural field, the plant should be evaluated allelopathically, as chemical exposure from previous plants, residues, related plants and even autotoxicity can adversely affect the cropping system. The results of experiments by Bulgarian scientists show that water infusions of hyssop contain secondary metabolites that show allelopathic effects in the early stages of growth of other plants in laboratory conditions (Dragoeva *et al.*, 2010). Other studies demonstrate that hyssop essential oil exhibited an allelopathic effect and inhibited seed germination and seedling development of wheat and barley (Zheljazkov *et al.*, 2021). But medicinal hyssop, which was cultivated in the extreme conditions of Southern Ukraine, was almost never studied.

According to A.M. Grodzinsky (1992) regarding allelopathy, the main issue of a biological phenomenon in which an organism produces one or more biochemical substances that affect the germination, growth, survival and reproduction of other organisms from the same community is the study of genes – their concentration and chemical composition. In addition, it is necessary to study all stages of the cycle – in plant secretions and precipitation, in the rhizosphere microflora and their allelopathic influence on the phytocenosis. The scientist believed that knees have a complex chemical nature, so their presence and allelopathic activity should be determined with the help of biological samples. Since each plant can be both a producer – a donor of physiologically active substances, and a recipient – their consumer, accordingly, a plant can create both a protective biological sphere, or be allelopathically active, and adapt to the presence of genes in the environment, that is, be allelopathic tolerant. These special properties make it possible to find out the possibility of using such a plant in combined crops or its ability to inhibit the growth and development of weeds. Accumulating and releasing genes into the environment, the plant creates an allelopathic sphere around itself (Grodzinsky, 1992; Aipova *et al.*, 2020; Grodzinsky, 1991).

Plant groups accumulate knees to a certain level, which determines the activity of their growth and development. There is a dependence between the production of knees and the accumulation of plant biomass: the higher the level of knees – the deterioration of the growth of the components of the grouping. A reduction in the production of knees weakens the growth and accumulation of plant biomass (Canarini *et al.*, 2019).

Thus, the allelopathic activity of a plant is determined by such main properties as the formation, ability to accumulate and release into the environment knees, and allelopathic tolerance – resistance to secretions of

other plants or one's own (Storozhyk, 2019). The method of labeled atoms confirmed the presence of root secretions (Laurent Simon *et al.*, 2019; Ćeranić *et al.*, 2020; Vivanco *et al.*, 2012).

But it should be taken into account that there are methodological difficulties in determining the allelopathic properties of a plant. Also, allelopathy is noted for its instability in natural conditions (Cheng *et al.*, 2015).

Allelopathy is a natural phenomenon that has a significant impact on the functioning of biocenoses. The phenomenon of allelopathy includes various types of chemical interactions between organisms and is carried out by the formation and release of metabolites with allelopathic activity into the environment (Polyak *et al.*, 2019; Aci *et al.*, 2022; Hussain *et al.*, 2021). The term "allelopathy" is most often used to characterize the relationships between plants, but it is also widely used to describe the relationships between microorganisms and between plants and microorganisms (Kucheryavay, 2020; Zorikova *et al.*, 2017).

By chemical composition, allelopathic substances vary from simple carbohydrates to complex polycyclic aromatic phenols, terpenes, flavonoids, polyacetylenes, fatty acids. Allelopathic substances play an important role in plant defense (Reigosa *et al.*, 2010; Khalid, 2002).

Allelopathy is associated with competition for resources and largely depends on many factors such as soil structure, moisture, temperature, plant parts, plant age, availability of nutrients, concentration of allelic components and their stability (Sira, 2021; Amb *et al.*, 2016).

MATERIALS AND METHODS

Research on model experiments of the Marquis medicinal hyssop, which is promising for cultivation in the conditions of the southern steppe of Ukraine, was conducted with plants of the first, second and third years of vegetation during 2019-2021 on the basis of the laboratories of the Mykolaiv National Agrarian University. The plant material, i.e. the aerial part of the medicinal hyssop, was selected in the phase of full flowering of plants, because this phase is the most indicative of the manifestation of allelopathic activity. Allelopathic activity in water-soluble secretions of hyssop plants (*Hyssopus officinalis* L.) was determined according to the generally accepted method of A.M. Grodzinsky (1991) using biological tests. Watercress seedlings (*Lepidium sativum* L.) of the same size and from the same crop were selected as the test crop. The choice was due to the fact that watercress has a high seed germination, so it is more sensitive to external factors. The next day after planting, the germination of the seeds of the test crop was observed. The research was conducted in laboratory conditions at a temperature of +23°C and a relative humidity of 60-70%. Water extracts of various concentrations from the leaves, stems and flowers of the plant in the flowering phase were used to

detect the allelopathic properties of hyssop. The main place of manifestation of allelopathic relationships is the soil (Scavo *et al.*, 2019). Therefore, the root layer of the soil of medicinal hyssop was also studied. Soil samples for research were taken in the rhizosphere zone of hyssop plants, in clear weather. To obtain aqueous extracts, fresh plant material was crushed and infused in distilled water for one day. After infusion, the aqueous extract was filtered. Aqueous soil extract with a concentration of 1:10, 1:50, and 1:100 was used for the research. In the experiment, aqueous extracts from leaves, stems and flowers of medicinal hyssop were used in concentrations of 1:10, 1:50, and 1:100.

Watercress seeds were germinated on filter paper moistened with medicinal hyssop extracts in labeled Petri dishes in a dark thermostat at a temperature of 25°C in the amount of 100 pieces for each variant of the experiment, which were carried out in 3 repetitions. Control test objects were germinated by moistening with distilled water. The distance between adjacent seeds was approximately the same.

To determine the effect of water extracts of different concentrations on the test object, the length of *Lepidium sativum* L. roots was measured with a ruler to the nearest 1 mm. The increase was calculated as a percentage of the increase in the length of the roots of the control seedlings, which were placed in distilled water, using the methods of mathematical statistics (Rozhkov *et al.*, 2016).

To improve the analysis of allelopathic data, the RI, response index, or inhibition index was determined, which characterizes the vector and relative magnitude of the effect of allelopathic substances on the growth rate of watercress seedlings, according to Williamson as follows:

- if $B > K$, then $RI = 1 - (K/B)$
- if $B < K$, then $RI = (B/K) - 1$

At the same time, B is the morphometric index of the embryo in the experiment, K is the morphometric index of the embryo in the control.

The stimulatory effect occurs when the value of $RI > 0$, the inhibitory effect occurs when the value of $RI < 0$ (Williamson & Richardson, 1988).

RESULTS AND DISCUSSION

In the process of growth and development, plants accumulate genes that are released into the environment, forming an allelopathic sphere around them. The allelopathic activity of a plant occurs within its surrounding space – the phytogenic field. Allelochemical substances can be primary and secondary metabolites of plants, produced during their development and dependent on environmental conditions. There is an allelopathic interaction in plant communities (Dragoeva *et al.*, 2010; Husain *et al.*, 2021). But allelopathic activity depends both on the soil and climatic conditions of cultivation, and on the characteristics of the plant species (Grodzinsky, 1991).

According to N. Zaimenko *et al.* (2021), under the influence of microflora and microfauna in the soil, there is a transformation of allelopathically active substances, which in turn change the composition and number of soil microbiota. Under the influence of allelopathic substances, physical and chemical processes in the soil change, which affect the growth and development of plants. Thus, each plant receives chemical signals that regulate its growth and development. M. Reigosa *et al.* (2010) believe that allelopathy in agroecosystems leads to a wide range of interactions between crops. As a rule, such an interaction leads to the problem of soil disease or can cause autotoxicity, which will adversely affect the yield of the agricultural crop. But scientists also do not rule out that allelochemical substances can be used in practice, for example, to fight against weeds and pests. The study determined the activity of knees in the allelopathic field of hyssop of the medicinal grade Marquis, which makes it possible to analyze and determine its effect on the soil during unchanged cultivation and use of this plant as a precursor.

The obtained results prove that the age of medicinal hyssop affects the allelopathic activity of the plant in relation to the germination of watercress seeds. Both the stimulatory and inhibitory effects of aqueous hyssop solutions on the germination of the seeds of the test object were revealed.

During 2019-2021, there was an accumulation of genes in the rhizosphere of hyssop of the medicinal variety Marquis, which have both a stimulating and an inhibiting effect on the germination of watercress seeds (Table 1).

Table 1. The effect of root secretions of hyssop plants of different growing seasons in the flowering phase on the growth of watercress roots (1:100 dilution)

Vegetation year	M±m	Cv, %	Filtrate dilution	
			Allelopathic activity, %	Allelopathic activity index (RI)
Control	3.36±0.13	39.42	-	-
First	5.37±0.15	27.33	+59.82	+0.38
Second	5.26±0.16	30.45	+56.55	+0.36
Third	2.99±0.11	37.45	-11.02	-0.11

Source: author's development

According to Table 1, it can be seen that in the plants of the first year of vegetation, the allelopathic activity of the soil in the rhizosphere zone of medicinal hyssop is more active in the flowering phase, which was expressed in the stimulating development of the test object and amounted to 59.82% relative to the control, in the second year – 56.55% in accordance. The experiment proves that already in the second year of growing medicinal hyssop, it is possible to observe a decrease in the positive effect of allelopathically active soil substances on the growth of watercress roots by 3.3%. This is also confirmed by the value of the allelopathic activity index (Fig. 1).

Figure 1 shows that the index of allelopathic activity of the soil, which expresses the inhibitory effect

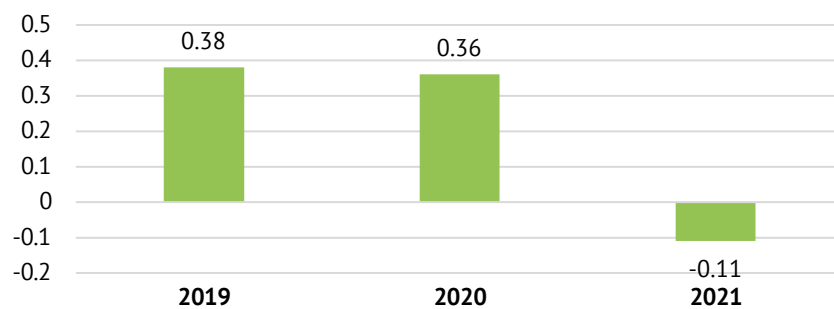


Figure 1. Changes in the allelopathic activity index of the root-containing soil layer over the years of research

Source: author's development

According to the results of the scientists' research, it was found that the effect of knees on the development of the test object was both inhibitory and stimulating. In addition, it was found out that the soil in the rhizosphere zone of the plant and the zone between the rows accumulates knees throughout the growing season, but the highest content of knees of inhibitory action is observed in the flowering phase.

Medicinal hyssop is absent in the natural range of Southern Ukraine, so the obtained results of the experiment can be explained by the fact that it is an introduced culture for the southern regions (Kucheryavii, 2020; Reigosa et al., 2010).

In addition, plants of the *Lamiaceae* family, which includes medicinal hyssop, differ in their ability to exhibit allelopathic activity. For example, the results of the study of water extracts of the leaves and rhizospheric soil of *Marubium vulgare* L. or *Common Shandra* showed that they significantly ($p < 0.05$) inhibited the germination and growth of *Sinapis arvensis* (weed) and *Lactuca sativa* (cultivated) seedlings, and their allelopathic activity was dependent on the concentration - with an increase in the concentration of the extracts, the allelopathic effects were more pronounced. Allelopathic activity may be due to the presence of allelochemical compounds, including tannins, phenolic acids, and flavonoids, which prevented seed germination

in the rhizosphere zone of medicinal hyssop, increases depending on the age of the plants. This indicator was the highest when using medicinal hyssop plants of the third year of life. An inhibition of the growth of the roots of the test object by 11.02% was observed, which was also confirmed by the index of allelopathic activity, which was a negative number (-0.11). That is, in the third year of growing hyssop of the medicinal variety Marquis, water infusion of the soil of the rhizosphere zone of this plant containing knees, inhibits the growth and development of watercress roots.

This is also confirmed by the results obtained by S.I. Sorokinoi & N.I. Hnatyuk (2017) in studies of the dynamics of allelopathic activity of water-soluble secretions from the soil and aerial parts of medicinal hyssop plants.

or caused seed death through chromosomal aberrations in dividing cells. In addition, terpenoids and phenolic substances are inhibitory substances in allelopathy. Phenolic compounds are rapidly adsorbed and/or oxidized by the soil and are most strongly correlated with inhibition of plant growth. In addition, it has been reported that toxicity may result from synergistic effects rather than either alone. In fact, allelochemical compounds that determine the success of seed germination can inhibit germination by altering membrane permeability, respiration, plant water balance, enzyme activity, etc. (Dallali et al., 2017).

It is known that the essential oil of hyssop is mainly accumulated in the leaves and flowers and not a large amount in the stems of the plant (Wolski et al., 2006). Hyssop essential oil contains secondary metabolites, the release of which can affect the growth and development of other plants (Zawiġlak, 2013). Therefore, the study analyzed the effect of aqueous extracts of different concentrations from the above-ground organs of hyssop of the medicinal grade Marquis on the selected test object.

The results of the analysis of the root length of the test object and the allelopathic activity of the water-soluble biologically active substances of the aerial organs of *Hyssopus officinalis* L. of the Marquis variety are shown in Tables 2 and 3.

Table 2. The root length of the test object depending on the age of the plants and the concentration of the solution, mm

Part of plant	Vegetation year	Concentration of the solution		
		1:100	1:50	1:10
Control	H ₂ O	3.36±0.13	3.36±0.13	3.36±0.13
	First	3.64±0.17	3.40±0.17	3.49±0.16
Leaf	Second	4.44±0.19	4.54±0.17	4.95±0.14
	Third	2.60±0.07	2.51±0.08	1.02±0.05
Stem	First	3.84±0.18	3.79±0.15	3.90±0.18
	Second	4.34±0.15	4.83±0.16	4.46±0.15
Flower	Third	2.73±0.09	2.59±0.09	1.46±0.07
	First	4.04±0.14	4.42±0.16	4.15±0.15
Leaf +stem	Second	4.73±0.16	4.56±0.16	5.36±0.15
	Third	2.96±0.11	2.81±0.10	1.85±0.06
Leaf +stem	First	4.07±0.15	4.37±0.13	3.45±0.13
	Second	4.73±0.18	4.83±0.19	3.80±0.12
	Third	1.39±0.05	1.12±0.05	0.68±0.03

Source: author's development

An aqueous solution of hyssop flowers of the first year of vegetation with a concentration of 1:50 accelerated the growth of the root system of the test object by 1.31 times compared to the control. Aqueous leaf-stem mixture reduced linear growth of watercress roots compared to aqueous flower solution. During the study and analysis of the allelopathic effect of the age of plants and their aerial organs on the growth of watercress roots, it was established that the aqueous solution of hyssop flowers of the second year of vegetation at a concentration of 1:10 had the greatest effect. Active growth

of the roots of the test object took place. On average, the length of watercress roots was 5.36 mm, which is 2.0 mm more than the control variant. When the concentration of the aqueous solution of hyssop flowers was reduced to 1:50-1:100, the length of the roots of the test object decreased to 4.56-4.73 mm, respectively.

Aqueous solutions of all variants of plant concentrations in the third year of vegetation slowed down the linear growth of watercress roots and inhibited their growth. This variant showed an inhibitory effect in all years of research (Table 3).

Table 3. Allelopathic activity of medicinal hyssop plant organs depending on age and solution concentration, %

Part of plant	Vegetation year	Concentration of the solution		
		1:100	1:50	1:10
Control	H ₂ O	-	-	-
	First	8.33	1.19	3.87
Leaf	Second	32.14	35.12	47.32
	Third	-22.62	-25.3	-69.64
Stem	First	14.29	12.8	16.07
	Second	29.17	43.85	32.74
Flower	Third	-18.75	-22.92	-56.55
	First	20.25	31.55	23.51
Leaf +stem	Second	40.77	35.71	59.52
	Third	-11.9	-16.37	-44.9
Leaf +stem	First	21.13	30.06	2.68
	Second	40.77	43.75	13.1
	Third	-58.63	-66.67	-79.76

Source: author's development

Aqueous solution of flowers of plants of the first year of vegetation at a concentration of 1:10-1:50 showed the highest allelopathic activity – 23.51-31.55%, respectively. When the concentration of the solution was reduced to 1:100, the stimulating effect on the linear growth of watercress roots also decreased.

Aqueous solutions from all above-ground organs of plants of the second year of vegetation had a varying but positive effect on allelopathic activity. It was found to be the lowest in an aqueous solution of a mixture of leaves and stems at a concentration of 1:10-3.1%, and the highest – 59.52% when using an aqueous solution of flowers at a concentration of 1:50.

It is characteristic to note that when using flowers in a concentration of 1:100 and 1:50, a positive effect is noted, but the allelopathic activity of plants of the third year of vegetation is significantly inferior to plants of the first and, especially, of the second year of vegetation.

This is confirmed by the experiments of A.P. Dragoeva *et al.* (2010), in which aqueous infusions of hyssop show an allelopathic effect on the early growth stages of *T. aestivum* and *C. sativus*. The effect of inhibition of root growth was stronger in *T. aestivum* than in *C. sativus*, which confirms the presence of secondary metabolites that exhibit allelopathic effects in leaves, stems, and flowers of hyssop plants. L.A. Kotyuk & D.B. Rakhmetov (2014), investigating the allelopathic effect of plant residues of 13 introduced species of the family *Lamiaceae* Lindl., including hyssop, found that aqueous extracts from *H. officinalis* plants slowed down seed germination in *Z. mays* and caused the highest phytotoxic effect against *T. aestivum*, i.e. inhibited growth processes.

The allelopathic potential of lavender plants, which also belong to the *Lamiaceae* family, as well as medicinal hyssop, were investigated. In order to determine the allelopathic potential of lavender plants, the seeds of the studied plants: corn, beans, wheat and lentils were placed in aqueous extracts of seeds and leaves in concentrations of 5%, 10%, and 15%. The percentage of germination, the length of roots and plumes, the total antioxidant activity and the amount of hormones in the seeds were monitored. Depending on the increasing concentrations of lavender extracts used in the tests, the inhibitory and phytotoxic effect on seed germination and growth of the tested plants increased (Ayşe Kuru, 2016).

Scientists of the Ferdowsi University of Mashhad Crop Research Center and Mashhad Botanical Garden (S. Sadeqifard *et al.*, 2022) collected different parts of plants – flowers, stems, leaves, roots (123 samples) belonging to 31 families of medicinal plants. The influence of the studied plants on the basal and hypocotyl growth of lettuce seeds, comparison with the control in different plant families was studied separately. In each plant family, the comparison was made at two levels of probability ($p \leq 0.05$; $p \leq 0.01$). A high percentage of inhibition (83-95%) of the growth and development of the roots of test subjects (*Lepidium sativum* L) was observed in extracts from lavender flowers of the common *Lamiaceae* family. The results of the calculation of the index of allelopathic activity of above-ground organs of Marquis hyssop plants show that (RI) had the option of using flower infusion at a concentration of 1:50 in plants of the second year of vegetation (2020) relative to the control (Fig. 2).

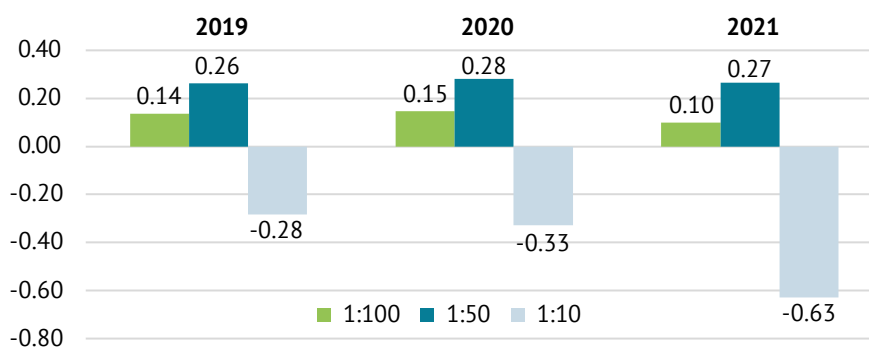


Figure 2. Index of allelopathic activity of aerial organs of Marquis hyssop plants during the years of research (2019-2021)

Source: author's development

As we can see on average over the years of research, the index of allelopathic activity of hyssop changes depending on the age of the plants and the concentration of the aqueous solution of biologically active substances of above-ground organs (Fig. 2). Thus, the highest index of allelopathic activity that caused a stimulating effect was noted at a concentration of 1:50 of the solution of flowers of plants of the

second year of vegetation. The inhibitory effect was observed at a solution concentration of 1:10.

These research data are confirmed by the results of other experiments regarding the allelopathic activity of medicinal hyssop. Thus, B. Jop *et al.* (2021) proved that hyssop oil is saturated with monoterpene ketones, such as isopinocampone – 42.1% and pinocampone – 10.6%. Hyssop oil inhibits the germination of wheat

and mustard, depending on the concentration. Visible suppression of wheat seedlings occurs already at a dose of oil of 1.0 g/l-1, and mustard – 2.8 g/l-1.

V. Pandey *et al.* (2014) obtained essential oil of hyssop from different parts of the plant: leaves, flowers and stems by hydrodistillation. It was found that the main components of the oil were cis-pinocamphon (49.7-57.7%), pinocarvone (5.5-24.9%), β -pinene (5.7-9.3%) and others. The comparative results clearly showed that the oil samples obtained from hyssop leaves and stems were quite similar in terms of cis-pinocamphon and pinocarvone content. However, the oil obtained from the flowers of the plant differed from the oil from the leaves and stems by the presence of a greater amount of pinocarvone. It is known that essential oils are mixtures of simple aliphatic and cyclic terpenoids, mainly mono- and sesquiterpenes, their alcohols and ketones with accompanying derivatives of benzoic acid and phenylpropane. Ketones, which include pinocarvone, deserve special attention. The biological effect of ketones is diverse, but despite their positive properties, it is necessary to note their possible toxic effect (Garna *et al.*, 2016). It can be assumed that the accumulation of cis-pinocamphon and pinocarvone over the years in hyssop stems, leaves and flowers gives allelopathic activity to the obtained solutions of different concentrations from parts of the hyssop plant in the third year of vegetation and from its rhizosphere zone relative to the linear growth of the roots of the test object, which requires further studies of the chemical composition of the aerial part of hyssop and its root-containing soil layer cultivated in the conditions of southern Ukraine.

CONCLUSIONS

Thus, in the years of research (2019-2021), it was found that the linear growth of the roots of the test object, which was used as a watercress, was allelopathically affected by aqueous solutions from all parts of hyssop plants of the Marquis variety. Analyzing the data of the experiment, it can be concluded that aqueous solutions of the root-containing layer of the soil and above-ground organs of hyssop plants of the first and second years of vegetation had a stimulating effect on the growth of the roots of the test object. The obtained result may indicate that there is no significant accumulation of inhibitory substances in the roots of medicinal hyssop plants during the first 2 years of growth and

development. Aqueous solutions of the soil layer of the root system where medicinal hyssop plants grew in the third year of vegetation have an inhibitory effect on the linear growth of watercress roots.

It was established that the variant with the use of hyssop flowers of the second year of vegetation in a concentration of 1:10 has the highest allelopathic activity. It was the largest in the leaf + stem variant at a concentration of the aqueous solution of 1:10. Accumulation of essential oil in hyssop occurs in flowers, leaves and to a lesser extent in stems. Studies confirm that substances with an inhibitory effect gradually begin to be localized in the organs of medicinal hyssop plants, which are able to accumulate essential oil, already in the second year of the crop's vegetation. On average, the index of allelopathic activity of water-soluble biologically active substances of above-ground organs of medicinal hyssop plants of the first and second years of vegetation had a stimulating effect at a solution concentration of 1:50, and an inhibitory effect when using plants of the third year of vegetation with a solution concentration of 1:10. This result confirms that the largest amount of allelochemicals, which can negatively affect the growth and development of other plants, accumulated in the third year of medicinal hyssop cultivation. It should be noted that despite the difference in the allelopathic activity of aqueous extracts from various organs of hyssop plants, the tendency to its growth occurs with each year of its cultivation in monoculture. The experiment proves that perhaps the recommended period of growing a plant in a monoculture is no more than 5 years, because already in the 3rd year of cultivation, hyssop shows a phytotoxic effect, but further research is needed for a more accurate result.

The results of the study of the allelopathic effect of hyssop plants of the Marquis variety on the growth of watercress roots showed that the assessment of their allelopathic potential is a promising direction for more effective practical use of these plants.

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CONFLICT OF INTEREST

The authors declare that the study was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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Алелопатична активність рослин *Hyssopus officinalis* L.

Євгенія Сергіївна Ткачова

Аспірант

Миколаївський національний аграрний університет

54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна

<https://orcid.org/0000-0002-4265-2934>

Михайло Іванович Федорчук

Доктор сільськогосподарських наук, професор

Миколаївський національний аграрний університет

54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна

<https://orcid.org/0000-0001-7028-0915>

Олег Анатолійович Коваленко

Доктор сільськогосподарських наук, доцент

Миколаївський національний аграрний університет

54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна

<https://orcid.org/0000-0002-2724-3614>

Анотація. Необхідність у фітомеліорації спонукає на введення у культуру рослин, які не тільки будуть мати декілька напрямків використання отриманої сировини, але й сприяти оздоровленню ґрунтів та бути добрим попередником для подальшого успішного вирощування наступних за ними сільськогосподарських культур. Відомо, що ефіроолійні культури активізують розвиток корисної мікробіоти та запобігають ґрунтовтомі. В статті наведено результати досліджень впливу на алелопатичну активність частин рослин гісопу лікарського (*Hyssopus officinalis* L.) сорту Маркіз з врахуванням вікових особливостей в умовах змін клімату півдня України. Метою роботи було виявити вплив алелопатичної активності водних екстрактів листків, стебел та квіток гісопу, ґрунту у зоні ризосфери та віку рослин на ріст коренів крес-салату. У процесі дослідження використовувалися емпіричні методи, зокрема, експеримент. В результаті проведених досліджень з культурою гісопу лікарського першого, другого та третього років вегетації на базі дослідного поля Миколаївського національного аграрного університету впродовж 2019-2021 років виявлено оптимальну концентрацію водних екстрактів культури зі стимулюючим ефектом. Показана залежність алелопатичної активності водорозчинних біологічно активних речовин надземних органів рослин гісопу лікарського і виявлено концентрацію розчину, яка визиває інгібуючий ефект. Так, найбільш висока алелопатична активність відмічалась на варіанті з використанням квіток гісопу лікарського рослин другого року вегетації в концентрації 1:10. Водні розчини шару ґрунту кореневої системи, де зростали рослини гісопу лікарського третього року вегетації, мають інгібуючий ефект на лінійний приріст коренів крес-салату. Найбільшою вона була у варіанті листок + стебло при концентрації водного розчину 1:10. Це говорить про те, що необхідно використовувати культуру гісопу лікарського в сівозміні обережно враховуючи її особливості онтогенезу. Отримані результати матимуть практичне застосування у підприємствах різних форм власності, які будуть мати бажання вирощувати культуру гісопу лікарського та використовувати його в структурі сівозміни

Ключові слова: гісоп лікарський; крес-салат; водні екстракти; концентрація розчину; алелопатія; стимулювання; інгібуючий ефект

Realization of the adaptive yield potential of the assortment of winter wheat in the Steppe zone under different growing conditions

Valerii Bazaliy

Full Doctor in Agrisciences, Professor
Kherson State Agrarian and Economic University
73006, 23 Stretenska Str., Kherson, Ukraine
<https://orcid.org/0000-0002-0581-7242>

Yevhenii Domaratskiy*

Full Doctor in Agrisciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0003-3912-1611>

Vitalii Pichura

Full Doctor in Agrisciences, Professor
Kherson State Agrarian and Economic University
73006, 23 Stretenska Str., Kherson, Ukraine
<https://orcid.org/0000-0002-0358-1889>

Olga Kozlova

PhD in Agrisciences, Associate Professor
Kherson State Agrarian and Economic University
73006, 23 Stretenska Str., Kherson, Ukraine
<https://orcid.org/0000-0002-9062-5981>

Anna Jarosiewicz

Doctor Habilitatus in Engineering, Professor
Pomeranian Academy
76-200, 22a Arciszewskiego Str., Słupsk, Republic of Poland
<https://orcid.org/0000-0002-7871-5968>

Abstract. Climate changes in recent decades have increased the degree of risks in crop production. The consequence of such processes is an increase in the temperature regime against the background of a significant moisture deficit in critical periods of plant growth and development. Accordingly, research aimed at establishing the adaptability of plants to such climatic changes is relevant and timely. The purpose of the research is to establish the principles of implementing the adaptive potential of new varieties of winter wheat of different types of development in the Steppe zone under the conditions of climate change. Records and their assessment were carried out according to the generally accepted methods of Ukrainian variety testing with mandatory statistical and dispersion analysis of the results of field experiments. The establishment of indicators of the stability of quantitative traits and plasticity was carried out using the Eberhard-Russell algorithm, which is based on a regression analysis of the dependence of the grain yield of winter wheat of different varieties on the environmental index. The results of the research

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*Corresponding author

established that universal type varieties with a stem length of 85-90 cm are the most suitable for irrigated and non-irrigated conditions. Regression analysis of the data on the plasticity and stability of the elements of the crop structure in different varieties of winter wheat proved that their variability directly depends on the genotype and ecological gradients. According to the results of the assessment of the adaptive potential, it was established that the parameters of plasticity ($b_i=0.804-0.989$) and yield (7.33-7.63 t/ha exceed the standard by 10.4-14.9%) showed winter wheat varieties of the universal type - Askaniyska, Askaniyska Bereginya, Perlyna, Znahidka Odeska, while Khersonska 99, Kirena, Yaroslavna, Kuyalnyk, etc. were characterized by an intensive type of development. Varieties of the universal type were more plastic and stable in the formation of ear productivity, compared to short and tall biotypes. The scientific significance of the research lies in the substantiation of scientific principles, practical recommendations for improving varietal agricultural technology of winter wheat, which had different genetic and ecological origins, in irrigated and non-irrigated conditions of the Steppe zone

Keywords: climate changes; variety; stability; plasticity; morphobiotype; productivity

INTRODUCTION

The last three decades have been characterized by an increase in the average annual temperature in Ukraine by 1.2°C (Pichura *et al.*, 2021). According to weather observations since the 1890s, the period from the end of the 20th century to today is considered the warmest in Ukraine in the entire history of monitoring (Pichura *et al.*, 2021). Such climatic transformations of recent years have increased the degree of risks related to the technological processes of crop production: establishing optimal sowing dates and sowing rates, growing varieties and hybrids of grain crops of different degrees of intensity and maturity groups, optimizing the application of mineral fertilizers, etc. They are caused by an increase in the temperature regime of the environment, the unevenness of precipitation or its complete absence in critical phases of the development of field crops (Pichura *et al.*, 2021). The rate of change in average, as well as maximum and minimum temperatures for the period 1961-2013 was 0.3°C every ten years (Didovets *et al.*, 2020). The last two decades have been characterized by a fairly dangerous trend from the point of view of the impact on crop production - the spread of heat waves. Their appearance leads to the formation of extremely difficult conditions for the vegetation of agricultural plants not only in the whole world, but also in the Steppe zone of Ukraine in particular. According to NASA, in the summer of 2021, a heat wave with a record temperature of +49°C was recorded in the city of Lytton in Canada. In the summer of 2022, large-scale heat waves were observed throughout the European continent, as a result of which massive forest fires were recorded in Central, Western and Southern Europe. All this led to considerable human casualties and the loss of biodiversity in large areas. The intensification of the field of crop production due to modern regional and global climate changes with their negative consequences requires not only an increase in the full productivity of the assortment of grain crops, but also their ecological stability of agrocenoses. Selection and varietal agrotechnics of agricultural crops are of primary importance in solving these problems. According to the results of research by Ukrainian and international scientists, the

increase in the yield of winter wheat due to the introduction of certain technological innovations and the improvement of agricultural cultivation techniques is up to 60%, and due to the fate of modern high-yielding varieties of intensive direction with appropriate varietal agricultural techniques – up to 40% (Domaratskiy, 2021; Williamson *et al.*, 2022). The absence of high-intensity varieties of winter wheat with an increased positive reaction to the nutrient regime of the soil would nullify the use of modern approaches in the intensification of crop production, namely: the introduction of increased doses and norms of mineral fertilizers, the use of new stimulators and plant growth regulators, etc. Conducting high-quality seed production and variety renewal are the most profitable and environmentally safe factors for increasing the gross harvest of winter wheat grain (Domaratskiy, 2021; Williamson *et al.*, 2022).

The yield indicator implements the effect of a set of factors on the plant organism during its growing season, and the yield is the result of a compromise between productivity and resistance to biotic and abiotic factors of the environment (Herrera *et al.*, 2021). For maximum harvest indicators, the characteristics of productivity and stability must be selected and adjusted in such a way that in each individual case they best correspond to the conditions of the external environment (Domaratskiy *et al.*, 2020; Panfilova *et al.*, 2021).

Increasing the yield of winter wheat depends, first of all, on the connection between individual components of productivity and establishing the main patterns of crop formation (Domaratskiy *et al.*, 2019; Panfilova *et al.*, 2020). Many scientists (Sewenet *et al.*, 2021; Ge *et al.*, 2022) indicate the important role of the linear relationship between the variability of traits and environmental conditions, this opens up new opportunities for studying quantitative traits, and also allows predicting the adaptive reactions of varieties during cultivation them in different conditions.

The purpose of the article is to establish and highlight the principles of implementing the adaptive potential of new varieties of typical winter and alternative wheat in the Steppe zone of Ukraine under the conditions of climate change.

MATERIALS AND METHODS

The research program included a comprehensive study of new varieties of the universal type under different growing conditions (irrigated, non-irrigated, sowing dates and rates). The researched varieties of soft winter wheat (Askaniyska Bereginya, Khersonska bezosta, Perlyna, Askaniyska, Zahidna Odeska) had different genetic and ecological origins, and were also included in the State Register of plant varieties suitable for distribution

in Ukraine. Field experiments were carried out in 2017-2021 in the conditions of the experimental field of the Kherson State Agrarian and Economic University (GPS: 46.743447, 32.481064, Kherson, Ukraine – point 1) and the Askaniysk DSDS of the National Academy of Sciences of the National Academy of Sciences (GPS: 46.55209, 33.82216, 40 Rokiv Peremohy Str., 16, Tavrychanka village, Kherson region, Ukraine - point 2), which are part of the Southern Steppe of Ukraine (Fig. 1).

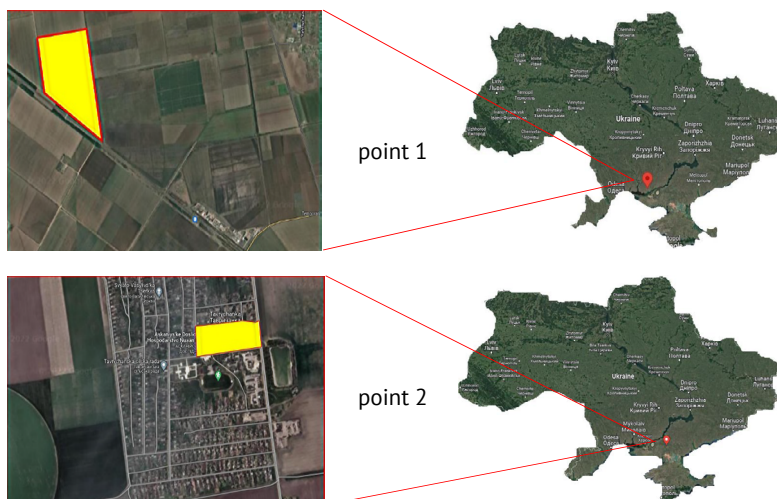


Figure 1. Points of field research

Notes: Point 1 – GPS: 46.743447, 32.481064 Kherson, Ukraine; Point 2 – GPS: 46.55209, 33.82216 40 Rokiv Peremohy Str., 16, Tavrychanka village, Kherson region, Ukraine

Assessment of winter wheat assortment, necessary records and observations were carried out in accordance with generally accepted methods of state variety testing. Statistical and dispersion analyzes were performed according to methodological instructions (Dospikhov, 1979; Lytun *et al.*, 1996).

The agricultural technique of growing winter wheat in the experiment was generally accepted for the south of Ukraine, which provides for the maximum accumulation and preservation of moisture in the seed layer of the soil at the time of sowing. This approach makes it possible to sow winter wheat every year at the end of the optimal period (in the last decade of September), even in non-irrigated conditions. The precursor for winter wheat in the experiment was black steam, both under irrigated conditions and without irrigation. The researched varieties were sown at the rate of 3.5 million similar seeds per hectare. Weeding of crops was controlled by spring application of a herbicide with the active substance tribenuron-methyl in the interphase period at the end of tillering - exit into the tube. Fungicidal protection against pathogenic microflora involved only the treatment of seed material before sowing with preparations containing the active ingredient tebuconazole 750 g/kg. To establish indicators of plasticity of varieties and stability of quantitative traits, the S.A. Eberhart & W.A. Russell (1966) algorithm was used. This algorithm is based on a regression analysis of the dependence of the grain yield of varieties on the environmental index.

RESULTS AND DISCUSSION

The productivity of the ear had a well-expressed genetic specificity in the formation of the crop as a whole according to the experiment. Over the years of research under different growing conditions, the highest mass of grain from an ear of corn was formed by the varieties Kirena, Khersonska 99, Askaniyska, Solomiya, Askaniyska Bereginya. These varieties were characterized by high ear productivity, mainly due to the increased intensity of grain filling, compared to other varieties of winter wheat. Variability of growing conditions did not have a significant impact on ear productivity indicators. This indicator was genetically determined and reached a high level. The highest mass of grain from the ear was formed by the studied varieties in the variant of sparse sowing during the late sowing period. From the point of view of yield formation under such conditions, the lower productive stalk was compensated by the higher productivity of the ear.

The studied varieties of winter wheat had their own specificity in terms of compensatory features in crop formation. Thus, winter wheat varieties Viktoriya Odeska, Znahidka Odeska, Askaniyska, Askaniyska Bereginya formed a highly productive ear (1.60-2.06 g) almost regardless of the density of the plants. As for Odeska semi-dwarf, Istok, Khersonska 99 and Kuyalnyk varieties, these varieties had a tendency to decrease the ear productivity index due to the increase in sowing rates. The decrease in the stem density in these varieties had a significant effect on the increase in the weight of the grain from the ear.

As for the number of grains in the ear of the studied varieties, this indicator increased in the late sowing period, similar to the overall productivity of the ear. Some variety types were distinguished by different reactions to the variability of growing conditions. Analyzing the

results of the experiment on the parameters of plasticity and stability of the elements of the crop structure in winter wheat varieties under different growing conditions, it was established that their variability was dependent on the genotype and environmental gradients (Table 1).

Table 1. Character of manifestation of structural elements in the ear of winter wheat varieties under different growing conditions

Sort	$\bar{x} \pm S_x$	Regression coefficient, b_i	Dispersion, S^2d
Askaniyska Berehynia	1.87±0.03	0.612	0.006
Khersonska bezosta	1.58±0.03	1.614	0.034
Perlyna	1.78±0.02	0.836	0.007
Askaniyska	1.74±0.02	0.759	0.005
Zakhidna Odeska	1.56±0.03	0.760	0.026
The number of grains in an ear, pcs.			
Askaniyska Berehynia	43.7±0.65	0.501	3.00
Khersonska bezosta	41.81±0.85	1.824	12.16
Perlyna	46.41±0.53	0.623	5.56
Askaniyska	48.77±0.65	0.814	4.84
Zakhidna Odeska	42.10±0.31	1.018	6.14
Length of ear, cm			
Askaniyska Berehynia	10.1±0.06	0.466	0.08
Khersonska bezosta	10.0±0.10	2.342	0.46
Perlyna	10.2±0.06	0.166	0.09
Askaniyska	10.7±0.07	0.648	0.11
Zakhidna Odeska	9.4±0.06	0.843	0.13

Source: developed by authors

From the results of the research, it was established that among the genotypes that were studied in the field experiment based on the indicator of grain weight from the ear, only one variety (Khersonska bezosta) was characterized by a significant reaction to the change in growing conditions ($b_1=1.614$). As for other new universal varieties (Askaniyska Berehynia, Askaniyska, Perlyna), they had a sufficiently high level of plasticity ($b_1=0.612-0.836$). Under such conditions, these varieties can also be considered stable in the formation of ear productivity ($S^2d=0.005-0.006$).

Similar results were also found in the formation of the number of grains in an ear. Thus, winter wheat varieties Askaniyska Berehynia, Askaniyska, Perlyna were characterized by higher indicators of plasticity ($b_i=0.501-0.814$) and stability ($S^2d=3.00-5.56$) in the manifestation of this characteristic of productivity under different growing conditions (Table 1). The variety Znahidka Odeska needs special attention, which is characterized by a significantly high level of reaction to the variability of growing conditions ($b_i=1.018$) and showed a high level of stability ($S^2d=6.14$) according to this characteristic, while the variety Khersonska bezosta with the greatest reaction to improvement (deterioration) growing conditions ($b_i=1.824$) was significantly unstable in the formation of the number of grains in the ear ($S^2d=12.16$).

The structural analysis of productivity elements proved that the number of grains and the mass of grain from the ear increased in all varieties at a lower plant density and later sowing dates.

Conducting a dispersion analysis of the mentioned characteristics makes it possible to state that they are largely modified by environmental conditions (46.5-53.2%). The rate of sowing had practically no influence on the variation of these characteristics (1.4-4.2%), the timing of sowing, on the contrary, was characterized by a significant influence (9.5-20.8%). The mass of grain from an ear is due to genotypic variability to a greater extent (25.6%) than the number of grains in an ear (14.1%).

Carrying out dispersion analysis of other important subcomponents of ear productivity (ear length, number of ears) made it possible to establish their significant dependence on the genetic properties of one or another variety and environmental gradients.

The indicator of spike length undergoes more significant modifications under the influence of environmental conditions (49.9%) with a slight manifestation of genetic variability (17.1%) compared to the number of spikelets in a spike. The last indicator had an average variability (28.3%) for a sufficiently high genotypic variability (55.6%).

The increase in the absolute expression of the length of the ear and the number of ears in it occurred against the background of the increase in the response of winter wheat varieties to a decrease in the density of sowing, which was formed under the influence of different norms and terms of sowing the crop.

The processes of formation of winter wheat varieties with a productive stem largely depend on the growing conditions and the indicator of the hydrothermal coefficient. A decrease in the number of productive

stems in plants per unit area caused by a decrease in sowing rates, a late sowing period and unfavorable weather conditions of the year is a general pattern. But the modification of this feature was largely determined by the architecture of the varieties.

New universal varieties (stem length 85-90 cm) Askaniyska, Askaniyska Bereginia, Perlyna formed significantly more productive stems compared to medium-growing varieties Khersonska bezosta, Dryada, Kirena, which was the result of their formation of higher productivity in all periods and sowing rates. This is primarily due to their biological morphological features, as well as the reaction of a certain variety to irrigation conditions (Bazaliy *et al.*, 2020).

With a late sowing period, the advantage of these varieties over medium-sized ones is even more obvious. Thus, in this case, due to the additional spring bushing of plants and the synchronicity of earing, the productivity of universal varieties decreased to a lesser extent than that of medium-sized varieties.

With an increase in the sowing rate, a general tendency to increase the productivity of varieties was observed, especially for the late sowing period. For plants of universal type varieties, this is explained by the synchronicity of stem formation and occurs as a result of an increase in spike-bearing shoots. On average, in different years of the tests, the largest yield was formed under optimal test conditions. The evaluation of varieties at different stem densities showed that a significant increase in productivity was observed in them with its increase.

The results of the research established that only during the late sowing period, the studied varieties had a positive reaction to the increase in the sowing rate, during other periods its increase did not have a reliable effect on the yield change. This dependence is especially typical for tall and medium-growing varieties of winter wheat (Dniprovsk 847, Yaroslavna, Khersonska bezosta and Kirena). These varieties, in most cases, had a mathematically proven decrease in productivity with an increase in sowing rates up to 7 million grains/ha (Bazaliy *et al.*, 2020).

The difference between varieties of intensive and semi-intensive type of development is that the former require a higher level of agrobio-conditions, moisture supply, agrotechnical conditions, etc. Deterioration of these conditions and their significant qualitative fluctuation leads to the impossibility of maximum realization of one's productivity potential. Along with this, the high sensitivity of intensive-type varieties to favorable growing conditions often limits their range of distribution in other agro-ecological zones, in which these varieties may not form high productivity indicators. Accordingly, the creation of universal varieties, which are characterized by an increased level of adaptive potential, is the main direction of winter wheat breeding in the conditions of further increasing the productivity of the agrocenosis. All this will guarantee the ecological stability of a specific variety.

Cultivated plants are constantly affected by adverse factors of the external environment, as a result of these processes there is a depression in the productivity of both individual plant organisms and agrocenoses as a whole. The degree of negative reaction of the investigated agrocenoses is characterized by the presence or absence of homeostasis mechanisms. At the same time, the inconsistency of growing conditions with the adaptive potential of plants is directly proportional to the expenditure of assimilation products on protective and compensatory reactions, which in turn must be lost precisely on crop formation. Such processes have a negative impact on the level of crop yield. The integral physiological indicator determines the general resistance of plants to negative environmental factors, it also affects the dispersion in the formation of agrocenosis productivity (Basu *et al.*, 2021).

The indicator of stability (ecological stability) should be understood as the ratio under stressful conditions to yield under optimal conditions. According to this formula for determining stability, we calculated indicators of yield stability in winter wheat varieties (Table 2).

Table 2. Indicators of yield stability in winter wheat varieties under different growing conditions (2017-2021)

Sort	Irrigation	No irrigation	Irrigation/ No irrigation
Khersonska bezosta	0.71	0.79	0.54
Khersonska 99	0.73	0.80	0.52
Khersonska ostista	0.76	0.79	0.54
Cyrene	0.64	0.71	0.49
Yaroslavna	0.57	0.68	0.43
Askaniyska	0.77	0.71	0.49
Askaniyska Berehynia	0.78	0.82	0.57
Perlyna	0.79	0.84	0.59
Odesa 267	0.79	0.83	0.58
Albatross Odesskyi	0.56	0.70	0.51
Kuyalnik	0.57	0.73	0.48
Znahidka Odeska	0.72	0.71	0.48

Source: developed by authors

As can be seen from Table 2, the varieties partially differed in indicators of ecological stability. Despite

the fact that they have different genetic origins and belong to different ecological groups, the stability

of their plants in terms of yield is higher under conditions of non-irrigated agriculture, which provided less intensive vegetation growth than under irrigation conditions, and this, in turn, led to smaller energy costs for the protection of compensatory reactions.

It should also be noted that in conditions of insufficient soil moisture, the varieties of universal type Askaniyska, Askaniyska Bereginya, Perlyna and Znahidka Odeska stood out in terms of absolute productivity and ecological stability. In 2021, Obriy, Odeska 162 varieties suffered from difficult factors of overwintering, mainly from frosts in autumn and early spring. The weather and climate conditions of a specific growing year have

a significant impact on the realization of the potential productivity of winter wheat varieties. This especially applies to risky farming zones in the south of Ukraine, including the Kherson region. The analysis of meteorological data for the last 30 years in the Kherson region shows high variability of the amount of precipitation by year (from 283 to 627 mm) and during the growing season from 59 to 255 mm. (Bazaliy et al., 2021). It is appropriate to consider the variety as a biological system through the prism of its reaction to environmental conditions. The ability of the variety to realize its genetic yield potential depends on this, thanks to the parameters of plasticity and its stability (Table 3).

Table 3. Character of manifestation of yield and plasticity parameters in winter wheat varieties under irrigation conditions (2017-2021)

Sort	Years of study	Height of plants, cm	Yeld of corn		Coefficient of plasticity, b_i
			t/ha	Regarding standard, %	
Khersonska bezosta	5	106	6.64	-	1.120
Khersonska 99	5	108	6.78	102.1	1.018
Khersonska ostista	5	110	6.65	100.0	1.203
Cyrene	5	106	6.84	103.0	1.314
Yaroslavna	5	108	6.64	100.0	0.980
Askaniyska	5	95	7.05	106.2	0.989
Askaniyska Berehynia	4	90	7.23	110.4	0.814
Perlyna	3	96	7.63	114.9	1.018
Odesa 267	5	110	6.24	93.5	1.105
Albatross Odesskyi	5	108	6.04	91.0	1.314
Kuyalnik	5	106	6.79	102.2	1.140
Znahidka Odeska	5	96	7.06	113.2	0.804

Source: developed by authors

According to the results of the assessment of the adaptive potential, it was established that the parameters of plasticity ($b_i=0.804-0.989$) and yield (7.33-7.63 t/ha exceed the standard by 10.4-14.9%) showed winter wheat varieties of the universal type – Askaniyska, Askaniyska Bereginya, Perlyna, Znahidka Odeska, while Khersonska 99, Kirena, Yaroslavna, Kuyalnyk, etc. were characterized by an intensive type of development.

The analysis of breeding lines of winter wheat of different genetic origin revealed that in a year with favorable weather conditions, genotypes with different plant heights have high yields, but the most optimal stem length for realizing productivity is 80-95 cm. This pattern was more evident in unfavorable growing conditions, when it was observed a sharp decrease in plant height. Thus, the study of identical lines under unfavorable growing conditions made it possible to differentiate them into only two groups based on plant height with a maximum stem length of 85-90 cm. These morphobiotypes were characterized by higher productivity of crop structure elements and yield than lines with lower plant height.

The creation of morphobiotypes with a stem length of 85-90 cm by crossing short forms with each other does not cause difficulties, because the output of taller genotypes in hybrid populations occurs in a

mass order. This significantly increases the possibility for targeted individual selection of highly productive morphobiotypes, in addition, such biotypes are usually characterized by a greater expression of adaptive traits compared to stunted forms of identical, genetic origin. The results of experimental studies revealed that under optimal conditions of moisture supply, morphobiotypes of winter wheat were characterized by a high absolute manifestation of grain mass from the main ear and ears of the second order and grain size.

Characteristically, the ratio of these elements of the crop structure during splicing was closer than under conditions without splicing. Thus, the exaggeration of the weight of the grain from the main ear to the weight of the ears of the second order under the conditions of splicing was 27.3-34.4%, and without splicing 32.6-41.0%, according to the weight of 1000 grains, respectively, 10.9-24.5% and 17.1-33.0%. So, in the conditions of splicing, the realization of indicators of the elements of the crop structure is significantly higher than in less favorable conditions (without splicing), therefore, the selection of genotypes resistant to adverse environmental conditions should be carried out only after their high potential productivity has been proven in favorable growing conditions.

An increase in the mass of grain from an ear, as one of the main elements of winter wheat productivity,

depends on the stability of the manifestation of the number of grains and their size. These signs have different variability under the influence of limiting factors of the external environment and from the genetic origin of breeding lines of winter wheat. Morphobiotypes that were selected from the hybrid populations Znahidka Odeska / NS 314, Askaniyska / Victoria Odeska, Khersonska bezosta / Perlyna and others showed the greatest stability of high ear productivity traits. The parameters of productivity traits in these hybrid populations are average in severity but quite stable in manifestation.

Thus, selection lines were selected from these hybrid populations, which in terms of ear productivity exceeded the standard Kherson seedless variety by 10-15%, which was mainly ensured by an increase in the number of grains in the ear and grain size.

The yield of winter wheat largely depends on the duration of the growing season, but in the southern Steppe of Ukraine, in the late-earing morphobiotypes, the process of grain formation occurs in less favorable conditions, compared to early-ripening forms, so they form low ear productivity and thin grain. In early- and mid-ripening hybrid populations, the selection of morphobiotypes with a longer period of grain formation (38-46 days) provided higher productivity under the conditions of splicing.

However, the theoretical justification and effectiveness of the selection of such morphobiotypes under the conditions of growth did not always confirm their high productivity when grown in unfavorable and unirrigated conditions.

Only forms with early earing (the first and second decades of May) and a long period of grain formation in some hybrid populations retained their advantage over other selection lines of different maturity groups, their high productivity was formed mainly due to an increase in grain size and ear productivity.

Late maturing selection lines practically did not confirm their high productivity in extreme growing conditions and without splicing.

Thus, there should be a differentiated approach to highly productive forms with a longer period of grain formation, and their use only after studying in the conditions of varietal agrotechnics. A difficult problem arose before the selection of winter wheat – the creation of varieties of a universal type, but at the moment it is impossible to create such varieties for all ecological zones and production conditions. The authors of the article established that high-yielding varieties are more adapted to favorable growing conditions, and low-yielding varieties and local morphobiotypes are more productive in stressful conditions, this coincides with the opinion of scientists S. Ceccarlli & S. Grando (1991), I. Stoeva & E. Penchev (1999), S. Boroevich (1984). A number of Ukrainian scientists and scientists of the European Union (Chuhrii *et al.*, 2022; Keser *et al.*, 2022) claim that despite the deterioration of growing conditions, selection for high potential productivity is necessary, because the higher the potential capabilities of the variety, the weaker it responds to environmental,

weather and other changes in environmental conditions.

Australian scientists D. Cann *et al.* (2023) also dealt with the problem of realizing the adaptive potential of winter wheat during 2018-2022. In their research, they established that morphobiotypes of winter wheat, which have an accelerated type of development, had a higher level of adaptation to adverse factors of the external environment, compared to ordinary varieties. Such conclusions completely coincide with the opinion of the authors of the article, this type of development is characteristic of winter wheat varieties studied in the field experiment. Australian researchers claim that under such conditions, phenology is already of secondary importance for the process of plant adaptation.

A team of Polish scientists M. Rapacz *et al.* (2022) based on their own six-year field research developed empirical models on the adaptive potential of winter wheat under climate change conditions until 2040, 2060 and 2080 under different scenarios. According to the forecasting results, it was established that the main problem of realizing the adaptive potential of agrocenoses will be cold deacclimatization associated with climate warming, which will be more important for the resistance of plants to adverse environmental factors than the general increase in winter temperatures. This conclusion coincides with the opinion of the team of authors of the article and indicates that resistance to deacclimatization should be included in the programs of creation and breeding of winter wheat varieties as a feature important for winter hardiness of plants in future winters, at least in Central Europe.

A team of US scientists consisting of scientists K. Kothari *et al.* (2019) conducted field studies to assess the impact of climate change on winter wheat production in the state of Texas. As well as evaluate potential strategies for plant adaptation to new conditions. These studies were conducted under irrigation conditions. Scientists see that there are certain expectations regarding the features of irrigation of field crops in the future, namely: the use of total volumes of water for irrigation of winter wheat will decrease due to the increase in the efficiency of water use due to the increased concentration of CO₂ in the atmosphere and the reduction of the duration of the growing season, as a consequence of increasing the temperature regime. These expectations are also confirmed by the results of the authors' observations.

Dryland yields are expected to tend to increase due to improved crop water use efficiency. Among the created virtual predictive models of the US scientists, tested for adaptation to climate change, it was found that an increase in the potential number of grains and the development of a stronger root system were the most desirable traits, as such varieties had higher yields and required less irrigation water than the control variety. Research has established that under the specified conditions, varieties with a longer growing season, whose leaf apparatus remained green longer, turned out to be impractical due to significantly more use of water for irrigation than the control variety. Overall, research results indicated that winter wheat production in the Texas

region could benefit from climate change under milder climate conditions (average growing season temperature $<13^{\circ}\text{C}$). In this case, the realization of the adaptive potential of the researched varieties and the increase in the level of productivity occurred due to the improvement of the architecture of the root system of plants.

To date, the research of the authors of the article is aimed at the creation and study of winter wheat varieties of the universal type, which could be grown both by intensive and conventional technologies. On the other hand, well-known Ukrainian breeders (Orlyuk *et al.*, 2002; Bazaliy *et al.*, 2020) believe that it is far from always possible to obtain a variant - a variety for characteristic specific conditions. Its productivity can vary greatly from year to year in the same farm, when grown according to the same predecessor, using similar agricultural techniques and other identical conditions. It is expected that in the future, our country will face a double problem: food and water security, which are already relevant today and will probably intensify in the future under the influence of further climate changes. The varieties of grain crops that use soil moisture and irrigation water most economically will be especially in demand, accordingly, the coefficient of use of irrigation water when growing such varieties will be in the optimal range. Such an approach can be considered key in solving these problems.

Analyzing the results of our own research and the work of other scientists, it is necessary to note that climate changes will most likely directly affect the development of agriculture in general and the field of crop production in particular. This poses a number of tasks for scientists to establish the dependence of the implementation of the adaptive potential of agricultural crops on such climatic changes, accordingly, the creation of a new assortment of grain crops and the study of such morphobiotypes which will have the highest degree of plasticity and yield stability, today are the most relevant and priority areas of crop production development in the countries of the European Union.

CONCLUSIONS

The analysis of the manifestation of the parameters of plasticity and stability of the elements of the crop structure revealed that under different growing conditions in winter wheat varieties, their variability and absolute manifestation depended on both the genotype and environmental gradients. Varieties of the universal type (plant height 85-90 cm) were more plastic and stable in the formation

of ear productivity, compared to short and tall biotypes, they respectively formed a higher and more stable yield.

A variety, as a biological system, should be considered through the prism of its reaction to environmental conditions and the ability to realize its genetic potential. The analysis of the results of research on the adaptive potential of winter wheat allowed us to draw a conclusion about the high degree of homeostaticity and high value of the universal type varieties Askaniyska, Askaniyska Bereginia, Perlyna, Znahidka Odeska.

Under different growing conditions, morphobiotypes with integral interaction of valuable ear productivity sub-characteristics were selected from winter wheat hybrid populations characterized by resistance or tolerance to adverse environmental conditions.

Studies have proven that a one-sided increase in the level of a separate characteristic increased its variability under the influence of limiting factors of the external environment, accordingly, the character of the manifestation of productivity elements in the complex has an average value. An inversely proportional dependence of the absolute individual manifestation of subcharacteristics with the adaptive capacity of morphobiotypes has been established. It is possible to break the specified negative relationship under conditions of activation of the work of the entire genetic and physiological system of homeostasis, which in turn significantly affects the complex manifestation of symptoms.

Under different growing conditions (splicing, without splicing) and environmental weather conditions, the advantage of good selection lines of the universal type compared to the standard variety Khersonska bezosta was steadily maintained within the range of 0.34-0.64 t/ha.

The prospect of further research is the development and improvement of the elements of varietal agrotechnics for the cultivation of new promising winter wheat varieties of the universal type under the conditions of global climate change, as well as the maximum realization of the genetic potential of each variety in the harsh climatic conditions of the Steppe zone of Ukraine.

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CONFLICT OF INTEREST

The authors declare that the study was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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Реалізація адаптивного потенціалу урожайності сортиментом пшениці озимої в зоні Степу за різних умов вирощування

Валерій Васильович Базалій

Доктор сільськогосподарських наук, професор
Херсонський державний аграрно-економічний університет
73006, вул. Стрітенська, 23, м. Херсон, Україна
<https://orcid.org/0000-0002-0581-7242>

Євгеній Олександрович Домарацький

Доктор сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0003-3912-1611>

Віталій Іванович Пічура

Доктор сільськогосподарських наук, професор
Херсонський державний аграрно-економічний університет
73006, вул. Стрітенська, 23, м. Херсон, Україна
<https://orcid.org/0000-0002-0358-1889>

Ольга Павлівна Козлова

Кандидат сільськогосподарських наук, доцент
Херсонський державний аграрно-економічний університет
73006, вул. Стрітенська, 23, м. Херсон, Україна
<https://orcid.org/0000-0002-9062-5981>

Анна Ярославич

Доктор габілітований інженерних наук, професор
Поморська Академія
76-200, вул. Арцишевського, 22а, м. Слупськ, Республіка Польща
<https://orcid.org/0000-0002-7871-5968>

Анотація. Зміни клімату останніх десятиліть посилили ступінь ризиків у веденні рослинництва. Наслідком таких процесів є підвищення температурного режиму на фоні істотного дефіциту вологи в критичні періоди росту і розвитку рослин. Відповідно, дослідження спрямовані на встановлення пристосованості рослин до таких кліматичних змін є актуальними та своєчасними. Метою досліджень є встановлення принципів реалізації адаптивного потенціалу нових сортів пшениці озимої різних типів розвитку в зоні Степу за умов зміни клімату. Обліки та їх оцінку проводили відповідно загальноприйнятих методів українського сортовипробування з обов'язковим статистичним і дисперсійним аналізом результатів польових дослідів. Встановлення показників стабільності кількісних ознак і пластичності проводилося за допомогою алгоритму Еберхарда-Рассела, в основу якого покладено регресійний аналіз залежності врожайності зерна пшениці озимої різних сортів від індексу довкілля. Результатами досліджень встановлено, що для умов зрошення і без зрошення найбільш пристосовані сорти універсального типу з довжиною стебла 85-90 см. Регресійним аналізом даних пластичності і стабільності елементів структури врожаю у різних сортів пшениці озимої доведено, що їх мінливість має пряму залежить від генотипу та екологічних градієнтів. Відповідно результатів оцінки адаптивного потенціалу встановлено, що за параметрами пластичності ($b_i = 0.804-0.989$) і врожайності (7.33-7.63 т/га перебільшення стандарту на 10.4-14.9%) показали сорти пшениці озимої універсального типу – Асканійська, Асканійська Берегиня, Перлина, Знахідка одеська, інтенсивним типом розвитку характеризувалися сорти Херсонська 99, Кірена, Ярославна, Куяльник та ін. Сорти універсального типу були більш пластичними і стабільними в формуванні продуктивності колоса, порівняно з низькорослими і високорослими біотипами. Наукова значимість досліджень полягає в обґрунтуванні наукових принципів, практичних рекомендацій щодо вдосконалення сортової агротехніки пшениці озимої, які мали різне генетико-екологічне походження, в зрошуваних та незрошуваних умовах зони Степу

Ключові слова: зміни клімату; сорт; стабільність; пластичність; морфобіотип; урожайність

Organizational and economic principles of creation and implementation of a circular business model of development

Olena Dovgal*

Full Doctor in Economics, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0003-3353-4749>

Abstract. The topicality of the topic is due to the problems of the essence and the basic principles of the formation and development of the circular economy. The well-known systems of circular economy principles 3R and 9R have been supplemented with new principles that more widely reveal the content and possibilities of transition to a closed-type economy. The purpose of the research is to determine improved organizational forms of closed-loop business models, developed on the basis of advanced principles of the circular economy, adapted to the realities of Ukraine. The research methodology consisted of a set of used methods, cognitive and systemic principles of research, a sequence of stages that included: the study of scientific literature, the analysis of the current state and international experience on issues of circular transformations, substantiation of one's own concept and organizational forms of a business model of a closed economy. The scientific work compares and summarizes the principles of circular economy development. Systematization of the classification features of types of circular business models proposed in modern practice has been carried out. On the basis of the conducted research, a scheme of the conceptual model of the R-economy is proposed. The main stages of implementing the circular business model in practical activities are proposed. The key advantages of the circular business model are defined as future long-term economic benefits that create additional potential for business competitiveness and contribute to solving public environmental problems. Based on the generalization, modern obstacles and socio-economic benefits from the transition to a circular model of development for business and society were identified. The modern practice of successful implementation of circular business models is analyzed. Proposals regarding the design of food production for the creation of a closed-type economic model are substantiated. Various archetypes of the organization of closed-type business models have been studied. The scheme of organizational forms of circular economy business models is presented, taking into account the specialty of the value chain, as one of its most effective mechanisms

Keywords: R-economy; closed-type economy; principles of closed-type economy; organizational forms of the economy; models of production and economic relations; socio-economic benefits

INTRODUCTION

For several years now, the limited resources of the Earth and the accumulation of environmental problems of its population have led to an active search for optimal models of development of world and national economies, where the priority is to ensure consumer demand, decent living conditions for mankind, while preserving the environment for the needs of current and future generations. The traditional linear model of the devel-

opment of economic relations, focused primarily on obtaining business bonuses, has practically exhausted its potential today. Society has come to the final conclusion that continued existence in the long term is possible only on the basis of taking into account environmental needs and reorienting the basic motives of social activity in the direction of ensuring environmentally safe development (Bocken *et al.*, 2019). Under such strategic

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*Corresponding author

guidelines, the issue of substantiating business models of a closed production cycle, the implementation of which will allow to ensure the achievement of business goals while simultaneously taking into account long-term environmental needs and requirements of social development, becomes extremely relevant.

The circular economy, thanks to its exceptional tools for saving resources and protecting the environment, today plays a central role in the formation of sustainable models of social development, in political strategies that are reflected in the strategic plans and programs of action of the governments of countries and their associations (Desing *et al.*, 2020). Circularity is increasingly seen as the preferred way to ensure economic growth and recovery (Gonchar *et al.*, 2020), is increasingly and more often integrated into business strategies, economic practices and supply chains (Elia *et al.*, 2020). At the same time, the development of circular processes in global and national practice is accompanied by certain difficulties of the dominant practice of the traditional linear economy, both at the level of the national economy and at the level of global economic ties. The imperfection and insufficient level of uniformity of global and national legislation, limited access to the markets of producers' resources, a high level of competition with linear business companies, and insufficient awareness of the issues of sustainable development of society today continue to form a framework of obstacles and reduce the intensity of circular business processes. Along with this, the demand for circular (sustainable) products and services is growing more and more actively in the modern market, the management of companies more often make "circular or closed" decisions in the field of choosing supply and service chains, and the amount of financial support for businesses based on the closed-loop model is also increasing. The development of such trends requires greater transparency in the practice of conducting circular business, the development and dissemination of effective business models of the closed type, the expansion of partnerships and economic relations based on the principles of sustainability and responsibility. Society, the environment and the ecological sphere, future generations become the biggest beneficiaries of the development and spread of the circular economy. At the same time, the achievement of a common effect for all participants of the socio-economic process is possible under the conditions when the business will see and experience real bonuses and economic benefits from the implementation of circular tools in practical activities. This objectively requires the development of specific business models based on the principles of the circular economy and the outline of their future priorities, mechanisms and prospects for implementation. The business model should describe the means of the company to create new value and realize the created value, that is, the nature of the distribution of interests of business process participants.

Studies of the theoretical and practical aspects of the transformation of traditional linear-type economic models to closed-type models are becoming extremely relevant for science and practice today. The relevance and significance of issues of the development of the closed cycle economy today unites the scientific views and approaches of most scientists. However, the methodological plane and practical principles of implementing circular economy tools today are open to discussion for various types of economic activity and levels of economic management. V.S. Shebanin & G.O. Reshetilov (2021) sees construction, mobility, transportation, food, products and services as the main areas of circular transformations. The main emphasis of the research of these scientists is focused on the study of the forms and methods of the circular economy at the level of a separate type of economic activity (industry). M.V. Ruda & Ya.V. Myrka (2020) investigates the implementation of tools of the closed cycle economy, first of all, from the standpoint of three-level management of economic activity (national, regional, local) and searches for effective regulatory levers at each relevant level. N.O. Horbal & I.V. Plush (2021), A.P.M. Velenturf & P. Purnell (2021) focus mainly on tools to optimize emissions and prevent environmental pollution. Desing *et al.*, (2020) when investigating the need to justify circular business models as the key motives for their implementation in practice, see the possibilities of using less resource-intensive production methods and the wide potential of using innovations aimed at extending the terms and expanding the use of finished products.

The development of a closed economy is part of the strategic course of the European Union countries, which is implemented in the context of the Green Deal strategic concept. At the same time, priority areas of economic activity in which there is a need to implement strategies of active circular changes are considered to be: electrical and electronic equipment, automotive, chemical industry, agricultural sector, material processing, textiles and furniture production (Elia *et al.*, 2020). Despite certain differences in methodological approaches to the study of the theoretical, methodological and practical foundations of the development of the closed cycle economy, views on the mechanisms of implementing circular transformations and methods of managing them, there is a single consensus among scientists regarding the existence of a powerful potential for increasing the opportunities for the development of circularity in many sectors and a common view regarding the irreversibility of such a circular concept to ensure the future development of the entire world (Trigkas *et al.*, 2020; Ekins *et al.*, 2019).

The purpose of the study is to systematize the key principles of the circular economy and to substantiate on their basis the organizational forms of closed-type business models that are promising for Ukraine.

MATERIALS AND METHODS

The main areas of research when writing a scientific article were the following: systematization of the results of scientific research in terms of the general principles of the development of a closed-type economy; abstract-analytical evaluation of data for substantiating the conceptual foundations of circular economy business models; development of proposals regarding priority forms of implementation of closed-type models in the practical activities of business entities.

In the first part of the article, information about the essence of the circular economy was collected and used. The materials for writing the article were primary data obtained on the basis of generalizations of the domestic practice of building business models for national companies. The information base was represented by works of scientists published in specialized scientific publications of Ukraine. Secondary sources included a review of the literature devoted to this scientific issue published in international scientometric databases. An important element of the research information base has become the results of scientific developments of scientists, highlighted in professional publications, which are included in the Scopus scientometric database. The method of scientific search and systematization of the obtained data made it possible to expand the methodological plane of the set of principles of formation and development of circular processes in the economy. The combination of methods of analysis, synthesis and comparison allowed to offer author's own view on the construction of the classification of types of circular economy, which was based on the types of its archetypes. In the second part of the article, on the basis of the study of modern methodological approaches, the meaningful characteristics of closed-type business models existing in modern practice were studied. Data from international organizations such as: the World Economic Forum, the Organization for Economic Cooperation and Development (OECD) were used as additional informational and analytical materials. Research of primary and secondary information sources, highlighting the problem of finding optimal circular business models, made it possible to outline the methodological contours of the author's conceptual scheme of the circular economy model. The main conditions for building the proposed closed-type economy model were the use of systematized R-principles and the importance of achieving the global goals of sustainable development. Creation of long-term value for the economy and society was chosen as the criterion for the feasibility of using the proposed model. The methodological basis of the proposed model of the circular economy structurally included a set of tools, target orientations and an analytical description of the results, which makes it possible to detail the possible options for the practical implementation of its various organizational and economic forms. Based on statistical observations, an assessment of the benefits of implementing circular business models in practical activities for the environment was carried out.

Procedures for collecting relevant data made it possible to present key indicators and indicators that fully testify to the potential effect of implementing closed-type business models into practice. The systematization of the results of scientific research in the spectrum of alternative options for the development of circularity for the economies of the world became the basis for substantiating proposals for a possible design of closed agricultural production for the economy of Ukraine.

The article included the results of a systematic study of literary sources devoted to analytical generalizations of global circular economy models. The use of the obtained data helped to develop the author's vision of the typology of organizational forms of closed-type business models according to the criterion of the phase of the value chain. When writing the article, a set of general scientific and specific methods of economic research was used, in particular: monographic method (when identifying trends in the development of the circular economy in the world and researching its key principles). The classification method was used in the study of the classification features of types and archetypes of the closed-type economy. The methods of analysis and synthesis were applied in the study of the extent of damage to the environment from the consequences of the linear economy. Using the abstract-logical method of scientific research, the conceptual scheme of the circular economy model and its organizational forms were substantiated. The method of generalization was used in the study of the principles and modern practice of the development of closed-type economic models. The review of literary sources, the systematization and expansion of the methodological basis for the construction of closed-type organizational models for national practice was supplemented by a graphical method of visualizing the results of scientific research.

RESULTS AND DISCUSSION

Circular economy or the economy of a closed cycle represents a new type of organization of social production relations. The business interests of the subjects of the circular economy are complemented by the priorities of environmental protection and rational use of available resource potential. Today, the circular economy is called an economy of a revolutionary model, which is based on the mechanism of managing the processes of recovery, regeneration and reuse of resources. The economy of the closed cycle is characterized as a modern model of production and consumption, which is able to ensure sustainable growth over time. With the help of tools and methods of the circular economy, management is able to ensure the optimization of resources, reduce the amount of consumption of materials and give them a new life as a newly created product. The goal of the closed-loop economy is to maximize the use of available resources (including their reuse), based on three basic principles: reduction, reuse, recycling.

The circular economy is called the 3R model: “Reduce”, “Reuse” and “Recycle”. Joining the global trend of development of circular processes in social production, I.L. Tatomir & L.G. Kvasnii (2021) supplement this methodical and practical basis with elements 9R: refuse (refusal of excessive use of resources), reduce (optimization of resource use), reuse (reuse of used goods), repair (extension of the product’s useful life), refurbish (updating and repair of goods), remanufacture (reproduction of goods from used elements), repurpose (additional

intended use of the product), recycle (processing and secondary use of materials), recover (production of energy from materials).

At the same time, today’s way of life, models of consumption and production, motives of business and social development, existing environmental trends and increasing the level of general culture and consciousness complement the circular model based on the unity of the 3R principles in a new complementarity (Table 1) (Gonchar *et al.*, 2020; Circular economy model..., 2021; Moving towards..., 2021).

Table 1. Principles of the modern circular economy

Principles of the circular economy	The content of the principle
REACTIVATE	Return used equipment/technology to use
REBUILD	Development of a system or technology with greater efficiency, less waste and costs
RECLAIM	Returning to practical use previously unusable resources (land, buildings, etc.)
RECONDITION	Disposal and restoration of products from certain parts of them while maintaining the quality parameters of products and services
RECONSIDER	Changing lifestyle and consumer attitudes and principles, increasing the level of consciousness and awareness of saving resources and preserving the environment
RECONSTRUCT	Restoration or new construction after product damage
RECOVER	Restoration (reimbursement) of the usefulness of resources, returning resources to their functional properties
REDESIGN	Viewing the appearance, purpose and functional characteristics of the resource (product). Design of new business approaches to greening production.
REFORM	Correction of incomplete use of resources and their conservation
REFURBISH	Repair, modernization, increasing the level of sustainability of resources and their compliance with environmental safety
REFUSE	Rejection of a lifestyle that harms the environment
REGENERATE	Investing in the restoration of the resource to restore its useful properties
REGULATE	Management and monitoring of resources, optimization of resource use
REHABILITATE	Restoration of the production and economic system to an optimal state with the help of training of personnel (consumers/producers) and raising the level of their social consciousness
REINVENT	Change in key factors that contribute to the sustainability of the product (service) in the long term
REINVIGORATE	Provision of new incentives for the development of the circular economy (taxes, benefits, subsidies, loans, etc.)
RELINQUISH/RENOUNCE	Conscious voluntary refusal to use and consume resources (products, goods) that harm the environment
RELOCATION	Transferring production to new places that are safe for the environment, minimizing the geographical factor of environmental disasters
REMANUFACTURING	The use of components and the use of multifunctional resources that can be re-directed to production
REMODEL	Changing the structure and shape of the product to ensure the possibility of its safe and ecological use
RENEWABLE	Predominant use of renewable types of energy
RENT	New principles of renting products and services, which allows to minimize resources for the production of new ones
REPAIR	Restoring the useful quality properties of the product and extending the term of their functioning
REPLACE	Replacement of scarce and expensive resources with more optimal and budget-friendly ones
REPURPOSE	A significant change in the functional properties, shape, design and other parameters of the product for the possibility of its reuse
RESOLVE	The ability to make decisions about changing the worldview, perception, consumer and production business behavior

Table 1, Continued

Principles of the circular economy	The content of the principle
RESPECT	Respect for nature, environmental laws and eco-responsible behavior of business entities and consumers
RESTABILIZE	Solving a complex problem, correcting a negative environmental situation using circular economy methods and tools
RESTORE	Return of resources that have been removed from the environment
RESTRICT	Limitation, monitoring and control of irrational use of natural resources
RESTRUCTURE	A fundamentally new organization of product elements by reducing resource costs and emissions
RETHINK	Rational assessment of long-term goals of social, ecological and economic development for the benefit of society
RETOOL	Improvement of technical and technological systems and management tools for the benefit of the interests of the environment
RETURN	The practice of returning products to the manufacturing company for further processing/reproduction
REVITALIZE	Formation of impulses for a new life of production, product under the conditions of increasing the level of their sustainability and compliance with environmental requirements
REWARD	Motivation and dissemination of best practices for sustainable use of resources and environmentally responsible behavior of consumers and business entities

Source: systematized by the author according to I.L. Tatomir & L.G. Kvasniy (2021); *Circular economy model... (n.d.)*; Ellen MacArthur Foundation...(2018)

In the opinion of the author, taking into account the system of these principles in the practical activity of the modern economy makes it possible to provide additional opportunities for economic growth and job creation, to increase the level of independence from resources, in particular, of imported origin, to obtain specific advantages of the local economy due to savings and optimization of resource use, to ensure protection environment.

The key advantage of the closed-loop economy is the presence of a powerful potential for value creation based on the transformation of waste into new value. The concept of a circular economy is relatively new to world theory and practice. However, the significant deterioration of the ecological situation and the emergence of new technological possibilities for its correction in recent years have significantly expanded the range of tools for implementing the circular economy in practical activities. Today, the circular economy is a modern and future economy in which a significant (mostly) part of waste is used as an element of the production cycle. Considering the content and configuration of these principles, modern practice focuses its efforts on researching six areas of management of transformations related to the preservation of ecosystems: 1) perspective of complexity (creating micro-principles of management); 2) contextual perspective (management policy, digital trends, financial instruments and financial entities); 3) management perspectives (consciousness, culture, institutions, knowledge); 4) geographical perspective (location of business, resources, elements); 5) agency perspective (individual and partnership forms of cooperation); 6) network perspective (exploitation of global network opportunities and social capital) (LaDeau *et al.*, 2017).

Until recently, production and society mainly existed on the basis of a linear model of production and economic relations, the formula of which was: "we extract – produce – throw away". Taking into account the trends of constant growth of the global population and the volume of consumption of products and goods, in which the rate of consumption is significantly accelerated, the linear model is quite fast and relatively effective, but it is not sustainable for society in the present and long-term perspective (Desing *et al.*, 2020).

The closed-cycle economy represents a more sustainable model of production and consumption, in which raw materials, materials and the final product are stored much longer, can be reused, which ensures a much smaller amount of resource consumption and waste. In recent years, the issue of building a circular model of economic development has become one of the most urgent tasks of science and practice. At the same time, foreign researchers are trying to form such a model in the context of finding tools for implementing the principles of sustainable development in the practical activities of business entities. N. Bocken *et al.* (2019) attempted to substantiate the archetypes of closed economy models that can contribute to the creation of value propositions that combine the interests of the environment, economy and society. Archetypes of such models are grouped by the authors according to the central type of innovative component, which is used in economic practices. According to this methodical approach, the following archetypes of business models are distinguished: "creating value from waste", "providing functionality, not property", "replacing disposable

products with renewable and natural ones". N. Calvo & O. Villarreal (2018) add three archetypes of material

and energy productivity to the existing business models of the closed economy (Fig. 1).

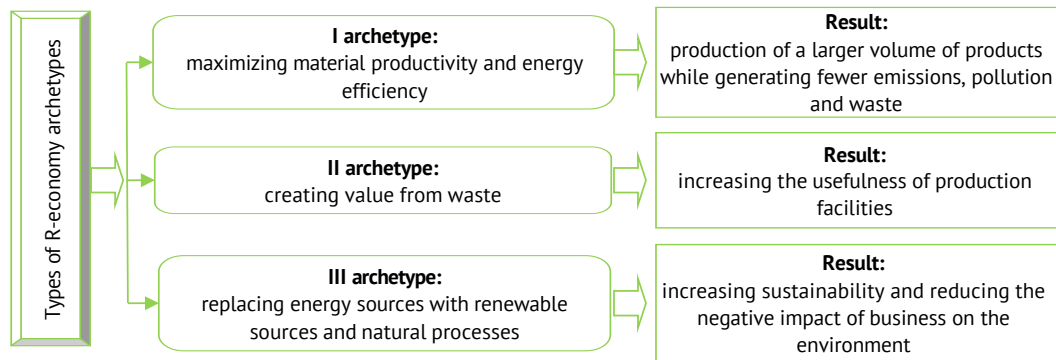


Figure 1. Classification of types of circular economy

Source: developed by author based on research by N. Calvo & O. Villarreal (2018)

A. Yablonsky & M. Marien (2020) in their research propose the formation of network business models of the circular economy, which have the potential of strategic drivers of business success and the creation of new values based on the principles of digitalization. The highly efficient generation of natural resources, the use of their ability to be processed and reused will form a new logic of income in the context of new business models. The ability to manage repetitive cycles can be ensured through digital management tools, which should become key drivers of creating new types of business models.

J. Ferreira & M. Dabik (2022) also support the perspective of the development of the digital business model of the closed-loop economy and note that "... innovations of the closed-loop business model and digitalization under modern conditions of business activity are consistent in the management structure, but uncertain in in

the field of identifying the effectiveness of the impact of digitization processes on the results of the development of the circular economy. The authors call digitization "the driving force behind revolutionary business models, which allows for more efficient collection and interpretation of data necessary for cyclical transformations".

The closed-cycle economy represents a more sustainable model of production and consumption, in which raw materials, materials and the final product are stored much longer, can be reused, which ensures a much smaller amount of resource consumption and waste. The author sees the content of the circular model of production relations in the fact that resources are stored in the economy for much longer, which allows for the optimization of the production process and the reuse of waste as raw materials for other cycles and branches of social production (Fig. 2).

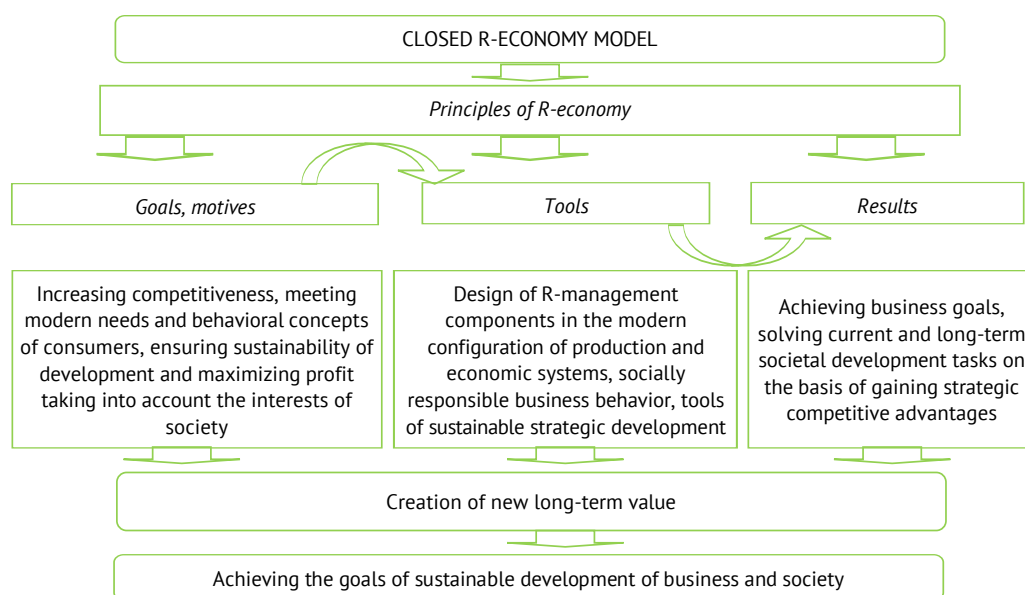


Figure 2. Conceptual diagram of the circular economy model

Source: author's development

Author considers it expedient to organize the implementation of the circular economy model according to the following main stages: 1) development of the life cycle and eco-design of a new product (works, services) based on the criterion of minimum consumption of raw materials and materials and extension of its useful life; 2) optimization of resources and production processes based on expanding the possibilities of using waste and reusing materials; 3) product production based on models that are alternative to linear models; 4) promotion and provision of sustainable consumption (socially responsible marketing and promotion and design of consumer behavior of buyers).

The main advantages of the implementation of the circular economy model in the practical plane can be: future long-term economic benefits. Thus, according to the results of studies conducted by the Accenture Corporation, in the period until 2030, the closed cycle economy is able to provide 4.5 trillion dollars. additional volume of production due to the creation of jobs and innovations (Benefits of the Circular..., 2022). The closed cycle economy is a system of production relations with reduced (optimal) use of resources, which forms the prerequisites for price competitiveness, reuse of materials, technical services, which, potentially, provides opportunities to save 70% of resources. The development of a circular economy has the power to create an additional 6 million in global production workplaces (Melnyk & Zlotnik, 2020). The analysis of the latest trends in circularity allowed the author to determine that the circular economy is one of the key elements of sustainable development on a global socio-economic and ecological scale, which is a strategic goal and requirement of modern society. Development business models based on the principles of a closed-loop economy should favor the emergence of long-term stable relations between producers and consumers, help to model consumer behavior and, on this basis, obtain strategic competitive advantages in balance with the needs and interests of social development. Other additional bonuses for business are believed to be increased levels of innovative activity and economic growth (Gonchar *et al.*, 2020; Linder *et al.*, 2021; Ekins *et al.*, 2019).

LaDeau *et al.* (2017) assessing the current state and possibilities of implementing a closed-type economy, point to the presence of certain shortcomings and obstacles of the modern stage of transformations: certain inconsistencies in the regulatory and legal framework regulating the processes of transition to the principles of a circular economy in the countries of the world; low level of awareness and awareness of a significant number of consumers about modern environmental problems and societal priorities; the need for technical and practical skills of the labor force of the closed cycle economy, which is being formed in developed countries; the presence of a significant amount of industrial and household waste, which is difficult to transform and recycle and has accumulated in the world on a significant scale.

One of the biggest contributors to climate change is the global food system: CO₂ emissions, increased pressure on land use, and consumption of large amounts of water and energy. In the EU, food systems account for about 30% of greenhouse gas emissions, with the contribution of each individual country varying between 25-42% (Crippa *et al.*, 2021). The negative impact of the industry on the environment is complemented by a high level of losses in food supply chains: according to UNEP, almost 17% of all food in the world is lost, and the amount of food waste per capita in Europe is characterized by the highest level in the world – 280 kg/year. Thus, food waste currently poses a significant threat to the sustainability of the global food system and the solution to the problem of food security. A closed food system opens up new opportunities and can provide significant economic and social benefits in the future. The Macarthur Foundation provides an estimate according to which the creation of a completely closed food system can provide economic benefits in the amount of 2.7 trillion dollars, USA by 2050, in addition, there will be additional savings of 4.3 billion tons of CO₂ emissions and 39.3 billion cubic meters of fresh water resources (Ellen MacArthur Foundation..., 2018). Accompanying bonuses will be received as a reduction in health care costs, treatment and prevention of diseases associated with the use of chemicals in food production.

Among the key processes that can appear in the basis of the creation of a closed business model of the agro-food sector is the increase in the circulation of resources, design and production and processing. The design of food products, related to the correct choice of ingredients and the configuration of the final product, which guarantees a low level of environmental impact, is of exceptional importance in such a model. An example of a circular economy business model in the agri-food chain is the activity of the American company Apeel, which has developed and uses plant-based coatings that keep fruits and vegetables fresh three times longer. This minimizes food waste in the value chain (Vieira & Shannon, 2020).

Studies of international experience allowed us to substantiate our own proposals regarding the design of food production for the creation of a closed-type economic model for Ukraine: 1) selection of components with a lower impact on the environment (for example, by replacing components of animal origin with plant ones); 2) diversification of ingredients to stimulate genetic diversity and strengthen sustainability potential; 3) processing of ingredients that are usually turned into waste; 4) wider use of regenerative components (which lead to a healthy lifestyle, preservation of biodiversity, improvement of water and air). A practical example of the implementation of such measures is the replacement of soybeans and other ecologically dangerous sources of proteins with grain and products of its industrial processing in feed production. Food waste can

be used as fertilizer, animal feed or compost to restore the fertility of agricultural land.

In order to successfully implement the principles of the closed loop economy in practical activity, it must have effective motivators and interest for business.

The business model of the circular economy is based on key R-principles and requires the implementation of the following basic rules in practical activities: 1) sources of raw materials and materials must be formed in the economy (the system of already existing production and economic relations), and not from ecological natural resources; 2) creation of value of products (goods, services) for customers should be based on already existing economic value; 3) expansion of business entry opportunities based on the common interests of producers, partners, and consumers.

Under the conditions of the transition to the principles of R-economy, various archetypes of the organization of business models of a closed type are possible. The first type: data-driven coordination of circular value chains - creating a product from recycling to reuse. The second type: circular design of the product (works, services) – creating a product with a maximum useful life and return of waste to the production system. The third type: reuse, sharing and repair – creating long-term use goods from recycled and reused elements that will become components for other business models. The fourth type: collection and reverse logistics - closing the life cycle of a material by creating a product that

is able to be recycled, repurposed and resold. The fifth type: sorting and pre-processing – finding alternative values in the parts that make up the product as a whole

The Organization for Economic Co-operation and Development (OECD) identifies five main models of the circular economy: 1) supply models that replace traditional resources with regenerative or biological ones; 2) resource models that use waste streams for subsequent operational cycles; 3) models focused on extending the product's service life and increasing its life cycle; 4) models of joint use, in which limited products (resources, services) are used jointly by several participants; 5) business models that substitute services for products (OECD. Business Models..., 2019). Various models of the organization of circular business models are characterized by appropriate management mechanisms and their tools. However, the main result at the output of closed-type business models is the creation of values that are greater than in traditional linear models of the organization of economic relations.

One of the most effective tools of circular business models is value chains. Thanks to the action of the mechanism of value chains, it is possible to organize a closed cycle in a certain type of economic activity (Circular model..., 2021; Benefits of the Circular..., 2022; Churikanova, 2020). Additional design in the practical implementation of such a model can serve as: logistics, marketing, repair, rental and other tools of organizational forms of its implementation (Fig. 3).

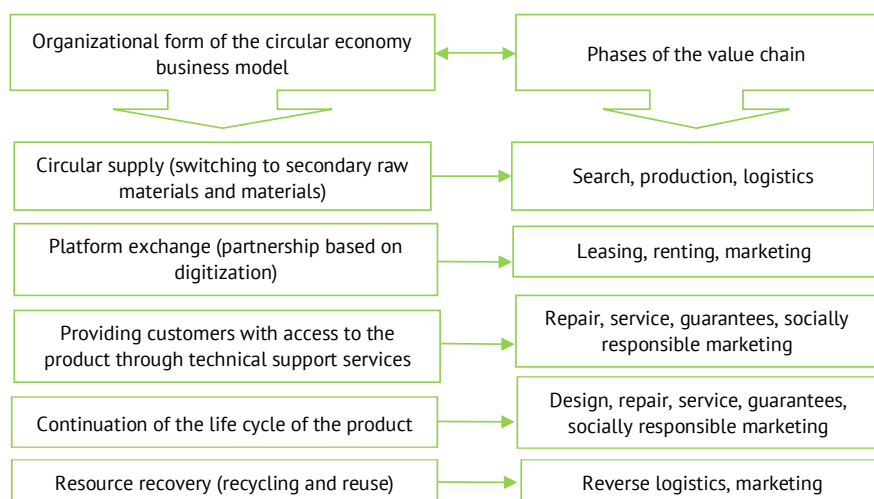


Figure 3. Organizational forms of closed loop business models

Source: author's development

The creation and promotion of business models of a closed cycle today finds increasing support in the world, both from government bodies and from leading socio-economic institutions. Thus, the World Economic Forum has created an accessible guide, Scale 360°, which provides assistance in scaling solutions for creating circular business projects and chains (Scale360° circular innovation..., n.d.). Innovations, without which

the implementation of circular economy projects is impossible, are accumulated within digital platforms and hubs with the simultaneous creation of specialized societies and partnerships that help develop closed-type business models (for example, the free and accessible UpLink innovation hub). Digital accessibility and transparency today appear to be a key condition for creating sustainable value chains based on circular processes.

At the same time, the transition to the principles of a circular economy is associated with certain risks, which domestic scientists include: environmental (illegal methods of using primary and secondary resources); economic (increase in the cost of production and decrease in efficiency); social (social inequality, corruption) (Churikanova, 2020).

The proposed organizational forms of closed economy business models, in contrast to the models considered by N. Bocken *et al.* (2019), take into account a wide range of implementation possibilities through the use of digital platforms. Digitalization will become a key tool in the near future that facilitates the formation of value chains and their logistics and it is possible to ensure the continuation of the phase of the product value chain through the use of mechanisms of leasing and renting of used products.

Developments by J. Ferreira & M. Dabic (2022) consider after-sales customer service guarantees as a possible form of product life cycle extension. Agreeing with this approach, it is expedient to focus attention on the organization of technical maintenance services for goods with the help of repair, restoration of useful consumer properties of goods and mandatory use of socially responsible marketing. A fundamentally new phase of value chains is such an element as reverse logistics, which is absent in the previously proposed models of A. Jabłonski & M. Marian (2020). In the studies of N. Calvo & O. Villarreal (2018), business models are classified based on material and energy productivity and have different results at the output of the process. According to the author's methodical approach, each organizational form of its implementation involves the saving of resources and energy with the simultaneous specification of the phase of the production and sales chain of value creation. In contrast to the forms of manifestation of the circular economy, which are mentioned in the scientific works of N.I. Horbal & I.V. Plish (2021), the author's approach takes into account not only the tools of environmental protection (reuse of raw materials and materials, extension of the product life cycle), but also the saving of resources, which becomes the basis of a closed-loop economy. The proposed conceptual scheme of the closed-type economy model can become a methodological basis for the practical implementation of the proposed organizational forms of R-economy business models. In the study, this model, in contrast to the approaches proposed by I.L. Tatomir & L.G. Kvasnii (2021), focused on creating long-term values and has a strategic nature. To ensure business interests, the conceptual model, unlike those proposed by M.V. Rudoyu & Ya.V. Myrka (2020), focused on gaining strategic competitive advantages, which can be formed over time by a closed-type economy. Also in the model, the design of the components of R-management, which includes the systematization

of all the principles of the circular economy, carried out by the author in this study, is taken into account.

For the successful implementation of the proposed models of the closed cycle in practical activity, the business must see real benefits and prospects, which will serve as effective motivators for the transformation of its economic activity in the direction of transition to the principles of a circular economy. It is believed that such business benefits in the strategic perspective can be: cost savings through the reuse of materials; increasing the usefulness of resources based on their dual use; development of new markets and attraction of new customers; increasing the level of loyalty of buyers and consumers; a more flexible response mechanism and satisfaction of consumer needs; increasing the degree of security and sustainability of own supply chains; access to innovations based on the use of specialized digital platforms; access to financial resources aimed at the development of the circular economy by government programs, expansion of the practice of financial partnership; building image capital, value of own brands and business as a whole.

CONCLUSIONS

The conducted studies showed that the issue of transformational transformations in the direction of circular economy development will become one of the most urgent aspects of management in the near future. On the basis of the conducted research, it was found that the system of closed-type economic principles can be extended to the 36R model. The main task of the circular economy model is to create long-term value, and the goal is to achieve the goals of sustainable development. Under modern conditions, the closed economy model expands its methodical and practical plane and is supplemented with new principles, tools and organizational forms of development. The implementation of circular models in practical activities is characterized by clear long-term benefits for business, society and the environment. At the same time, at the current stage, it is necessary to increase the degree of public awareness of the advantages of circular and sustainable models of production and consumption, create business models based on the demonstration of real economic benefits for producers, form the infrastructure for supply chains, increase the degree of transparency of partnerships and the system of economic relations closed type.

Based on the results of the study, promising organizational forms of closed-type business models for Ukraine were substantiated, in particular: transfer of production to secondary raw materials and materials; development of partnership on the basis of using the possibilities of digital platforms; development and distribution of goods maintenance services; extension of the life cycle of the product; recycling and reuse of resources. Each organizational form corresponds to a

certain phase of the value chain. Support for the processes of creation and implementation of circular business models in practice should be accompanied by the use of various forms of state financial assistance, the spread of concepts of responsible consumption in society, increasing the level of transparency of value creation chains, active consultation and information support, processes of unification of regulatory and legal regulation at the level of international management and development of national economies. The prospects of further scientific research in the selected con-

text will be the substantiation of an effective toolkit for business stimulation before the implementation of circular business models in practice.

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CONFLICT OF INTEREST

The author declare that the study was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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Організаційно-економічні засади створення і реалізації циркулярної бізнес-моделі розвитку

Олена Валеріївна Довгаль

Доктор економічних наук, доцент

Миколаївський національний аграрний університет

54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна

<https://orcid.org/0000-0003-3353-4749>

Анотація. Актуальність теми обумовлена проблемами сутності та основними засадами становлення й розвитку циркулярної економіки. Відомі системи принципів циркулярної економіки 3R та 9R доповнено новими принципами, які більш широко розкриваються зміст та можливості переходу на економіку замкнутого типу. Мета дослідження полягає у детермінації удосконалених організаційних форми бізнес-моделей замкнутого циклу, розроблених на основі розширених принципів циркулярної економіки, адаптованих до реалій України. Методологію дослідження становила сукупність використаних методів, пізнавальний та системний принципи проведення дослідження, послідовність етапів, які включали: вивчення наукової літератури, аналіз сучасного стану і міжнародного досвіду з питань циркулярних трансформацій, обґрунтування власної концепції та організаційних форм бізнес-моделі економіки замкнутого типу. У науковій праці здійснено порівняннн та узагальнення принципів розвитку циркулярної економіки. Здійснено систематизацію класифікаційних ознак видів циркулярних бізнес-моделей, які пропонується у сучасній практиці. На основі проведених досліджень запропоновано схемую концептуальної моделі R-економіки. Запропоновано основні етапи реалізації циркулярної бізнес-моделі у практичній діяльності. Ключовими перевагами циркулярної бізнес моделі визначено майбутні довгострокові економічні вигоди, що створюють додатковий потенціал конкурентоспроможності для бізнесу та сприяють розв'язанню суспільних екологічних завдань. На основі узагальнення виявлено сучасні перешкоди та соціально-економічні вигоди від переходу на циркулярну модель розвитку для бізнесу і суспільства. Проаналізовано сучасну практику успішного досвіду реалізації циркулярних бізнес-моделей. Обґрунтовано пропозиції відносно дизайну виробництва продуктів харчування для створення економічної моделі замкнутого типу. Досліджено різні архетипи організації бізнес-моделей замкнутого типу. Представлено схему організаційних форм бізнес-моделей циркулярної економіки у урахуванням фахи ланцюга вартості, як одного з найбільш дієвого її механізму

Ключові слова: R-економіка; економіка замкнутого типу; принципи економіки замкнутого типу; організаційні форми економіки; моделі виробничо-економічних відносин; соціально-економічні вигоди

Clonal micropropagation *in vitro* of essential oil plants of the family *Lamiaceae* Lindl.

Tetiana Manushkina*

PhD in Agrisciences
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0001-5843-271X>

Tetiana Kachanova

PhD in Agrisciences
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0003-0032-3996>

Mykola Samoilenko

Full Doctor in Agrisciences
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-3292-9717>

Olena Petrova

PhD in Agrisciences
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0001-8612-3981>

Abstract. The relevance of research on the development of biotechnology for clonal micropropagation of plants of the family *Lamiaceae* Lindl. is determined by the need for mass production of healthy, pure-grade planting material for the establishment of industrial plantations and the expansion of areas of essential oil crops in Ukraine. The aim of the research was to develop biotechnological methods of clonal micropropagation of essential oil plants of the *Lamiaceae* family – *Lavandula angustifolia* Mill., *Mentha x piperita* L., *Salvia officinalis* L. and *Monarda fistulosa* L. The task of the research was to select optimal conditions for effective cultivation of plants of the *Lamiaceae* family at four stages of clonal micropropagation. The main methods of research: laboratory, field, analytical, mathematical and statistical. The optimal nutrient media for the induction of *in vitro* morphogenesis and the multiplication stage were determined based on the basic medium of Murashige and Skoog: for *L. angustifolia* supplemented with kinetin (1.0 mg/l) and gibberellic acid (1.0 mg/l), for *M. x piperita* – with 6-benzylaminopurine (1.0 mg/l) and gibberellic acid (0.1 mg/l), for *S. officinalis* – with 6-benzylaminopurine (1.0 mg/l) and IOLK (0.5 mg/l), for *M. fistulosa* – 6-benzylaminopurine (1.0 mg/l) and β -indolyl-3-oleic acid (0.1 mg/l). At the stage of multiplication, it is advisable to carry out seven to eight cycles of cultivation. At the stage of rooting of microshoots, the most effective for all studied plant species was determined to be the Murashige and Skuga nutrient medium with a halved concentration of components, supplemented with β -indolyl-3-oleic acid (0.5 mg/l) and β -indolyl-3-acetic acid (0.5 mg/l). The optimal substrate for plant adaptation to *in vivo* conditions is peat: perlite in a volume ratio of 3:1. Incorporation of the developed biotechnology of

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*Corresponding author

clonal micropropagation into the seeding system of essential oil crops of the *Lamiaceae* family will allow to quickly obtain healthy pure-bred planting material and introduce new productive varieties into production

Keywords: *Lavandula angustifolia* Mill.; *Mentha x piperita* L.; *Salvia officinalis* L.; *Monarda fistulosa* L.; reproduction coefficient

INTRODUCTION

Family *Lamiaceae* Lindl. is one of the largest families of flowering plants, which includes about 250 genera and more than 7,000 species distributed throughout the world. It is considered an important source of essential oils and such valuable components as menthol, geraniol, eucalyptol, camphor and thymol (Mesquita *et al.*, 2019). Plants in this family are herbs or shrubs that produce large amounts of essential oil, which allows them to withstand high temperatures in summer (Raja, 2012).

Essential oils in different types of plants accumulate in different organs: flowers, leaves, fruits, seeds, rhizomes, and others. These volatile aromatic substances include a mixture of organic compounds: hydrocarbons, alcohols, monoterpenes, phenols, ethers, aldehydes, ketones, and organic acids (Rozhkov & Ogurcov, 2017; Dehsheikh *et al.*, 2020). The essential oil is obtained by steam distillation and has sedative, diuretic, tonic, antispasmodic and antiseptic properties (Raja, 2012). It is used in the pharmaceutical industry, perfumery, cosmetology and the food industry (Rozhkov & Ogurcov, 2017). Recent scientific studies have proven the anti-tumor properties of essential oils from plants of the *Lamiaceae* family (Mesquita *et al.*, 2019). The species of this family are promising potential sources of natural antioxidants due to their high content of polyphenols. In addition, increasing scientific and epidemiological evidence links consumption of polyphenol-rich foods to health benefits such as reduced risk of cardiovascular disease through anti-inflammatory effects (Tzima *et al.*, 2018). In Ukraine, narrow-leaved lavender, peppermint, clary sage, clary sage, monarda, hyssop, lemon balm, nepeta, rosemary, savory and others are cultivated as essential oil plants of the *Lamiaceae* family (Rozhkov & Ogurcov, 2017). In modern conditions, the agro-ecological advantages of growing plants of this family are important, such as the ability to grow on unproductive eroded soils, form stable phytocenoses on man-made disturbed lands, and act as phytomeliorants (Dobrovolskyi *et al.*, 2021).

Narrow-leaved lavender *Lavandula angustifolia* Mill. – perennial evergreen semi-shrub containing 1-2.5% of essential oils in inflorescences (Lis-Balchin, 2002; Manushkina, 2019). The main components of lavender essential oil are linalool (10-20%) and linalyl acetate (30-50%) (Küçük *et al.*, 2018; Pokajewicz *et al.*, 2021).

Peppermint *Mentha x piperita* L. is a perennial herb that is a hybrid type of mint that does not occur in the wild. Essential oils are contained in all above-ground organs of plants: leaves (2-4%), inflorescences (4-6%),

stems (up to 0.3% of the mass of dry matter). Aerial parts of plants in a withered state or dry leaves are used as raw materials. The main components of peppermint essential oil are menthol (41-92%), menthone (9-25%), pinene, limonene and other substances, as well as phenolic compounds with antioxidant properties (Rozhkov & Ogurcov, 2017).

Medicinal sage *Salvia officinalis* L. is a multi-stemmed subshrub reaching a height of 80 cm. The main biologically active substances are phenolic compounds (flavonoids, tannins, hydroxycinnamic acids) and terpenoids (Jasicka-Misiak *et al.*, 2018). Various medicinal forms created on the basis of a combination of these groups of biologically active substances from plant raw materials are characterized by the high antimicrobial and antioxidant potential of medicines based on sage (Hudz *et al.*, 2020; Schmiderer & Novak, 2020; Francik *et al.*, 2020). The content of phenolic acids and flavonoids depends on the variety of plants and environmental conditions of cultivation (Čavar Zeljković *et al.*, 2021; Karalija *et al.*, 2022).

Monarda fistulosa L. is a perennial herbaceous and ornamental plant. The essential oil has antiseptic, expectorant and repellent properties (Shanaida & Mashtaler, 2016). It belongs to non-official medicinal plants, it is not included in the State Pharmacopoeia of Ukraine, but it is promising for use as an essential oil plant (Shanaida & Pokryshko, 2015).

In connection with the mentioned economic and ecological advantages of essential oil plants of the *Lamiaceae* family, it is advisable to increase their area in Ukraine, in particular, to grow them as niche crops. The yield and the quality of essential oil depend significantly on the pureness of the planting material used for planting plantations. Since in many species of the *Lamiaceae* family, during seed reproduction, splitting is observed for economically valuable traits, vegetative reproduction is used in seed production. This method allows you to maintain the genetic identity of planting material, but has a low reproduction rate and a high probability of transmission of infectious diseases.

Currently, for effective vegetative reproduction of plants, it is advisable to use the method of clonal micropropagation in *in vitro* culture, which is characterized by a high reproduction ratio, preservation of the genotype, and recovery from pathogens of the planting material. According to the modern classification, two types of clonal micropropagation are distinguished - activation of the development of meristems already present in the

plant and induction of the development of buds or embryoids *de novo* by direct or indirect morphogenesis. For most plants, reproduction *in vitro* culture is carried out according to the first type, since it ensures the preservation of the genotype of the obtained seedlings identical to the original plants. Maintenance of genetic stability of apical meristems is ensured by a number of mechanisms: cells contain a diploid set of chromosomes, are maintained in an embryonically active state, they are organized in the form of discrete zones characterized by high activity of DNA repair systems and negative selection of altered cells. In connection with the above, research on the development of technological measures of clonal micropropagation of essential oil plants of the *Lamiaceae* family for the mass production of pure planting material is relevant.

The task of the research is to choose optimal conditions for effective cultivation of plants of the *Lamiaceae* family at four stages of clonal micropropagation.

The purpose of the research was to develop biotechnological methods of clonal micropropagation of essential oil plants of the *Lamiaceae* family L., *angustifolia* Mill., *M. x piperita* L., *S. officinalis* L., *M. fistulosa* L. The task of the research is to choose optimal conditions for effective cultivation of plants of the *Lamiaceae* family at four stages of clonal micropropagation.

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MATERIALS AND METHODS

The experimental work was carried out on the basis of the laboratory of clonal micropropagation of farming "Agrolife" (hereinafter referred to as Farm "Agrolife") of the Mykolaiv Region, a branch of the Department of Agriculture, Geodesy and Land Management of the Mykolaiv National Agrarian University. As material for research, lavender plants of the narrow-leaved L. *angustifolia* varieties Sinyeva, Hemus, Imperial Gem, peppermint *M. x piperita* L. varieties Lebedina pisnia, Mama, medicinal sage *S. officinalis* L. variety Shans, monarda tubular *Monarda fistulosa* L. Fortune variety were used.

The main methods of research: general scientific (analysis, synthesis, generalization) and special (laboratory, field). In the course of conducting experimental studies, methods generally accepted in plant biotechnology were used (Kalinin et al., 1984; Kumar & Loh, 2012).

The development of biotechnological measures was carried out in four stages of clonal micropropagation: I stage - isolation of the explant, introduction and initiation of its development *in vitro*; II stage - multiplication; Stage III - rooting of microshoots; Stage IV - adaptation of microplants to *in vivo* conditions.

In stages I and II, Murashige and Skoog (MS) was used as the basic nutrient medium (Murashige & Skoog, 1962). At the III stage, the MS nutrient medium with a halved concentration of components ($\frac{1}{2}$ MS) was used as the base. At the first three stages of clonal micropropagation, the composition of hormones in the nutrient medium was changed in various combinations and concentrations to stimulate the necessary path of morphogenesis (Table 1).

Table 1. Hormones included in nutrient media for clonal micropropagation of plants of the *Lamiaceae* family

Full name	Symbolic designation
6-benzyloaminopurine	BAP
6-furfurilaminopurin	kinetin
gibberellic acid	GA
β -indolyl-3-butyric acid	IBA
β -indolyl-3-acetic acid	IAA

Source: developed by authors

The acidity of the medium was adjusted to pH 5.5-5.6 using 0.1 n HCl or 0.1 n KOH before autoclaving. The nutrient medium was autoclaved at a temperature of 120°C, a pressure of 0.8 atm. within 20 min.

Donor plants were grown in closed soil conditions. Shoots were separated from the plant, washed in a soap solution, washed in running water and in sterile distilled water. Then they were divided into segments with one pair of buds and staged sterilization was applied according to the scheme: ethanol 70% solution (40 s), sodium hypochlorite 1% solution (5 min). After sterilization, apical or axillary buds were isolated and introduced into *in vitro* culture. Aseptic work was carried out in a laminar box BBPO2a. Isolation of explants was carried out under a MBS-9 binocular microscope

and cultivated one at a time in chemical test tubes with a volume of nutrient medium of 10 ml.

At the stage of multiplication, microshoots, the development of which was initiated in the first stage, were divided into microcuttings 5-10 mm long with one pair of axillary buds, and additional microshoots were separated and cultivated in 250 ml vessels with a volume of 30 ml of nutrient medium. 6 explants were placed in one culture vessel.

At the stage of rooting, the main shoot of the obtained meristem plants was cut on a 5-10 mm long microcutting with one pair of leaves, and additional microshoots were also separated. Cultivated in vessels with a volume of 250 ml with a volume of nutrient medium of 30 ml for 6 microshoots. To stimulate rhizogenesis, auxins were added to the nutrient medium.

At three stages of *in vitro* clonal micropropagation, explants were cultured in a thermostatically controlled culture room. Cultivation conditions: temperature 25-26°C, illumination 2-3 klk, photoperiod 16 hours, relative humidity 60-70%.

At the stage of adaptation to *in vivo* conditions, micro-plants were grown in cassettes in climatic chambers at a temperature of 20-22°C and constant humidification, with periodic ventilation, the time of which was increased as the adaptation period increased. Substrates for cultivation in cassettes consisted of peat and perlite in different ratios by volume – 1:1; 2:1; 3:1; 4:1; 5:1. Adapted plants were transplanted into pots with a volume of 250 ml and cultivated in climatic chamber conditions for 30-56 days, depending on the type of plants.

The repetition of all experiments is twofold, the sample size is 20 plants.

The multiplication factor was calculated according to formula 1:

$$MF = \frac{Rf \times Nms \times Nls}{100} + \frac{Ffas \times Nas}{100}, \quad (1)$$

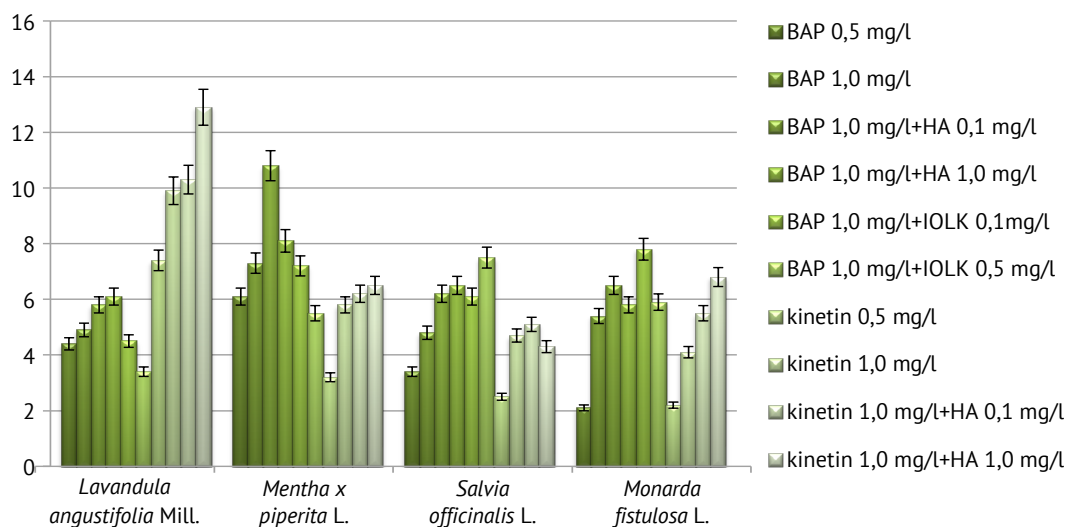


Figure 1. The coefficient of reproduction of plants of the Lamiaceae family at the stage of explant isolation, introduction and initiation of its development *in vitro* depending on the composition of hormones

Source: developed by the authors

It was determined that nutrient media based on the basic medium of MS are optimal for inducing morphogenesis *in vitro*: for *Lavandula angustifolia* Mill. supplemented with kinetin (1.0 mg/l) and HA (1.0 mg/l), for *Mentha x piperita* L. – BAP (1.0 mg/l) and HA (0. mg/l), for *Salvia officinalis* L. – BAP(1.0 mg/l) and IOLK (0.5 mg/l), for *Monarda fistulosa* L. – BAP (1.0 mg/l) and IOLK (0.1 mg/l).

II stage – multiplication. At the second stage, the multiplication of shoots is achieved in two ways. First, due to the addition of increased concentrations of

where *Rf* – regeneration frequency, %; *Nms* – number of main shoots, pcs.; *Nls* – number of pairs of leaves on the main shoot, pcs.; *Ffas* – frequency of formation of additional shoots, %; *Nas* – number of additional shoots, pcs.

Mathematical processing of the results was performed in the Microsoft Office Excel 2007 program using descriptive statistics (Rozhkov *et al.*, 2016). The statistical characteristics of quantitative variability were calculated: the arithmetic mean, the error of the arithmetic mean. The reliability of the difference between the mean values was determined by the Student's t-test.

RESULTS AND DISCUSSION

Stage I – isolation of the explant, introduction and initiation of its development *in vitro*. After the use of stepwise sterilization using ethanol and sodium hypochlorite, the infection rate of explants of all types of plants did not exceed 15%, the viability was at least 80%. The regeneration rate reached 90.0-100.0%. However, the hormonal composition of nutrient media significantly influenced the formation of shoots, and therefore, the reproduction coefficient, which is an integral parameter that includes the frequency of regeneration and formation of the main and additional shoots (Fig. 1).

cytokinins to the nutrient medium to remove apical dominance and stimulate the development of lateral and adventitious buds. Secondly, by carrying out several cycles of subcultivation until obtaining the required number of shoots. By combining these two ways, it is possible to achieve a multiplication factor of up to 105-106 per year (Kalinin *et al.*, 1984). At the multiplication stage, the effectiveness of the hormonal composition of the nutrient media was evaluated by the reproduction coefficient indicator (Fig. 2).

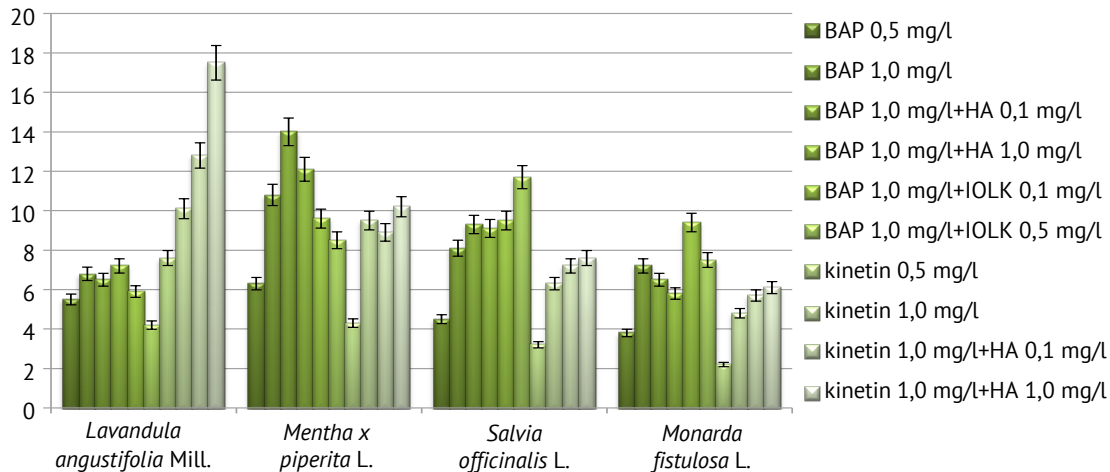


Figure 2. The coefficient of reproduction of plants of the Lamiaceae family at the multiplication stage depending on the composition of hormones

Source: developed by the authors

It was established that for the *in vitro* cultivation of *L. angustifolia* plants at the multiplication stage, the optimal nutrient medium is MS with the addition of kinetin (1.0 mg/l) and HA (1.0 mg/l), which provided the highest multiplication factor – 17.5. A tendency was noted that nutrient mediums with the addition of kinetin stimulated the process of shoot formation more compared to BAP cytokinin, with the use of which vitrified shoots were formed (up to 65%), which cannot be used for further micropropagation. The addition of HA contributed to the increase in the length of the internodes of the shoots, which allows dividing them into separate microcuttings with one pair of buds for further cultivation in the next cycle, and, accordingly, increases the reproduction ratio. The inclusion of auxin IOLK in nutrient media containing BAP caused the formation of callus at the base of the cutting, and with increasing concentration, the frequency and intensity of callusogenesis increased. Callus formation is unacceptable during clonal micropropagation, as indirect hemogenesis and the formation of somaclonal variants are possible.

For the cultivation of explants of *M. x piperita*, *S. officinalis*, and *M. fistulosa*, the addition of MS BAP to

the basic nutrient medium was more favorable for stimulating hemogenesis compared to kinetin. On media with BAP, the development of a greater number of additional and adventitious shoots was noted, while their vitrification was not observed as in *L. angustifolia* explants. The addition of HA or IOLK contributed to the optimization of shoot development. Optimum nutrient media for the induction of *in vitro* morphogenesis and the stage of multiplication were determined based on the base medium of MS: for *M. x piperita* – BAP (1.0 mg/l) and IOLK (0.1 mg/l), for *S. officinalis* – BAP (1.0 mg/l) and IOLK (0.5 mg/l), for *M. fistulosa* – BAP (1.0 mg/l) and IOLK (0.1 mg/l).

At the multiplication stage, micropropagation propagation can be carried out in several cultivation cycles to achieve the required number of plants, therefore it is advisable to study the effect of the micropropagation cycle on morphogenesis in *in vitro* culture. This allows to find out the possibility of carrying out subcultivation without changing the morphometric parameters and the reproduction ratio. The dynamics of the reproduction coefficient of plants of the Lamiaceae family during ten cycles of cultivation depended on the type of plants (Fig. 3).

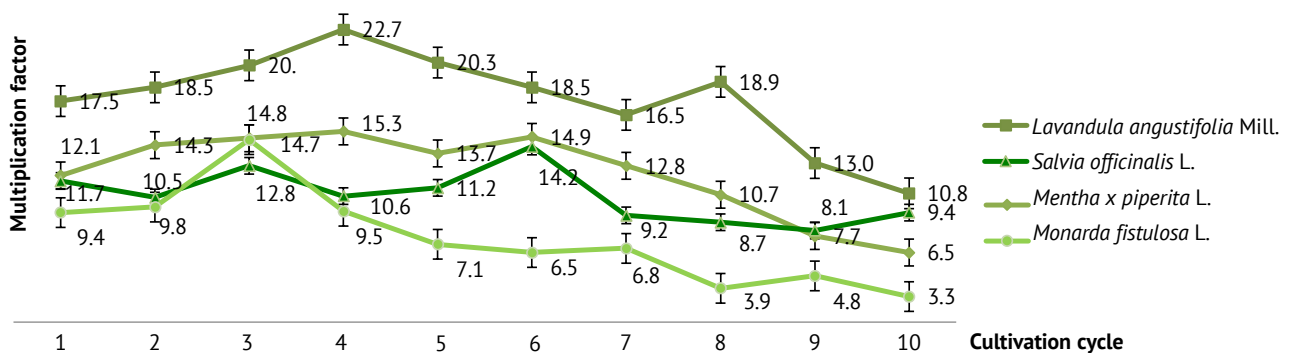


Figure 3. The multiplication factor of plants of the Lamiaceae family depending on the cycle of cultivation

Source: developed by the authors

The highest reproduction ratio was observed in *L. angustifolia* plants, it ranged from 16.5 to 22.7 and remained stably high from the 1st to the 8th cycle of cultivation, and decreased to 10.8-13.0 in the 9th to 10th cycles. A similar trend was observed in *M. x piperita* plants, the reproduction coefficient remained stable during eight cycles of cultivation within the range of 10.7-15.3, and in subsequent cycles it decreased to 8.1-6.5. The multiplication factor of *S. officinalis* was the highest in the 6th cultivation cycle – 14.2, the lowest – 7.7, in the 9th passage, and slightly increased to 9.4 in the 10th passage. The reproduction coefficient of *M. fistulosa* was the lowest among the studied plant species and ranged from 6.5 to 9.4 during 1-7 cycles of cultivation, except for the 3rd cycle, when this parameter was the maximum – 14.7. A significant decrease in the multiplication factor to 4.8-3.3 was observed in 7-10 cycles.

The obtained data make it possible to recommend seven to eight cycles of cultivation during clonal micropropagation of plants of the *Lamiaceae* family, during which they maintain high morphogenetic potentials and provide a stable multiplication factor of 6.5-22.7, depending on the biological characteristics of the species.

Stage III – rooting of microshoots. Stimulation of rhizogenesis in plants is carried out under the influence of auxins, which induce division of shoot parenchyma cells, as a result of which differentiation of root primordia occurs in its basal part. It has been shown that for *in vitro* rooting of microshoots of plants of the *Lamiaceae* family, the nutrient medium of ½ MS supplemented with IOLK (0.5 mg/l) and IOCK (0.5 mg/l) is optimal (Fig. 4). On this nutrient medium, the frequency of rooting was 80.0-97.5%, the highest height shoots were also formed – 56.8-51.5 mm and the largest number of roots – 3.5-4.7 pieces.

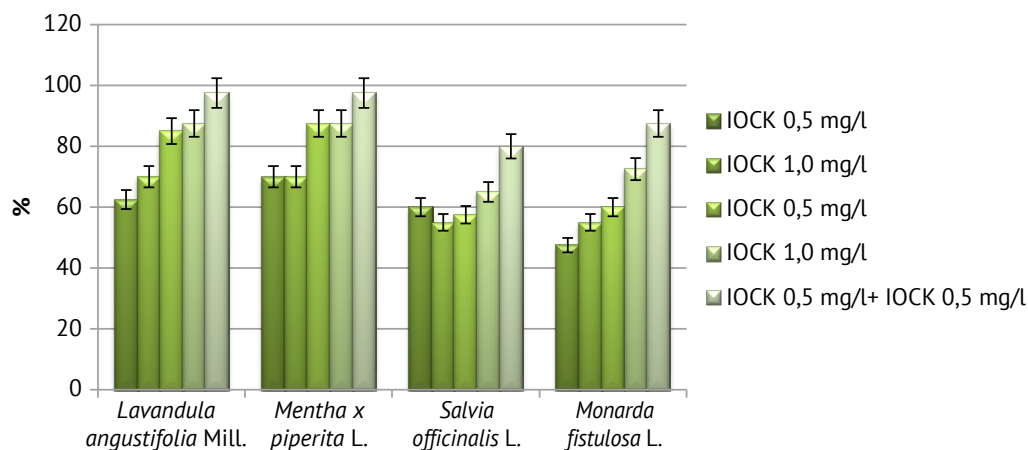


Figure 4. The frequency of rooting of microshoots of plants of the *Lamiaceae* family depending on the composition of auxins

Source: developed by the authors

It is obvious that IOLK and IOCK auxins in combination provided a synergistic effect. When added individually, they acted less effectively even at a concentration of 1.0 mg/L. The frequency of regeneration was significantly lower compared to this indicator on the medium with a combination of auxins. Also, when the concentration of auxins increased to 1.0 mg/L, inhibition of shoot growth was observed.

Stage IV – adaptation of microplants to *in vivo* conditions. During the transfer of plants from *in vitro* conditions to *in vivo* conditions, cultivation parameters change – temperature, relative humidity, substrate, lighting. Therefore, it is important to develop adaptation measures that contribute to the optimal survival of mericlons.

In plants of the *Lamiaceae* family, after 7-10 days, depending on the species, there were clearly visible signs of the growth of shoots and the formation of the root system. It was determined that 14-20 days are enough for the adaptation of meristem plants, during which 2-3 pairs of leaves were formed. It should be noted that the

viability of meristem plants and their growth depended significantly on the composition of the substrate. It was established that the optimal substrate for adaptation is peat: perlite in a volume ratio of 3:1, on which the survival rate of all studied plant species was 82.5-100.0%, while with an increase or decrease in the proportion of perlite in mixture, this indicator decreased.

During the period of adaptation and cultivation in the collection nursery, meristem plants of all studied species had morphological characteristics typical for the varieties. In order to further research the processes of growth and development of plants obtained in *in vitro* culture, a model experiment was established in the collection nursery of the Ukrainian National Academy of Sciences, while the survival rate of plants was 95.0-100.0%.

As a result of the experiments, the processes of morphogenesis in the *in vitro* culture of *L. angustifolia*, *M. x piperita*, *S. officinalis*, and *M. fistulosa* were investigated, and technological measures were developed at the four stages of clonal micropropagation (Fig. 5).

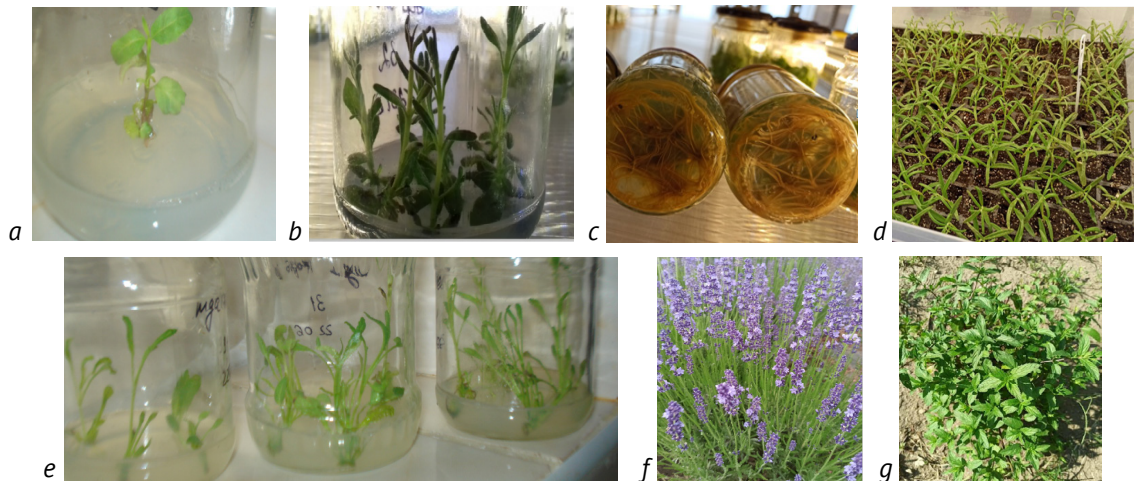


Figure 5. Development of plants of the Lamiaceae family at different stages of clonal micropropagation: a – *M. fistulosa* (I stage); b – *L. angustifolia* (II stage); c – *M. x piperita* (III stage); d – *L. angustifolia* (IV stage); e – *S. officinalis* (II stage); f – *L. angustifolia* (collection nursery); g – *M. x piperita* (collection nursery)

Source: developed by the authors

The revealed features of cultivation, in particular, the optimal composition of the nutrient medium, the multiplication factor and its dynamics depending on the cultivation cycle, the conditions of rooting and adaptation of microplants differed for *L. angustifolia*, *M. x piperita*, *S. officinalis* and *M. fistulosa*. For the clonal micropropagation of *L. angustifolia*, the most effective at the stages of *in vitro* culture introduction and multiplication was determined to be a nutrient medium based on the MS basic medium, supplemented with kinetin (1.0 mg/l) and HA (1.0 mg/l). D. Leelavathi & N. Kuppan (2013), T. Manushkina (2017) also indicate that the use of kinetin affected the formation of more shoots without morphological changes in *L. angustifolia*. A. Hamza et al. (2011), D. Andrys et al. (2017) found that plants that produced the highest number of shoots were grown on medium with BAP (0.8-2.0 mg/l). According to A. Kumar et al. (2015), the use of MS with the addition of cytokinin BAP (2.0 mg/l) and auxin IOCK (0.5 mg/l) affects the increase in the number of shoots. This study showed that the cultivation of the studied varieties on MS nutrient medium with the addition of BAP (1.0 mg/l) stimulated the development of shoots, but 65% of them were vitrified, excessively hydrated, and the addition of BAP to the nutrient medium together with IOLK caused the formation of callus at the base of the cutting. Both processes are unacceptable in clonal micropropagation. J. Koefender et al. (2021) also noted excessive hydration in *Lavandula dentata* plants grown on MS medium supplemented with BAP (5.0 µM).

For *M. x piperita*, it was determined that in the first two stages of cultivation, the optimal nutrient medium is MS supplemented with BAP (1.0 mg/l) and HA (0.1 mg/l). Such results are consistent with those obtained in the work of A. Islam et al. (2017), in which the specified hormones were applied, but in stages. The

largest number of shoots was obtained on the medium containing BAP (3.0 mg/l). For further elongation, microshoots were transferred to media with different concentrations of HA. The greatest length of shoots with a frequency of 100% was achieved on the medium containing 1.0 mg/l HA. In the work of T. Talankova-Sereda et al. (2016) also determined as optimal the MS medium supplemented with BAP (0.75 mg/l) and HA (0.5 mg/l), but additionally used adenine and IOCK at a concentration of 0.05 mg/l.

Initiation of development and multiplication of shoots in the *in vitro* culture of *S. officinalis* took place most effectively on the nutrient medium of MS with the addition of BAP (1.0 mg/l) and IOLK (0.5 mg/l), and *M. fistulosa* – with the addition of BAP (1.0 mg/l) and IOLK (0.1 mg/l). Similar results were presented by M. Petrova et al. (2015), who showed maximum shoot proliferation from seedling segments obtained *in vitro* when cultured in MS medium supplemented with BAP (2.22 µM) and IOLK (0.57 µM). I. Grzegorzczak-Karolak et al. (2021) during clonal micropropagation of *Salvia bulleyana* based on leaf segments, the highest regeneration frequency (95%) was obtained on MS medium containing BAP (2.0 mg/l) and naphthylacetic acid (NOC) (0.1 mg/l). However, researchers P. Santos-Gomes & M. Fernandes-Ferreira (2003) showed that the greatest accumulation of essential oils and the greatest increase in shoot biomass was obtained when kinetin (2.0 mg/l) and 2,4-dichlorophenoxyacetic acid (0.05 mg/l).

At the stage of rooting of microshoots of plants of the Lamiaceae family, the highest frequency of rooting (80.0-97.5%) was ensured on nutrient medium ½ MS, supplemented with IOLK (0.5 mg/l) and IOCK (0.5 mg/l). The same auxins in a concentration of 0.5-2.0 mg/l were used in the work A. Islam et al. (2017) to root *M. x piperita* microshoots. Among them, the greatest root

proliferation was obtained on the medium containing IOLK (1.5 mg/l). J. Łyczko *et al.* (2020) revealed a high degree of rooting (97-100%) on MS medium with the addition of IOLK (0.5 mg/l). The researchers Andrys *et al.* (2017) show a significant influence of the *L. angustifolia* genotype on the rooting process. For two cultivars, the optimal effect on root length was noted on ¼ MS nutrient medium with the addition of 0.2 mg/l IOLK or (NOC), while for the third cultivar, the best results were obtained on the MS medium with the addition of 0.2 mg/l NOC. In the work Hamza *et al.*, (2011) it was found that the use of ½ MS medium with the addition of NOK (1.0 mg/l) resulted in more roots, but IOLK (2.0 mg/l) had the most positive effect on root length.

The viability of plants obtained by the method of clonal micropropagation in field conditions was 95.0-100.0%. Similar results were obtained in the work of researchers Islam *et al.* (2017).

In general, the direction of morphogenetic processes at individual stages of clonal micropropagation of plants of the *Lamiaceae* family was similar. However, the hormonal regulation of morphogenesis varied, which is obviously due to genotypic differences in the morphogenetic reactions of plants in *in vitro* culture, as well as different explants, growing conditions of donor plants, the season of explantation, and other factors. The works Andrys *et al.* (2017), Islam *et al.* (2017) emphasize that the hormonal conditions for reproduction depend on the species and variety of the source plants. The biotechnological measures of clonal micropropagation of essential oil plants of the *Lamiaceae* family developed in this study are effective and can be recommended for inclusion in the technologies of obtaining planting material.

CONCLUSIONS

Based on scientific research, a biotechnological method of cloning and micropropagation of essential oil plants *Lamiaceae* *L. angustifolia* Mill., *M. x piperita* L., *S. officinalis* L., *M. fistulosa* L. was developed.

The most effective for the stages of introduction into culture *in vitro* and multiplication are nutrient media based on the basic medium of MS, supplemented with hormones: for *L. angustifolia* – kinetin (1.0 mg/l) and HA (1.0 mg/l), for *M. x piperita* – BAP (1.0 mg/l) and HA (0.1 mg/l), for *S. officinalis* – BAP (1.0 mg/l) and IOLK (0.5 mg/l), for *M. fistulosa* – BAP (1.0 mg/l) and IOLK (0.1 mg/l).

At the stage of multiplication, plants maintain high morphogenetic potentials in *in vitro* culture and provide a stable multiplication factor of 6.5-22.7 during seven to eight cycles of cultivation, depending on the biological characteristics of the species.

At the rooting stage of microshoots, the nutrient medium ½ MS, supplemented with IOLK (0.5 mg/l) and IOLK (0.5 mg/l), was determined to be optimal, which ensured a rooting frequency of 80.0-97.5%.

The most effective for the adaptation of plants to *in vivo* conditions is a substrate containing peat and perlite in a volume ratio of 3:1, on which the survivability of all studied plant species was 82.5-100.0%.

Prospects for further research are in the development of an integrated system of seed production of essential oil plants with the aim of obtaining standard planting material and studying the characteristics of growth and development, forming the productivity of plants of the *Lamiaceae* family for the development of technological measures for their cultivation in the conditions of the Southern Steppe of Ukraine.

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CONFLICT OF INTEREST

The authors declare that the study was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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Клональне мікророзмноження *in vitro* ефіроолійних рослин родини *Lamiaceae* Lindl.

Тетяна Миколаївна Манушкіна

Кандидат сільськогосподарських наук
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0001-5843-271X>

Тетяна Володимирівна Качанова

Кандидат сільськогосподарських наук
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0003-0032-3996>

Микола Олександрович Самойленко

Доктор сільськогосподарських наук
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-3292-9717>

Олена Іванівна Петрова

Кандидат сільськогосподарських наук
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0001-8612-3981>

Анотація. Актуальність дослідження щодо розробки біотехнології клонального мікророзмноження рослин родини *Lamiaceae* Lindl. зумовлюється необхідністю масового одержання оздоровленого чистосортного садивного матеріалу для закладання промислових плантацій та розширення площ ефіроолійних культур в Україні. Метою досліджень було розробити біотехнологічні заходи клонального мікророзмноження ефіроолійних рослин родини *Lamiaceae* – *Lavandula angustifolia* Mill., *Mentha x piperita* L., *Salvia officinalis* L. і *Monarda fistulosa* L. Завдання дослідження – підібрати оптимальні умови для ефективного культивування рослин родини *Lamiaceae* на чотирьох етапах клонального мікророзмноження. Основні методи дослідження: лабораторний, польовий, аналітичний і математико-статистичний. *Визначено* оптимальні для індукції морфогенезу *in vitro* та етапу мультиплікації живильні середовища на основі базового середовища Мурасиге і Скуга: для *L. angustifolia* доповнене кінетином (1,0 мг/л) і гібереловою кислотою (1,0 мг/л), для *M. x piperita* – 6-бензиламінопуріном (1,0 мг/л) і гібереловою кислотою (0,1 мг/л), для *S. officinalis* – 6-бензиламінопуріном (1,0 мг/л) та ЮлК (0,5 мг/л), для *M. fistulosa* – 6-бензиламінопуріном (1,0 мг/л) та β-індоліл-3-олійною кислотою (0,1 мг/л). На етапі мультиплікації доцільно проводити сім-вісім циклів культивування. На етапі укорінення мікропагонів найбільш ефективним для усіх досліджуваних видів рослин визначено живильне середовище Мурасиге і Скуга зі зменшеною вдвічі концентрацією компонентів, доповнене β-індоліл-3-олійною кислотою (0,5 мг/л) та β-індоліл-3-оцтовою кислотою (0,5 мг/л). Оптимальним для адаптації рослин до умов *in vivo* визначено субстрат торф: перліт у співвідношенні за об'ємом 3:1. *Включення розробленої біотехнології клонального мікророзмноження до системи насінництва ефіроолійних культур родини Lamiaceae* дозволить прискорено одержувати оздоровлений чистосортний садивний матеріал та впроваджувати нові продуктивні сорти у виробництво

Ключові слова: *Lavandula angustifolia* Mill.; *Mentha x piperita* L.; *Salvia officinalis* L.; *Monarda fistulosa* L.; коефіцієнт розмноження

Determining the probability of failure of marine diesel engine parts

Gennady Ivanov*

PhD in Technical Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-3861-7300>

Pavlo Polyansky

PhD in Economics, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0001-5661-8166>

Abstract. Maritime transportation is the essence of the international economy. Today, about ninety percent of world trade is carried out by sea through 50,000 merchant ships. Most of these vessels are powered by mainline diesel engines due to their reliability and fuel efficiency. Reliability of system elements in general depends on random failures, significant wear during operation, additional wear during start-up. Accidental damage to diesel engine components is a major hazard during operation, as some parts (such as cylinder liners and pistons) are usually replaced during repairs. On the other hand, preventive service does not eliminate random malfunctions. Therefore, in the general problem of assessing the reliability of a diesel engine, there is a mathematical problem of assessing the reliability and durability, taking into account only the random failures of its elements, which are of the greatest practical importance. The purpose of the work is a mathematical study of the reliability of parts of the cylinder-piston group of the main engines of dry cargo ships. Using a systematic approach and a probabilistic statistical method, it was established that the most common and difficult case is the simultaneous action on a system element (for example, a cylinder sleeve) of factors that cause wear during the period of operation (including during the start-up period) and accidental failures. It was determined that the quality of the cylinder-piston system in ships of the "Ostriv Rosiyskiy" type is higher than in the ships of the "Simferopol" and "Murom" types. Empirical formulas for estimating the probability of emergency failure of main engine system elements during the period of operation between factory repairs were obtained, where the main danger during the period of operation was carried by accidental failures. Based on the results of the study, it is possible to establish a schedule for the periodicity of maintenance of the ship's main engine and the cost of losses due to ship downtime due to failures, and can also be used in the reliability study of other types of ship's main engines. The results make it possible to determine the reliability of the parts of the cylinder-piston group of the main engines of dry cargo ships. and, in particular, to establish the maintenance schedule of the ship's main engine and the cost of damages due to ship downtime due to failures, and can also be used in the study of the reliability of other types of main engines of other series of ships

Keywords: wear; operating time; cylinder sleeve; piston; cylinder cover

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*Corresponding author

INTRODUCTION

The problem of quality and reliability for sea transport is of particular importance, as it is related to the safety of navigation. In order to predict the quality and reliability of the ship's main diesel engines, it is necessary to study the operating conditions of the main power plants, determine and forecast the probability of an emergency failure in any period of time, as well as the probability that there will be no emergency failures for the entire period or an emergency failure will occur in the first transition. Trampert *et al.* (2008) emphasize the importance of accurately defining the boundary conditions and the sensitivity of the service life of cast iron cylinder heads to the defined engine operating boundary conditions.

On the basis of operational data and results, which are verified with the help of a computer program to determine the relevance of the obtained results, it is established that the reliability of system elements in general depends on the effect of component aging on system reliability (Mihanović *et al.*, 2021).

Munir & Shah (2015) discuss available analysis methods, also a step-by-step approach to systematic qualitative analysis of engine reliability.

J. Kowalski *et al.* (2017) propose an automatic system based on machine learning for intelligent fault diagnosis of marine diesel engines.

Wear of main engine parts during maneuvers for transport refrigerated vessels of the "Surf" series, the average number of starts and reverses during one stop (7 days) is 20. For quantitative assessment, it is assumed that one start from a cold state corresponds to the amount of wear for 5 hours of running time. The amount of wear during one hot start or reverse – one time of running time. In the total number of starts, 25% belong to the cold state. All reversals are considered hot, since less than 4% belong to the cold state. Then the average wear during one parking lot corresponds to the wear during 34.5 hours of normal work. The additional time proportional to maneuvering wear (for parking time) will be: with 31 parking spaces per year, this time is 1070 hours/year. With an average annual running time of 2,300 hours, the additional time is 46.5%.

The identification of car failures as a way to increase its reliability is considered in the work (Pagán Rubio *et al.*, 2018; Vera-García *et al.*, 2019). In the conditions of the operating company, in order to increase the operational reliability of the car, it is important to classify failures by the source of occurrence. Today, most modern enterprises implement a quality management system in order to increase the efficiency of their activities. From the point of view of the quality management system, taking into account its continuous improvement, it is necessary to identify problem areas of operational reliability and direct appropriate efforts to increase it.

The issue of information systems for monitoring the technical condition of cars, a general approach to

the formation of models for evaluating the technical condition of a car in operating conditions, and the study of an agent approach to control the technical condition of vehicles are discussed in works Anantharaman *et al.* (2019), Fang & Cui (2020), Zhang *et al.* (2022).

Predicting the fatigue life of the main engine cylinder head and taking into account accurate and acceptable models is discussed by Jing *et al.* (2022).

Detection and elimination of marine diesel engine failures based on real-time diagnostic signals, i.e., symptoms and their relationship to failures in an extended form with symptom onset time tracking and based on human expert heuristic knowledge, is discussed by Sánchez-Herguedas *et al.* (2021), and for more accurate identification of wear defects, a multi-model fusion system based on the rule of evidentiary reasoning is proposed (Xu *et al.*, 2020).

The article by Lazakis *et al.* (2018) proposes a systematic approach to the identification of critical systems/components of ship equipment and the analysis of their physical parameters. Critical systems/components of the ship's main engine are used as inputs to a dynamic time series neural network to monitor and predict future values of physical parameters associated with critical ship systems.

The development of a 4-stroke high-speed marine diesel engine used on military and civilian vessels as a main engine is described in work Pagán Rubio *et al.* (2018). The failure simulator is based on a one-dimensional thermodynamic model developed, adjusted and validated with experimental data from a real engine on a test bench. The novelty of this work is the applied methodology that combines asset expertise, methodology and failure modeling to obtain an accurate and reliable database for failure prediction, which is a key element of diesel engine failure.

The authors Sánchez-Herguedas *et al.* (2022) presented a new method for calculating the optimal time interval before preventive maintenance and developed a mathematical expression represented by a system of differential equations.

In their study, Zhang *et al.*, (2022) analyze relevant data collected from various sources to determine the most plausible failure model representing a particular component. The collected data and the developed model will be very useful for assessing the reliability of ship engines and planning maintenance activities on board the ship. This can lead to a reduction in marine engine failures, which will ultimately contribute to a reduction in accidents in the shipping industry.

The purpose of the study is to study the operating conditions of the main power plants, to determine and forecast the probability of an emergency failure in any period of time, as well as the probability that there will be no emergency failures for the entire period or an emergency failure will occur in the first transition.

MATERIALS AND METHODS

A systematic approach and a probabilistic statistical method were used to obtain empirical formulas that allow determining the probability that there will be no emergency failures during the entire period or that an emergency failure will occur on the first transition and to predict the probability of emergency failures of parts of the cylinder-piston group of the main engines.

It is presented that the ship's main diesel engine is a sequence of chains of N elements (parts or assembly units), the reliability of which depends on the overall failure-free operation of the engine.

First, the law of the distribution of random failures of elements is determined, which is expressed by the reliability function – the probability of trouble-free operation $P(t)$ for the time from 0 to the moment t , as well as the time of operation, wear and failure of each element, separately for the following cases: 1 – failure with replacement, where it is possible to determine the time after which all the initially delivered parts will fail, i.e. the term of their work; 2 – failure with replacement and recovery, where the parts that failed are replaced with new ones, so there will be mixed parts in the work. This will allow you to calculate the number of failures of parts of this type for a given period of time.

Knowing the laws of distribution (the number of accident-free transitions during the normative period), we find the mathematical expectation – the average number of error-free transitions. The time interval T can be considered random, since its choice did not require the condition that T is the standard service life, and it can be replaced by any time interval from the start of operation to the moment t . Then it is necessary to calculate for engine cylinder liners. Having obtained the result, it can be argued that at the current rate of failure of the bushings, none of them will reach the wear limit.

Significant wear occurs when starting and revving the engine. This additional wear is quantified based on the number of starts and reverses.

To maintain reliability at a sufficiently high level at time points t_1, t_2, \dots, t_i , the number of preventive inspections and repairs is determined. They must be performed during parking times so that the running time is not affected.

The failure data together with the failure time is used, comparing the preventive interval obtained after applying the methodology with the interval obtained when only the failure data without hours of attendance are known. As a result, there is a need to compare the exponent calculation for cylinder sleeves with the average data to determine the adequacy and validity of our dependencies.

Having determined the time loss due to failures of each part for the entire inter-repair period or the number of failures of parts, it is possible to estimate the full cost of operational time for failures at sea (in hours), which is one of the main factors that affect the cost of transportation and maintenance of main diesel engines in trouble-free operation work.

RESULTS

A diesel turbopiston engine is considered as a sequential chain of N elements (parts or assembly units), the reliability of which depends on the overall reliability of the engine. Reliability of system elements mainly depends on random failures, basic wear and tear during operation, additional wear and tear during start-ups.

Accidental failures of diesel engine system elements are the primary danger during operation, because some parts (for example, cylinder liners and pistons) are replaced, as a rule, during repairs. On the other hand, accidental failures are not eliminated by the preventive service. That is why, in the general problem of diesel engine reliability assessment, the mathematical problem of reliability and durability assessment taking into account only random failures of its elements has the greatest practical importance.

The law of the distribution of random failures of elements is expressed by the reliability function – the probability of failure-free operation $P(t)$ for the time from 0 to the moment t :

$$P(t) = \exp(-\alpha t), \quad (1)$$

where t – time in thousands of hours; α – coefficient of the exponential law of parking time distribution.

The rate of wear of the cylinder liners during operation will be assumed to be constant and independent of accidents, which is natural for the period of normal operation. The amount of wear ξ during one transition is a random variable ($\xi = v \cdot \tau$) with an exponential distribution law:

$$f(x) = \lambda \exp(-\lambda x). \quad (2)$$

Here $\lambda = \frac{\beta}{v}$, $x \geq 0$; β – the coefficient of the exponential law of the transition time distribution.

For the following decisions, it is necessary to have the value of α , which refers to the details we need under different conditions. Note that the failure exponent should be determined for the relative proportion of parts that fail. If there is an information about z_s of ships, and the ship's engine has z_c of parts of this type, then their total number is equal to the product of $z_s z_c$. The number of failures in any interval of the statistical series is determined by the ratio $m_i / (z_s z_c)$.

The final expression will be written in the following form:

$$\exp(-\alpha t) = 1 - \frac{m_i}{z_s z_c}. \quad (3)$$

Hence, for the given value of t , there is an opportunity to find the value of α for the following cases:

1. Rejection with replacement of α_z . It is possible to determine the time after which all the initially supplied parts will fail, i.e. the term of their operation.

2. Failure with replacement and restoration of α_v . The parts that failed are replaced with new ones, so there will be mixed parts in the work. This will make

it possible to calculate the number of failures of parts of this type for a given period of time (mixed failures).

The value of α for the main engines of some types of vessels is given in Table 1.

Table 1. The value of α for the main engines of some types of ships

Ships series	Value $\alpha \cdot 10^{-2}$, 1/thousands of hours		
	cylinder liners	pistons	cylinder covers
"Simferopol"	2.08/3.38	2.08/2.40	–
"Murom"	2.80/3.38	2.70/3.04	3.13/3.46
"Lysychansk"	1.75/2.38	–	–
TR "Ostriv Rosiyskiy"	0.47/0.74	0.75/1.21	0.87/0.87

Note: The numerator is the value of α_2 , the denominator is α_v

Source: author's development

Currently, shipping companies and administrations have introduced a four-year period of operation of ships between factory repairs, so the reliability calculation for this period is of undoubted interest. The working time corresponding to this period will be determined, as it is called, normative.

Knowing the laws of distribution of the value of η_m (the number of accident-free transitions during the regulatory period):

$$P(\eta_m = k) = \frac{a^k(1-a)}{(k-1)!} [k, (\alpha + \beta_n)T_n] + a \frac{(\beta_n T_n)^k}{k!} \exp[-(\alpha + \beta_n)T_n]; \quad (4)$$

$$P(\eta_m = 0) = \frac{\alpha}{\alpha + \beta_n} \exp[-(\alpha + \beta_n)T_n]. \quad (5)$$

There is an opportunity to find the mathematical expectation – the average number of error-free transitions:

$$M\eta_m = \frac{\beta}{\alpha} [1 - \exp(-\alpha T)]. \quad (6)$$

Formulas (4) and (5) give the final solution to the problem. The first formula gives the probability that there will be no failures during the entire period, and the second – that the failure will occur on the first transition.

Expression (6) can be represented in the form:

$$M\eta_m = Q(T) \cdot M\eta. \quad (7)$$

That is, the average number of failure-free transitions for the normative period T is equal to the multiplication of the probability of a random failure during this period by the average theoretical number of failure-free transitions.

In formulas (6) and (7), the time interval T is considered random, since its selection did not require the condition that T is the standard service life, and it can be replaced by any time interval from the start of operation to the moment t.

For cylinder liners of vessel engines, the calculation according to formula (8) gives the result (values of coefficients α , β , b and λ are given in Table 2).

Table 2. Values of coefficients α , β , b, λ

Ships series	α_2 , 1/(thousands of hours)	β , 1/(thousands of hours)	b, mm	λ , 1/mm
"Simferopol"	0,0208	5,75	6,5	261
"Murom"	0,0280	7,00	6,5	279
"Lysychansk"	0,0175	3,40	7,0	170
TR "Ostriv Rosiyskiy"	0,0047	7,40	4,5	7350

Source: author's development

That is, at the current rate of bushing failure, none of them will reach the wear limit. This statement is also true for pistons.

As you know, significant wear and tear occurs when starting and revving the engine. This additional wear is quantified based on the number of starts and reverses. For example, for transport refrigerated vessels (TR) of the "Kamchatka Mountains" type, the additional time proportional to wear on maneuvers (during docking) is

870 hours or 38% of working time. This value is 800 hours or 20% of the average annual working hours on dry cargoes of the "Morom" series.

The probability of failure-free operation of the element before its replacement at the specified level "b" of the wear limit is:

$$P(b) = \left(\frac{\beta}{\alpha + \beta}\right) \exp\left(-\frac{\alpha \lambda \beta}{\alpha + \beta}\right). \quad (8)$$

Indeed, the average time to reach the wear limit, expressed in the number of transitions, can be defined as:

$$M(b) = \lambda \cdot b. \quad (9)$$

The calendar time of reaching the wear limit (in hours and thousands of hours) is found from the expression:

$$T_k = \frac{M(b)}{k}, \quad (10)$$

where k is the average annual number of conversions.

Finally, there will be a period of random failure of the cylinder liners due to accidental breakages:

$$T_{vc} = \frac{4.6}{\alpha_z}. \quad (11)$$

The values of the numbers included in formulas (9)-(11) are given in the Table 3.

The time to reach the limit of wear is such that the bushings are discarded much earlier than necessary, and their wear period will exceed another period between factory repairs (four years).

Table 3. Values of quantities $M(b)$, T_k , T_{vc}

Ships series	$M(b)$, transitions	T_k		T_{vc} , thousands of hours
		years	thousands of hours	
"Simferopol"	1700/1410	69.0/57.0	290/240	221
"Murom"	1830/1500	65.5/53.5	262/214	164
"Lysychansk"	1190/995	59.0/49.3	352/294	263

Source: author's development

Thus, the main safety during operation, in particular directly during transitions, is created by accidental (emergency) failures that cause stops (delays) at sea to eliminate them. This leads to an unproductive waste of time, increasing the transition time. In addition, sometimes it

is necessary to finish the transition or even travel at a reduced speed after eliminating a malfunction at sea.

Various parts and assemblies can fail in main engines at sea. An example of indicators for transportation of refrigerators and dry cargo is given in Table 4.

Table 4. Indicators for transport refrigerated and dry cargo vessels

Parts and assembly units of main engines	Refusals in the sea	
	Quantity	Percentage of the total
TR "Ostriv Rosiyskiy":		
High pressure fuel pumps	396	53.0
Injectors	227	30.0
TR "Sea of Okhotsk":		
Injectors	102	16.0
Cylinder cover	89	14.0
High pressure fuel pumps	84	13.5
"Murom":		
Injectors	56	26.0
Bearings	51	24.0

Source: author's development

The average indicators of the number of failures, warnings and disclosure of the main parts and assem-

bly units of the main engines of the ships of the "Murom" series at sea are shown in the Table 5.

Table 5. Average indicators of the number of failures, prevention of parts of the main engines of the “Murom” series ships at sea

Detail of the assembly unit Injectors	Values			
	Δn_{ms}	Δn_{tr}	T_{ms}	T_{tr}
Bearings	0.3800	0.1680	2.63	5.95
Piston-sleeve	0.3460	0.2380	2.89	4.20
Fuel pumps	0.2720	0.7760	3.67	1.29
Cylinder covers	0.1360	0.1145	7.35	8.74
Outlet valves	0.1220	0.2415	8.20	4.15
Gas turbochargers	0.0952	0.1350	10.50	7.40
Telescopic pistons	0.0340	0.2210	29.40	4.53
Detail of the assembly unit	0.0340	0.1520	29.40	6.58

Source: author's development

They are obtained by calculations according to the formulas:

$$\Delta n_{ms} = \frac{n_m}{z_s \cdot T_{avg}}; \Delta n_{tr} = \frac{n_{tr}}{z_s \cdot T_{avg} \cdot z_c};$$

$$T_{ms} = \frac{1}{\Delta n_{ms}}; T_{tr} = \frac{1}{\Delta n_{tr}}. \quad (12)$$

Here, Δn_{ms} is the number of failures at sea for one vessel per 1,000 hours of operation; n_m – the number of failures at sea; z_s – number of vessels; T_{avg} – vessel operating time, thousand hours; Δn_{tr} – number of disclosures and warnings per element per 1,000 hours of work; n_{tr} – number of cases of discovery, transfer and prevention on the dock; z_c – the number of parts of this

type of engine; T_{ms} – the average operating time of the vessel between element failures, thousand hours; T_{tr} – the average operating time of the element between opening and warning, thousand hours.

The probability of failure-free operation of the part during the standard time is determined by the formula:

$$P(T_n) = \exp(-\alpha_v T_n), \quad (13)$$

where α_v is the rate of failures with replacement and restoration, 1/(thousand hours), see Table 1; T_n – standard time, thousands of hours. The values of parts of the cylinder-piston group of ships of the “Simferopol”, “Murom” and “Ostriv Rosiyskiy” series are given in the Table 6.

Table 6. Values of $P(T_n)$ for parts of the cylinder-piston group of ships of the “Simferopol”, “Murom” and “Ostriv Rosiyskiy” series

Details	Time intervals, thousands of hours	$P(T_n)$		
		“Simferopol”	“Murom”	“Ostriv Rosiyskiy”
Cylinder bushings	0-8	0.763	0.763	0.943
	0-16	0.583	0.583	0.888
	0-32	0.340	0.340	0.790
Pistons	0-8	0.825	0.784	0.908
	0-16	0.682	0.616	0.823
	0-32	0.464	0.379	0.678
Cylinder covers	0-8	–	0.758	0.880
	0-16	–	0.574	0.774
	0-32	–	0.330	0.599

Source: author's development

The average number of accident-free transitions during the standard period is determined by formula (6). The average number of transitions for the established period between factory repairs is based on statistical information about the operating experience. It is equal to 112 and 32, respectively, during the four-year period of operation of the ships of the “Murom” and “Ostriv Rosiyskiy” series. The above dependencies allow you to calculate the number of failures.

The number of element failures that may occur during the established repair period can be determined by the formula:

$$z = \frac{M_{per}}{M\eta t} = \frac{M_{per}}{\frac{\beta}{\alpha}[1 - \exp(-\alpha_v T_n)] + 1} \cdot \quad (14)$$

The values of the average number of accident-free transitions and the number of failures of engine parts of the above-mentioned vessels are given in the Table 7.

Table 7. The value of the average number of accident-free transitions and the number of failures of engine parts of dry cargo and transport refrigerated ships

Time intervals, thousands of hours	$M(T_n)$			z, pcs		
	“Simferopol”	“Murom”	“Ostriv Rosiyskiy”	“Simferopol”	“Murom”	“Ostriv Rosiyskiy”
Cylinder bushings						
0–8	40.2	49.0	57.2	2.40/2.0	2.30/2.0	0.55/1.0
0–16	71.0	86.5	113.0	1.40/1.0	1.30/1.0	0.28/0
0–32	112.0	137.0	212.0	0.88/1.0	0.82/1.0	0.82/1.0
Pistons						
0–8	42.0	49.7	56.0	2.36/2.0	2.25/2.0	0.56/1.0
0–16	76.0	88.5	108.0	1.30/1.0	1.27/1.0	0.28/0
0–32	128.0	143.0	196.0	0.78/1.0	0.78/1.0	0.16/0
Cylinder covers						
0–8	–	48.0	56.0	–	2.33/2.0	1.57/1.0
0–16	–	86.0	104.0	–	1.30/1.0	0.31/0
0–32	–	136.0	181.0	–	0.83/1.0	0.17/0

Note: in the denominator is the number of refusals accepted for calculation

Source: author's development

Comparing the calculation based on the exponent for cylinder sleeves with the average data in the Table 5. The running time of the “Murom” series vessel over four years of operation is $T_n=16$ thousand hours. Then the probability of failures will be $Q(16)=1-\exp(-0.28 \cdot 16)=0.36$. So, out of six engine bushings (on one vessel), bushings will fail and need to be replaced. This will cause two vessel delays at sea. The average time between exits is thousand hours. According to the Table 5, it is possible to calculate that bushing and piston failures are distributed equally, the average working time between failures will be equal to

$2 \cdot 3.67=7.34$ thousand hours, that is, a little more than the calculated one. This ratio is also valid for pistons.

For cylinder covers, the ratio between the calculation results and the data in the Table 5 will be different. Indeed, for $T_n=16$ thousand hours there will be: $Q(16)=1-\exp(-0.0313 \cdot 16)=0.39$.

Therefore, $0.39 \cdot 6=2.34$ covers need to be replaced. The average time of operation of the cover between failures will be $16 \cdot 2.34=6.85$ thousand hours, which is less than the data in the Table 5. This is explained by the fact that covers that have received water flow can be replaced at the parking lot, and this does not lead to

delays at sea. At the same time, it should be noted that the calculation results and the data in the Table 5 are close to each other.

Estimated data for the “Ostriv Rosiyskiy” TR (at the value of running time for 4 years of operation $T_n = 10$ thousand hours) are given in Table 8.

Table 8. Calculation data for TR type “Ostriv Rosiyskiy”

Indexes	Cylinder-piston group of ships		
	Cylinder bushings	Piston cylinder covers	Piston cylinder covers
Failure probability $Q(10)$	$1 - e^{-0.0087 \cdot 10} = 0.09$	$1 - e^{-0.0075 \cdot 10} = 0.073$	$1 - e^{-0.00787 \cdot 10} = 0.05$
Number of failures	$0,09 \cdot 24 = 2.16$	$0.073 \cdot 24 = 1.75$	$0.05 \cdot 24 = 1.2$
Average time between failures, thousands of hours	$10 / 2.16 = 4.64$	$0 / 1.75 = 6.45$	$10 / 1.2 = 8.30$

Source: author's development

The main negative result of failures at sea is the loss of operational time. For example, the average time of forced stops, obtained by averaging information on vessels of the “Murom” series, ranges from 0.5 to 4 hours. The loss of time due to failures of each part for the entire inter-repair period is (in hours) $\tau_{ei} = z_i \cdot \tau_i$. Here z_i is the number of part failures.

The total cost of operational time for failure at sea (in hours):

$$\tau_{\Sigma tl} = \sum_{i=1}^n z_i \cdot \tau_i. \quad (15)$$

Damage (thousand hryvnias) arising from forced downtime at sea due to failures:

$$R = C \cdot \tau_{\Sigma tl}. \quad (16)$$

Here C – the cost of maintaining one vessel during the day, thousand hryvnias.

As an example, let's calculate the damage only for parts of the cylinder-piston group (piston, bushing, cover) of vessels of the “Murom” series over a period of 4 years. Taking into account that two of the named parts fail in a year, and the time spent on each output for bushings and pistons is 4 hours, for covers – 2.3 hours, we get for a four-year period: $R = 2.98 \frac{4}{24} (2 \cdot 4 + 2 \cdot 4 + 2 \cdot 2.3) = 10.23$ thousand UAH.

DISCUSSION

The researchers Xu *et al.* (2020) proposed a multi-model fusion system for more accurate identification of wear defects. Authors agree that it is necessary to consider marine diesel engines, which consist of many tribological systems, such as cylinder liner-piston ring system, main bearing system, and that almost 50% of engine failures are caused by abnormal wear of friction pairs, the authors also consider a chain sequence

of N elements (parts or assembly units), the reliability of which depends on the overall health of the engine.

The authors Sánchez-Herguedas *et al.* (2022) proposed a method for detecting and eliminating ship diesel engine failures, based on real-time diagnostic signals and on the basis of human expert heuristic knowledge, which may not provide fully accurate information about the true state of the parts and underestimate the period of trouble-free operation. However, the authors of the study derived dependencies that allow determining the probability of fault-free operation of elements based on statistical data.

In the research paper (Vera-García *et al.*, 2019), authors use a methodology that combines expert knowledge of the object and modeling of technical inspection to obtain an accurate and reliable database for predicting diesel engine failures based on a failure simulator. Lazakis *et al.* (2018) proposed a systematic approach to the identification of critical systems, components of the ship's main engine are used as input data to a neural network of dynamic time series for monitoring and forecasting future values of physical parameters related to critical ship systems. Zhang *et al.* (2022) propose a method for reconstructing dynamic fault trees to find weak links at the component level. Basurko *et al.* (2022) presented engine performance monitoring and fault detection to create a three-layer forward neural network of engine operation. Kowalski *et al.* (2017) presented an experiment consisting of measurements made during the operation of a laboratory engine with simulated faults to create a classification of fault patterns. The authors Rao *et al.* (2022) propose online condition monitoring and self-healing for in-service diesel CLPRs from a tribosystem perspective in a real-time maintenance context. However, the authors of the study use a probabilistic statistical method, which is a faster way to determine the prediction of diesel engine failures. The study of the operational reliability of the main

engines of marine transport vessels was carried out taking into account the operating conditions and load level. The applied restoration theory apparatus is most convenient in the conditions of engine operation with alternating transitions and ship stops.

Trampert *et al.*, (2008) in their article predict the fatigue life of the cylinder head of the main engine. The authors similarly investigated the ultimate wear of the sleeve. In addition, the authors considered the joint effect of semi-random and random failures: main wear during running time; additional wear during maneuvering time associated with parking lots; accidental (emergency) failures.

The authors Anantharaman *et al.* (2019) are suggested to draw up an optimal maintenance plan taking into account the advice of engine manufacturers and/or chief engineers and ship captains. The authors obtained empirical formulas that allow determining the probability of work for the entire period or at the first transition. This method of calculation: the number of failures, stops at sea with or without replacement, emergency failures of parts of the cylinder-piston group. For this purpose, the value of the failure exponent indicator is determined for several cases: failure with replacement, which allows you to trace the gradual failure of the initial group of parts. It is possible to determine how long it will take for all initially delivered parts to fail, i.e. trace their service life; failure with replacement and recovery. Rejected parts are replaced with new ones, so there will be a mixed composition of parts in the work. This allows you to determine the number of failures of parts of a given type in a given period of time (mixed failures), failures with replacement and stoppage at sea; failure without replacement, but with a stop at sea.

CONCLUSIONS

The diesel turbopiston engine was considered as a sequential chain of N elements (parts or assembly units). The overall reliability of the engine depends on its reliability. On the basis of operational experience, it was established that the reliability of the system elements, for the most part, depends on random failures, basic wear and tear during operation, and additional wear and tear during start-ups.

The elements that make up the marine engine system, which are considered, work in conditions defined

by various distribution laws, which are established during the statistical processing of information obtained from operational documents.

The given dependencies allow you to determine the probability of failure-free operation of the element before its replacement and the probability of failure-free operation of the part during the standard time.

It has been proven that the case of simultaneous action on an element (for example, on a cylinder sleeve) of factors that cause wear during the period of operation (including during the start-up period) and accidental failures is common and difficult. Other elements of the system under consideration correspond to the same complex of conditions or its partial case.

The calculation showed that the probability of failure-free operation of parts of the cylinder-piston group for the standard time of 8 and 32 thousand hours in the vessel of the "Ostriv Rosiyskiy" type is 0.943 and 0.790, respectively, and in the dry cargo vessels of the "Simferopol" and "Murom" series – 0.763 and 0.340, which indicates higher quality details in the first type of vessels.

It has been studied that when the elements of the system reach the limit of wear during the set period of operation, between factory repairs is practically excluded, so the main danger during the period of operation is accidental failures. The period of accidental failure of cylinder liners is determined.

Empirical formulas were obtained for the first time, which make it possible to determine the probability that there will be no emergency failures during the entire period; that a failover will occur on the first transition.

Taking into account the different reliability of elements of the marine engine system, which affect the behavior of the control system as a whole, the results make it possible to establish the periodicity of their maintenance and the cost of downtime losses due to failures.

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CONFLICT OF INTEREST

The authors declare that the study was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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Визначення імовірності відмов деталей суднових дизельних двигунів

Геннадій Олександрович Іванов

Кандидат технічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-3861-7300>

Павло Миколайович Полянський

Кандидат економічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0001-5661-8166>

Анотація. Морські перевезення є суттю міжнародної економіки. Сьогодні близько дев'яноста відсотків світової торгівлі здійснюється морським транспортом через 50000 торгових суден. Більшість цих суден приводиться в рух головними дизельними двигунами завдяки їх надійності та паливній ефективності. Надійність елементів системи в загальному випадку залежить від випадкових відмов, значного зносу в процесі експлуатації, додаткового зносу при пуску. Випадкова поломка компонентів дизельного двигуна є великою небезпекою під час експлуатації, оскільки деякі деталі (наприклад, втулки циліндрів і поршні) зазвичай замінюються під час ремонту. З іншого боку, профілактична служба не усуває випадкові несправності. Тому в загальній проблемі оцінки надійності дизеля – математична задача оцінки надійності і довговічності з урахуванням тільки випадкових відмов її елементів, що мають найбільше практичне значення. Метою роботи є математичне дослідження надійності деталей циліндро-поршневої групи головних двигунів суховантажних суден. Використовуючи системний підхід та ймовірно-статистичний метод, було встановлено, що найбільш загальним і важким є випадок одночасної дії на елемент системи (наприклад на гільзу циліндра) факторів, що викликають зноси в період експлуатації (в тому числі в період пусків) і випадкові відмови. Визначено, що якість циліндро-поршневої системи у суден типу «Острів російський» вища, ніж у суден типу «Сімферополь» і «Муром». Отримано емпіричні формули оцінки ймовірності аварійної відмови елементів системи головних двигунів за період експлуатації між заводськими ремонтами, де основну небезпеку в період роботи несли випадкові відмови. За результатами дослідження можна встановити графік періодичності проведення технічного обслуговування головного суднового двигуна та вартість збитків простоїв судна внаслідок відмов, а також можуть бути використані при дослідженні надійності інших типів суднових головних двигунів. Результати дають можливість визначити надійність роботи деталей циліндро-поршневої групи головних двигунів суховантажних суден. і, зокрема, встановити графік проведення технічного обслуговування головного суднового двигуна та вартість збитків простоїв судна через відмови, а також можуть бути використані при дослідженні надійності інших типів головних двигунів інших серій суден

Ключові слова: знос; експлуатаційний час; втулка циліндра; поршень; кришка циліндра

Bioenergetic efficiency of drip irrigation modes of grapes

Ivan Shevchenko*

Full Doctor in Agrisciences, Professor
Mykolaiv National Agrarian University
54000, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0003-0539-7062>

Natalia Nikonchuk

PhD in Agrisciences, Associate Professor
Mykolaiv National Agrarian University
54000, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-9425-2684>

Abstract. In modern conditions of water scarcity, the research of the energy evaluation of different modes of drip irrigation to reduce the consumption of irrigation water, material and energy resources, their effective use on irrigated grape plantations cultivated on the sandy chernozems of the left bank of the Lower Dnieper, where only irrigation is the guarantee of annual, constant high yield of vineyards. The purpose of the research was to study the energy efficiency of grape drip irrigation regimes, determine the volume and structure of resource costs, and the level of their payback. Field and comparative-calculation methods were used during the research. The establishment and conduct of experiments were carried out according to the methodology of the research case. The paper presents the results of research on the energy efficiency of drip irrigation modes of grape plantations. It is established that maintaining an unhindered moisture supply to plants during the growing season is achieved by an additional cost of 9.29 GJ/ha of anthropogenic energy. A more economical regime of humidity of the active soil layer during the growing season reduces energy costs to 5.2-7.7 GJ/ha. The structure of additional energy costs, regardless of the irrigation regime of plantings, is dominated by the energy of irrigation water – 80% and energy carriers – 18 %. The practical significance of the research is to conduct an energy assessment of different modes of drip irrigation of grapes to reduce the consumption of irrigation water, material and energy resources and their efficient use

Keywords: moisture consumption; differentiated irrigation regime; optimal soil moisture; energy; energy intensity

INTRODUCTION

In the world where drinking water is becoming an increasingly scarce resource, 80% of which is used for irrigation of crops, optimizing water use should be a top priority for agriculture (Bulukazari *et al.*, 2022). This is especially true in viticulture, where the trade-off between crop loss and improved quality can be economically costly for producers and highly dependent on water supply. In arid regions, where limited precipitation is a limiting factor for the grape plant, irrigation plays an important role in compensating for water scarcity (Silvestroni *et al.*, 2020).

Global warming leads to changes in precipitation patterns and an increasingly negative water balance during the growing season of plants, which increases the risk of drought (Tabari, 2020; Korkhova & Mykolaichuk, 2022).

Changes in namely an increase in the average annual temperature by more than 2°C (Avalos & Araujo, 2021), observed over the past decades, a reduction in the precipitation rate and a violation of the precipitation regime significantly increase the likelihood of an acute shortage of moisture supply to grapes, very often before

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*Corresponding author

the beginning of the first phase of bush vegetation. In the subsequent stages of grape development, the lack of moisture consumption only increases, so you can prevent the harmful effects of drought by using artificial irrigation of plantings. Drip irrigation has the greatest prospects, the use of which provides an optimal water regime with lower irrigation water costs, it activates the production processes of plants during the defining periods of growth and development, and guarantees the most complete realization of the biological potential of various grape varieties (Miras-Avalos & Araujo, 2021; Ma, 2020). In turn, the effectiveness of reception directly depends on the humidity regime of the active soil layer.

Numerous studies and extensive practice of using drip irrigation of vineyards show that the greatest efficiency of local irrigation is provided at clearly defined upper and lower thresholds for moistening the local soil volume (Scholasch & Rienth, 2019; Romero *et al.*, 2022). Violation of the irrigation regime increases the consumption of irrigation water, financial and energy resources, it reduces the yield of plantings, worsens the quality and marketability of berries, which directly affects the economic efficiency of the industry (Gomez-Zavaglia *et al.*, 2020). It complicates the determination of the efficiency of viticulture as a branch of agricultural production, additional costs of energy resources and the use of various units of measurement: Hryvnia, kg, T, L, m³, people/hour, kWh, which increase the probability of error in economic calculations, limit the search for promising areas for reducing technological costs, rational use of Natural Resources (Noha, 2022; Sassu *et al.*, 2021). In addition, in a market economy, the efficiency of viticulture in general, and irrigated, in particular, depends on fluctuations in prices for energy carriers, fertilizers, plant protection products, the level of wages of workers, the demand and cost of viticulture products, and therefore complicates an objective assessment of the balance of costs and revenues from the sale of viticulture products (Strub & Loose, 2020; Sylva *et al.*, 2021). In this sense, the greatest prospect is energy analysis, which is based on the application of constant energy indicators that do not depend on constant changes in the price of viticulture products, fertilizers, fuels and lubricants, pesticides, etc. Comparison of the energy parameters of grape cultivation technology allows objectively determine the difference in the balance of technogenic and biological energy consumption. Energy analysis is particularly relevant today in the context of global and regional climate changes and the urgent need for economical use of resources, development and use of agricultural measures aimed at moisture accumulation and reducing the cost of moisture for the formation of a unit of viticulture production (Leeuwen *et al.*, 2019; Droulia & Charalampopoulos, 2022; Xyrafis *et al.*, 2022). This corresponds to a detailed justification of the bioenergetic efficiency of various modes of drip irrigation of grapes, as it allows you to establish the most effective mode of drip irrigation of plantings, to ensure an optimal balance of man-made energy costs and energy receipts synthesized by plants (Shevchenko *et al.*, 2021).

Purpose of research was to study the energy efficiency of drip irrigation modes of grapes, determine the volume and structure of resource costs, the level of their payback.

LITERATURE REVIEW

Agriculture, including industrial viticulture, is based on the process of converting solar energy through plant photosynthesis into the energy of macro-energy bonds of organic matter (Cataldo *et al.*, 2021). The volume of bound solar energy in the form of plant biomass is an integral indicator of the efficiency of cultivation of all crops, including grapes (Simon & Hülsbergen, 2021).

In the absolute majority of examples, the high productivity of modern grape growing technologies involves substantial costs for soil cultivation, fertilization, plantation care, irrigation, which directly affects the efficiency and terms of cultivation and the prospects of viticulture, causes negative changes in the environment, often irreversible. Permanent improvements and introduction of new methods of cultivation technology of grape plantations do not reduce the overall energy intensity, but involve certain additional financial and material costs, often significant, which in the absolute majority of cases are not fully covered by the additional harvest of berries (Mynkin, 2020). That is, the increase in productivity is achieved by the constant growth of direct and indirect costs of anthropogenic energy tenfold, and in the event of their termination or reduction, the production system degrades. One of the high-energy methods for optimizing environmental conditions is the widespread use of irrigation in the practice of growing a high yield of traditional agricultural crops, including grapes (Neupane & Guo, 2019).

Almost until the beginning of the 21st century, most often soil moisture was maintained by applying sprinkling and irrigation on the soil surface, which was achieved by high costs of man-made energy, natural energy resources (water), and their inefficient use (Vytoptova & Bondarenko, 2010). Producers have several options for minimizing the negative impact of drought, including switching to more efficient irrigation technologies, which are understood as technologies that increase the share of water available to the root system of a plant with a smaller amount of it (Novikov *et al.*, 2021; Bayala & Prieto, 2020). Recently, drip irrigation has been introduced into the practice of growing grape crops, which, unlike continuous moistening methods, provides humidity at a given level of 20-25% of the design volume of soil, which varies within 0.75-0.9 m³/bush and depends on the area of plant nutrition and their age, the depth of maximum root system development, which significantly reduces the cost of man-made and natural energy resources (Pisciotta *et al.*, 2018; Mirás-Avalos & Araujo, 2021). However, the different level of pre-irrigation humidity of the active soil layer, during the growing season of grapes, causes significant fluctuations in the consumption of irrigation water, energy carriers, and affects the productivity of grape plantations in different ways, the specific consumption of water, man-made energy per unit of production, and so on.

Irrigation of vineyards is one of the most expensive technological techniques for growing grapes in conditions of insufficient natural moisture. This problem becomes especially important in connection with the shortage of water all over the world and irrigated agriculture is one of the most inefficient consumers of this resource. Low water use efficiency (WUE) combined with increased competition for water resources with other industries is forcing producers to adopt new irrigation methods that use water more economically. In areas with arid and hot climates, deficit irrigation strategies, such as regulated deficit irrigation or partial root desiccation, have been used to conserve water, allowing crops to withstand moderate water stress with little or no reduction in yield and quality (Miguel Costa *et al.*, 2007). In their opinion, the irrigation deficit helps to save irrigation water in viticulture. Thus, a better understanding of grapevine response to water and heat stress combined with temperature-based yield monitoring will help optimize irrigation and soil management in viticulture.

T. Scholasch & M. Rienth (2019) indicate that when the root mass and root absorption sites are concentrated near the soil surface, the water consumption of the grape plant depends on the moisture content of the soil, which is located below the surface. K. Nader *et al.* (2019) acknowledge that older vines do have deeper and more developed root systems, making them more drought tolerant than younger plants.

Despite some inconsistencies in the obtained research results, all the mentioned authors believe that the greatest efficiency of local irrigation, reduction of energy consumption, and high efficiency of their use are achieved at clearly defined upper and lower thresholds for moistening the local soil volume (Vozhehova *et al.*, 2017; Lemos-Paiao *et al.*, 2022; Scholasch & Rienth, 2019). Reducing soil moisture, or increasing it beyond the established limits, reduces the yield of plantings, the quality of berries, and the efficiency of using energy resources (Weiler *et al.*, 2018).

The vast majority of studies on the effectiveness of various drip irrigation regimes of grapes were conducted on plantings cultivated on heavy loamy or southern chernozems of the country (Zelenyanska & Borun, 2021). Such studies are especially relevant for irrigated grape plantations cultivated on sandy loam chernozems of the left-bank lower Dnieper region, where only irrigation guarantees an annual, stable high yield of vineyards.

Problem statement – conducting an energy assessment of various modes of drip irrigation of grapes to reduce the consumption of irrigation water, material and energy resources, and their efficient use.

MATERIALS AND METHODS

The experiment was conducted during 2019-2021 carried out on 15-year-old plantings of the Rkatsiteli variety cultivated in Agricultural Private Firm (APF) "Tavria" of the Kherson region.

The study scheme included the following options:

1. Control (without irrigation);

2. Humidity of the active soil layer at the level of 100-80% the lowest moisture content during the growing season of plants;

3. 100-80% by the end of the flowering phase, subsequent phases (berry growth, crop maturation) 100-70% the lowest moisture content;

4. 100-70% the lowest moisture content during the entire growing season of plants.

The experiments were performed in a three-dose repetition. In each variant, there are 45 accounting bushes, 15 in repetition. There are 180 registered bushes in total.

The scheme of planting plants is 3.0×1.25 m, the formation of bushes is a high – stamp two – shoulder border with a height of 120 cm. The load of bushes with shoots in all variants of the experiment ranged from 32.4-33.1 PCs/bush.

The technology of drip irrigation of grapes uses irrigation pipelines with a diameter of 16 mm with integrated water outlets in increments of 0.6 m and a water flow rate of 3.8 dm³/ha, mounted on the lower wire of the trellis. The timing of regular irrigation, irrigation rates, and the duration of the inter-watering period were determined based on monitoring the dynamics of moisture reserves in the root layer of the soil, the regime and rate of precipitation. Moisture reserves were monitored every decade by the thermostatic-weight method.

Industrial grape plantations of the farm, including the experimental site, are cultivated on unproductive lands of the left-bank lower Dnieper region, which annually receive a large amount of heat and light, are characterized by high evaporation and aridity.

The soil of the experimental site, as well as the entire array of perennial plantings, is sandy loam chernozem with a humus content in a layer of 0-100 cm in the range of 0.4-0.6%. The volume weight of the soil is 1.42 g/cm³, the duty cycle is 41%, and the lowest moisture capacity is 17.1%. The type of water regime is not washing, the main natural moisture reserves of the soil are formed during the autumn-winter period.

During the research, agrobiological records of the development of eyes and elements of fruitfulness were carried out according to the generally accepted method in viticulture. Records of the berry yield were carried out by weight method, separately for each of the variants of the experiment. Water and electricity consumption was recorded using meters installed directly in the pumping station. The energy intensity of irrigation regimes, the use of natural and man-made energy resources for irrigation of plantings, and the volume of biological energy synthesis were calculated according to methodological recommendations (Tarariko, 2005; Lyannoy *et al.*, 1994).

RESULTS AND DISCUSSION

The dominant factor in the growth, development of grapes and high yield is the humidity of the active soil layer during the growing season of plants, which depends on the norm of precipitation and the mode of their precipitation. In most cases, the main soil moisture reserves in the region are formed during the autumn-winter period and reach 2200-2500 m³/ha, of

which 1500-1600 m³/ha are available for plants and ensure unhindered moisture consumption of grapes until the end of the flowering phase. In subsequent phases, plants vegetate in conditions of acute shortage of moisture consumption, which is not eliminated by summer precipitation, with the exception of individual years.

On average, over three years of research (2019-2021), the total moisture reserves of the active soil layer at the beginning of the first phase of vegetation also ranged from 1850 m³/ha to 2100 m³/ha, which potentially provided optimal conditions for plant moisture consumption until the end of the growth phase shoots. However, the high temperature regime that is established in the Steppe zone in the first decade of April,

insignificant amounts of precipitation, or their long-term absence cause a significant loss of moisture and accelerate the formation of an acute deficit of moisture consumption already in the middle of the second phase of vegetation, and humidity at the level of 80% of the lowest moisture content was formed already at the beginning of the shoot growth phase.

Reducing moisture reserves to the lower threshold of optimal moisture content for the second version of the experiment became the basis for regular irrigation of plantings. Soil moisture at the level of 80% the lowest moisture content during the growing season was provided by 14 waterings with an average irrigation rate of 81 m³/ha (Table 1).

Table 1. Drip irrigation mode of grape plantations depending on the level of pre-irrigation humidity of the local soil volume Agricultural Private Firm "Tavria", Rkatsiteli variety

RPVG, % the lowest moisture content	Number of waterings	Irrigation rate, m ³ /ha	Inter-irrigation period, days	Irrigation rate, m ³ /ha
Control (without irrigation)	-	-	-	-
100-80	14	81	7	1134
100-80-70	9	105	11	945
100-70	5	127	19	635

Source: authors' own research

According to the data in Table 1, the irrigated water rate for the growing season of grapes in this version of the experiment was 1134 m³/ha, with fluctuations, depending on the conditions of the year, up to 12%. The differentiated irrigation regime, which was applied with the beginning of the berry growth phase, reduced the number of waterings to 9, while irrigation water standards increased by almost 30% and amounted to 105 m³/ha. The irrigated water rate in this version of the experiment decreased by 17% and amounted to 945 m³/ha. The lowest total irrigation water consumption was achieved by

maintaining the lower threshold of optimal soil moisture at the level of 100-70% the lowest moisture content. For three years of research (2019-2021), the optimal soil moisture at the level of 100-70% the lowest moisture content was provided by 5 waterings carried out after 19 days at a rate of 127 m³/ha.

The conditions for providing plants with moisture that have developed under different irrigation modes have had different effects on the structure of energy consumption, the energy intensity of irrigation modes for grape plantations (Table 2).

Table 2. Structure and energy intensity of drip irrigation regimes for grapes APF "Tavria", Rkatsiteli variety

Regimes of irrigation, % HB	Energy intensity of resources, MJ				Energy intensity of irrigation modes, MJ/ha
	Irrigation water	Energy carriers	Technical means	Live work	
100-80	7439	1670	125.7	62.5	9297.2
100-80-70	6200	1395	104.5	54.7	7754.2
100-70	4165	957	70.2	35.8	5228.0
%	80.0	18.0	1.35	0.65	100.0

Source: authors' own research

According to the data in Table 2, the structure of energy consumption is dominated by the energy of irrigation water, the share of which is 80% and it does not depend on the irrigation regime of plantings. The power consumption used for the operation of pumping and filtering equipment, water supply, creation and maintenance of the required pressure in the irrigated network depends on the operating time of the equipment and ranges from 1670-957 MJ/ha, or 18.0% of the total energy intensity of reception.

The energy costs of the technical means involved and live labor are directly related to each other and are aimed at maintenance of pumping and filtering equipment, monitoring the state of the drip irrigation network, and ensuring its reliable operation. The share of these energy costs is insignificant and ranges from 188.2-159.2 MJ/ha, or 0.65-1.35% of the total energy consumption.

The level of pre-watering humidity of the active soil layer directly determines the overall energy intensity

of irrigation of grape plantations. Unhindered moisture consumption of grapes at the level of 100-80% the lowest moisture content, during the growing season causes the consumption of 9.29 GJ/ha of energy, which is equivalent to 218 kg of diesel fuel. The introduction of a differential irrigation regime for plantings with a threshold of 100-80-70% the lowest moisture content reduces the energy intensity of reception by 16.7%. Maintaining the pre-watering humidity of the active soil layer

during the growing season of grape plantations at the level of 100-70% the lowest moisture content, reduces energy consumption to 5.2 GJ/ha or almost 1.7 times.

The conditions for providing plants with moisture that have developed under different irrigation regimes have had different effects on the development of grapes, the volume of biological energy synthesis, the energy intensity of the biological mass of plants and Berry yield, and the level of payback of man-made energy spent (Table 3).

Table 3. Bioenergetic efficiency of drip irrigation modes of APF "Tavria" grapes, Rkatsiteli variety

Regimes of irrigation, % HB	Yield of grapes, t/ha		Synthesized energy (Eb) in the crop, MJ		Specific energy consumption, MJ/t of berries	Energy consumption on 1 t additional berry yield, MJ/t	Kee irrigation modes, T*=Tb/Tt
	biological	yield of berries	biological	berries			
Control (without irrigation)	10.1	7.8	45564	24804	5807	-	0.547
100-80	14.3	11.7	66616	37206	4639	2383.9	0.685
100-80-70	14.1	11.3	61884	35934	4695	2215.5	0.677
100-70	13.4	10.7	58766	34026	4586	1802.8	0.673

Note: E* = Eb, biological / Et, technogenic; Kee - defined for the berry yield

Source: authors' own research

According to the data in Table 3, total energy consumption on the site without irrigation, control – 45.5 GJ/ha. The energy intensity of modern technology for cultivating industrial grape plantations ranges from 45-47 MJ/ha and includes two components: energy costs for creating plantings and caring for them before they enter full fruiting and annual costs for caring for fruit – bearing plants.

The use of irrigation of plantings increases the consumption of man – made energy by an average of 17-20% and depends on the annual volume of soil moisture of natural supply, the efficiency of its use, and the pre-irrigation level of soil moisture maintained by irrigation.

Unhindered moisture supply of grapes at the level of 100-80% the lowest moisture content, during the entire growing season of plants, is achieved by additional man-made energy costs in the range of 9.29 GJ/ha and increases the energy intensity of Berry cultivation technology to 54.27 GJ/ha. A differentiated irrigation regime at the level of 100-80-70% the lowest moisture content reduces the cost of man-made energy by an average of 8%.

As a result of research, it was established that the lowest total cost of man-made energy for growing a grape crop consists in constantly maintaining the humidity of the active soil layer at the level of 100-70% the lowest moisture content, and it does not exceed 49.1 GJ/ha. Under the influence of the moisture supply regime of grapes, the specific energy costs for growing a berry crop also change significantly. With natural moisture supply, the energy consumption for growing 1 ton of berries is, on average, 5.8 GJ of man-made energy. In irrigated areas, regardless of the level of pre-irrigation soil moisture maintained during the growing season, specific energy consumption is reduced to 4.5-4.6 GJ/t

of berries, due to the elimination of stress on plants, more efficient use of the natural potential of the environment by plants in irrigation conditions. Optimization of soil moisture has become a key factor in reducing, by more than 50%, the specific cost of man-made energy for growing an additional crop of berries of irrigated variants of the experiment. In addition to the direct impact of the irrigation regime on the energy intensity of the technology, pre-irrigation soil moisture also changes the efficiency of biological energy synthesis, its volume in the biological mass, and the yield of grapes.

The most intensive synthesis of natural energy by plants was observed with an unhindered intake of moisture (100-80% the lowest moisture content) and amounted to 66.6 GJ/ha in the biological yield and 37.2 GJ/ha in grape berries. The differentiated regime of soil moisture at different stages of the growing season, worsening the conditions of plant moisture supply, reduced the total amount of energy synthesized by plants to 61.8 GJ/ha, including in the berry yield to 35.9 GJ/ha. The same trend was observed in the area where soil moisture was constantly maintained at the level of 100-70% the lowest moisture content.

The above analysis shows that the amount of synthesized energy in the berry crop is significantly less than the amount of man-made energy spent on caring for plants during the growing season, regardless of the soil moisture regime that was maintained during the growing season of plants.

Analyzing the level of payback of man-made energy costs by grapes in various conditions of moisture supply, it should be noted that irrigation of plantings contributes to a more efficient synthesis of organic matter

in the biological crop and the accumulation of 58.7 GJ/ha of energy in it, which is 19.5-24.0% higher than the cost of anthropogenic resources.

At the control site, the volume of synthesized energy in the biological mass of the grape crop was 45.5 GJ/ha, which is equivalent to its cost for caring for plantings during the growing season.

Agroclimatic conditions of the southern regions of Ukraine potentially allow binding about 4-5% of photosynthetically active solar radiation, which is equivalent to the yield of grapes in the range of 10-12 t/ha.

DISCUSSION

According to the results of many years of research performed both in Ukraine and in countries with an arid type of climate (USA, Spain, Latin American countries), increasing the lower threshold for optimal moisture content of the active soil layer from 60% the lowest moisture content to 70% the lowest moisture content, during the growing season, increases the consumption of irrigation water and energy resources by almost 42% (Sun *et al.*, 2022; Mboyerwa *et al.*, 2021; Vozhehova *et al.*, 2017). Reduce the consumption of irrigation water, energy and funds allows a differentiated irrigation regime of plantings, which provides for the humidity of the active soil layer at the level of 100-80% the lowest moisture content in the growth phase of shoots and flowering, and its subsequent reduction to 10-70% the lowest moisture content during the berry growth phase and 100-65% the lowest moisture content during the ripening period of the berry crop (Lemos-Paiao *et al.*, 2022). Current research established that the moisture supply of grapes at the level of 100-80% RH, during the entire growing season of the plants, is achieved by additional costs of man-made energy in the range of 9.29 GJ/ha and increases the energy intensity of the berry crop cultivation technology to 54.27 GJ/ha. Differentiated mode of irrigation at the level of 100-80-70% the lowest moisture content reduces man-made energy consumption by an average of 8%.

Previous studies show (Shevchenko *et al.*, 2012) that all modern grape growing technologies used in Ukraine are characterized by high energy intensity, which is 4.6-7.2 times higher than the recommended international standards (15 GJ/ha year). Significant energy costs have a negative effect on the state of grape bushes, significantly reduce the efficiency of using artificial energy. Thus, the irrigation regime has different effects on the efficiency of the use of irrigation water, the consumption of which for the formation of 1 ton of berry crop with an unimpeded supply of moisture (100-80% RH) during the growing season of grapes is 476 m³/t. Irrigation water is used most sparingly in the irrigation mode at the level of 100-70% RH, which reduces specific water consumption to 266 m³/t. On the site of this variant, the yield of berries was 10.5 t/ha, that is, it decreased by 8.6%. At the same time, the specific consumption of water decreased by 38.3% compared to similar indicators of the site with unimpeded moisture inflow (Shevchenko *et al.*, 2021).

One of the promising ways of reducing energy costs in irrigated viticulture is the further improvement of irrigation regimes, the use of more modern diagnostic methods to adjust the timing of successive irrigations. Mynkina (2021) recommends adjusting the timing and rates of irrigation in years with insufficient rainfall, which may not coincide with long-term practice. Thus, in dry years, it is recommended to irrigate grape plantations at the beginning of the shoot growth phase at the rate of 80-100 m³/ha for local irrigation methods. It is advisable to coordinate the timing of subsequent waterings and irrigation rates with the dynamics of the moisture content of the active soil layer of a specific site, using tensiometers or other methods of diagnosing the next watering periods. On the basis of this information, also determine irrigation rates, which is confirmed by current research. Thus, the results confirm the need for a differentiated irrigation regime, which was applied at the beginning of the berry growth phase, which helped reduce the number of irrigations to 9, while the irrigation water rates increased by almost 30% and amounted to 105 m³/ha.

In research, the optimization of soil moisture became a key factor in reducing, by more than 50%, the specific costs of man-made energy for growing an additional crop of berries in the irrigated variants of the experiment. In addition to the direct influence of the plantation irrigation regime on the energy intensity of the technology, the pre-irrigation soil moisture also changes the efficiency of the synthesis of biological energy, its volume in biological mass and the yield of grape berries. Similar results were obtained by a number of scientists (Vozhehov *et al.*, 2021), who established that the use of drip irrigation according to a resource-saving and biologically optimal scheme ensured an increase in yield by 16.8-28.3% – up to 7.9-9.2 t/ha. It was established that drip irrigation regimes had the maximum influence on the yield of grapes, as their share of influence was the highest and amounted to 59.8%.

Some researchers, (Cooley *et al.*, 2017; Linares Torres *et al.*, 2018; Scholasch, 2018) to increase the efficiency of water use in vineyards, recommend the use of increased irrigation rates after a period of moderate drought to reduce the water stress of the grapevine. For this purpose, the maximum amount of water that the root system zone can accommodate is applied, while the maximum possible level of vine transpiration (Kcb, max) is achieved and the next watering is postponed as far as possible. Between waterings, drought periods of varying intensity are established in accordance with production tasks. In their opinion, the changes in water deficit between two large irrigations are smoother compared to those observed between irrigations of a smaller volume. These strategies tend to promote water and energy savings and are currently supported by water agencies and energy conservation agencies (Scholasch & Rienth, 2019). Authors of the current research support these assumptions. Thus, the lowest total consumption of irrigation water was achieved with the support of the lower threshold

of optimal soil moisture at the level of 100-70% RH. During the research period, the optimal soil moisture at the level of 100-70% RH was provided by 5 irrigations carried out every 19 days at the rate of 127 m³/ha.

At the very end, it should be noted that studies of the influence of drip irrigation regimes on the grape plant in conditions of limited moisture supply have achieved significant results. The attention of scientists was mainly devoted to the study of the influence of irrigation on the productivity and yield of grapes. But in the modern conditions of agricultural production, in connection with limited water resources in the conditions of climatic changes, the energy assessment of all technological methods of crop cultivation becomes especially relevant. Thus, in the future, research in this direction should become the focus of attention of scientists, where the most important is the study of water-saving methods of viticulture, methods of limited irrigation to save energy resources.

CONCLUSIONS

As a result of research conducted on 15-year-old plantings of grapes of the Rkatsiteli variety cultivated on irrigated sandy chernozems of the left bank of the Lower Dnieper in the Kherson region, an energy assessment of various modes of drip irrigation was carried out in order to reduce the consumption of irrigation water, material and energy resources with their effective use. Relevant conclusions are drawn:

The lowest total costs of man-made energy for growing a crop of grapes consist of constant maintenance of the humidity of the active layer of the soil at the level of 100-70% RH, and do not exceed 49.1 GJ/ha.

In irrigated areas, regardless of the level of pre-irrigation soil moisture that was maintained during the

growing season, the specific energy consumption is reduced to 4.5-4.6 GJ/t of berries, due to the elimination of stress on plants, more effective use by plants of the natural potential of the environment under irrigation conditions.

Maintaining an unhindered moisture supply to plants during the growing season is achieved by an additional cost of 9.29 GJ/ha of anthropogenic energy. A more economical regime of humidity of the active soil layer during the growing season reduces energy costs to 5.2-7.7 GJ/ha.

The specific consumption of man-made energy for growing 1 ton of grapes ranges from 5.8 GJ for control without irrigation and 4.51-4.69 GJ for areas of different levels of pre-irrigation soil moisture.

Bioenergetic analysis of modern technology of cultivation of industrial plantings allows us to identify the most energy-intensive techniques, provide directions for their improvement for gradual optimization of anthropogenic energy costs, and its more efficient use.

In order to increase the efficiency of water use, the reaction of the variety, its physiology, the characteristics of the soils on which it is grown and energy costs should be studied in order to optimize the irrigation strategies of grape plantations in accordance with production tasks.

Further research should be focused on the study of optimal irrigation regimes in conditions of limited natural moisture when growing a certain variety in specific soil and climatic conditions to reduce material and energy costs.

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CONFLICT OF INTEREST

The authors declare that the study was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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Біоенергетична ефективність режимів краплинного зрошення винограду

Іван Васильович Шевченко

Доктор сільськогосподарських наук, професор
Миколаївський національний аграрний університет
54000, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0003-0539-7062>

Наталія Володимирівна Нікончук

Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54000, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-9425-2684>

Анотація. В сучасних умовах дефіциту водних ресурсів актуальними є дослідження енергетичної оцінки різних режимів краплинного зрошення. Воно важливе для скорочення витрат поливної води, матеріальних та енергетичних ресурсів, їх ефективного використання на зрошуваних насадженнях винограду, що культивуються на супіщаних чорноземах лівобережного Нижньодніпров'я, де тільки зрошення являється гарантом щорічної, сталої високої врожайності виноградників. Метою досліджень було вивчення енергоефективності режимів краплинного зрошення винограду, визначення обсягів та структури ресурсних витрат, рівня їх окупності. Під час дослідження використано польовий та порівняльно-розрахунковий методи. Закладання та проведення дослідів проводили згідно методики дослідної справи. В роботі отримані результати досліджень із вивчення енергетичної ефективності режимів краплинного зрошення насаджень винограду. Встановлено, що підтримання безперешкодного вологопостачання рослин протягом вегетації досягається додатковими витратами 9,29 ГДж/га антропогенної енергії. Більш ощадливий режим вологості активного шару ґрунту протягом вегетації рослин скорочує енергетичні витрати до 5,2-7,7 ГДж/га. В структурі додаткових енергетичних витрат, незалежно від режиму зрошення насаджень, домінує енергія поливної води – 80 % та енергоносіїв – 18 %. Практичне значення досліджень полягає в проведенні енергетичної оцінки різних режимів краплинного зрошення винограду для скорочення витрат поливної води, матеріальних та енергетичних ресурсів та їх ефективного використання

Ключові слова: вологоспоживання; диференційований режим зрошення; оптимальне зволоження ґрунту; енергія; енергоємність

Non-traditional fertilizers to optimize winter rape nutrition

Aleksandrs Adamovics

Full Doctor in Agrisciences, Professor
Latvia University of Life Sciences and Technologies
LV-3001, 2 Liela Str., Jelgava, Latvia
<https://orcid.org/0000-0003-1725-4421>

Rihards Berkis

Master in Agrisciences
Latvia University of Life Sciences and Technologies
LV-3001, 2 Liela Str., Jelgava, Latvia
<https://orcid.org/0000-0003-3029-3935>

Lydiia Antypova*

Full Doctor in Agrisciences, Professor
Mykolaiv National Agrarian University
54020, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0003-2609-0801>

Abstract. The relevance of the topic is due to the need to optimize the nutrition of winter rape (*Brassica napus* L.), including the use of non-traditional fertilizers, taking into account the limited amount of low-cost mineral fats. The purpose of the research was to study the influence of a mixture of production by-products (wood ash and digestate) on the yield and quality of winter rapeseed. Field experiments were conducted at the "Peterlauki" research farm (Latvia). In agriculture, both wood ash and biomass digestate are used separately as materials for liming and fertilizers, while a high-quality fertilizer can be obtained from their mixture. The authors evaluated mixtures of cattle manure digestate and wood ash in different ratios. Analyzes from the groups of systemic, statistical and comparative were used. The next research methods are applied: generally accepted in crop production, field and laboratory – to clarify the interaction of the object of research with agrotechnical and natural abiotic factors; calculated and weighted - to determine the productivity of crops; calculation and comparison; mathematical and statistical (dispersion) – in order to estimate the probability of research results. It was determined that, using mixtures of wood ash and digestate, it is possible to obtain appropriate crops of winter rapeseed without the use of mineral fertilizers. A higher yield of this crop – 2.45 t/ha was obtained in cases where fertilizer rates of 10 t/ha were used for fertilization. Winter rape seeds had a higher oil content in variants with the use of a fertilized mixture of 5 t/ha, but without ammonium nitrate. The bulk weight (nature) of winter rapeseed in the investigated variants slightly exceeded 670 g/l. The scientific novelty is that the influence of the mixture of digestate and wood ash on productivity, including the oiliness of winter rapeseed, was evaluated. The practical value lies in the improvement of the technology of cultivation of the researched culture by means of a correctly selected mixture to optimize nutrition and obtain high-quality oil

Keywords: *Brassica napus*; digestate; wood ash; yield; oil content; harvest quality

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*Corresponding author

INTRODUCTION

Winter rapeseed (*Brassica napus* L.) is widely cultivated in Latvia, while the yield is increasing (from 2.5 t/ha in 2010 to 3.3 t/ha in 2020) and the total cultivation area (from 67.6 thousand ha in 2010 to 127.7 thousand ha in 2020) (Areas, gross harvests..., 2020). According to the State Statistics Service of Ukraine, the area of winter rapeseed crops in Ukraine reached 1.4 million hectares in 2022, which is 40% more than in the previous year. The average annual yield of rapeseed in Ukraine is 2.67 t/ha (Areas, gross harvests..., 2022), which indicates the interest of farmers in the cultivation of winter rapeseed and the development of its cultivation technologies.

For the production of winter canola, special attention should be paid to agronomically and economically justified use of fertilizers, thus reducing costs and potential risks of environmental pollution (Litke et al., 2019).

E. Shahini et al. (2022) studied that the use of "smart" fertilizers is an important approach to increasing the volume of food production, which is extremely necessary both to provide it to the population and to support proper economic development. Scientists say based on their research that such fertilizers can be a solution to the problems of both biodiversity and food security in difficult times. Different types and doses of fertilizers are used to optimize the feeding conditions of rapeseed.

According to the conclusion of O.O. Matsera (2020), the best conditions for the synthesis of organic matter, thanks to which plant productivity is formed, is the rate of fertilizers $N_{240}P_{120}K_{240}$.

According to V.V. Bazalii et al. (2015) in the years of research (2009-2010, 2010-2011, 2012-2013) determined changes in the yield of winter rape in a very wide range - from 0.39 to 2.82 t/ha. A higher seed yield (on average 2.18 t/ha) was formed in the model where the estimated dose of mineral fertilizers was applied together with the use of complex organo-mineral liquid biofertilizer Rostkonzentrat, which exceeded the benchmark by 100.5%, and other fertilized options by 15.3-59.1%.

Fertilizer application efficiency varies from year to year depending on the fertilization system (Garbar et al., 2018; Hospodarenko et al., 2022).

M. Kolomiets (2001) analyzed a number of literary sources and concluded that increasing the dose of nitrogen fertilizers contributes to the increase in yield. At the same time, the absolute value of the yield increase per unit of applied nitrogen decreases.

Currently, biogas cogeneration plants and various solid fuel boilers, whose byproducts are digestate and wood ash, are widely used in Latvia for heat and energy production. Until now, these materials have been used in agriculture separately as liming materials and fertilizers (Patterson et al., 2004; Koszel et al., 2020).

At the same time, mixtures of wood ash and digestate can provide a high-quality fertilizer that can be used to fertilize a wide range of agricultural crops (including winter rape), providing increased productivity and crop quality (Hejzman et al., 2011; Koszel et al., 2020).

Therefore, the purpose of the research was to study the influence of a mixture of digestate and wood ash on the yield and quality of winter rapeseed.

LITERATURE REVIEW

Rapeseed (*Brassica napus* L.) is an annual herbaceous plant belonging to the cabbage family (*Brassicaceae*). Currently, rapeseed is recognized as the second oil content in its composition after soy. It is considered a strategic crop for oil production. Oil products are primarily used in the food industry. Due to its properties, rapeseed oil competes with olive oil. Rapeseed oil is used as a raw material for the production of such products as biodiesel, lubricants, and plastic. It is in demand in the paint industry. Two types of resin are extracted from rapeseed, which is used for the production of ink. Beekeepers consider this culture to be one of the most common honey plants, because the period when rape blossoms lasts more than 30 days. One hectare of rapeseed can provide the opportunity to collect about 100 kg of honey (Malyna, 2020; Food and Agriculture Organization of the United Nations, 2019).

O. Malyarchuk (2012) conducted a study of the growth and development of winter rapeseed plants in the fields of short-rotational crop rotations. The soils under the experiment are dark chestnut. It has been established that in the southern region, the most favorable conditions for the formation of winter rape seeds can be considered systems of various depth of the main fallowing of the soil, or differentiated treatment with the use of deep loosening for rape seeding. Fine processing can be carried out if 40 cm deep slits are made under the previous crop. According to the scientist, the dose of nitrogen fertilizers is necessary in the range of $N_{100}-N_{130}$ for the formation of a high yield.

J. Beres et al. (2019) confirmed a statistically significant effect of fertilization in the autumn period on the increase in aboveground biomass and root growth. The influence of nitrogen application on the formation of the seed crop was also statistically confirmed. When applying 40 kg/ha of nitrogen, the yield was the highest, on average 10.6% higher than the control (5.7-6.5 t/ha), on the other hand, the dose of N_{80} kg/ha increased seed yield by only 7.4% on average (5.4-6.3 t/ha), that is, it was less effective. It is emphasized that the above dose of N_{40} complies with the rules of the Nitrates Directive, supports the strengthening of oilseed rape before winter and intensifies its growth and development to increase seed yield.

K. Jankowski & M. Sokolski (2018) on the basis of research conducted at the agricultural experimental station in Balcyny (north-eastern Poland), assure that it is advisable to apply mineral fertilizers as a starter or strip, which is effective. Thanks to these methods, the doses of fertilizers are reduced (the costs of their application) and the environmental risk is minimized (the stratification of nutrients is reduced, their emissions into surface water, ground water and the environment are reduced). Local application of fertilizers leads to increased

drought resistance of plants. At the same time, foci with an increased content of nutrients are formed in the soil, where active root branching occurs.

Foliar feeding of winter rapeseed at the stage of formation of 4-6 leaves (VVSN 14-16) is effective, which helps increase winter hardiness by 8-11%. Autumn fertilizing with non-root macro- and micronutrient fertilizers leads to an increase in seed yield, significantly increases the content of crude fat (by 1.3-7.4 g/kg of dry matter), increases the content of oleic acid, reduces the concentration of linoleic acid, and the content of glucosinolates (Jankowski *et al.*, 2019).

E. Gutiérrez-Moya *et al.* (2021) found that the actual level of fertilizer application in different countries of the world is quite different. Most of them are made in the Netherlands. In this country, a total of 258 kg of fertilizers are used for 1 hectare of arable land for agricultural production. Somewhat less of them are applied in Great Britain – 247 kg, Germany – 202 kg, France – 169 kg, USA – 137 kg, Turkey – 107 kg.

According to M. Makadi *et al.* (2012), a fertilizer in which plant nutrients are present in a more easily assimilated form plays an important role in the production of competitive crops. The digestate contains a relatively large amount of nutrients that are easily absorbed by plants, and has a high level of nitrogen and phosphorus mineralization. During the fermentation process, various changes occur (ammonium content, pH, carbon and nitrogen ratio, etc.), which affect the amount of trace and macroelements available to plants.

Literary sources testify to the fluctuation of opinions regarding the norms and doses of fertilizers for

winter rapeseed, their application methods, insufficient amount of cheap drugs to optimize the nutrition of the studied crop, which can be considered an unused reserve for increasing the productivity of plants of this species.

MATERIALS AND METHODS

Field experiments were conducted at the educational and research farm "Peterlauki" (56°53'N, 23°71'S) of the Latvian University of Natural Sciences and Technologies: the soil is turf-carbonate, heavy loam; soil reaction pH 6.7%; the content of plant-available phosphorus (P_2O_5) – 60 mg/kg; potassium content (K_2O) – 144 mg/kg; the content of organic matter is 2.6%.

Sowing of winter rape was carried out using fat mixtures of cattle digestate (D) (obtained from Ziedi JP JSC) and wood ash (P) (obtained from Gren Jelgava LLC) in different ratios:

- B1–D;
- B2–D+P1:1;
- B3–D+P2:1;
- B4–D+P3:1;
- B5–D+P3:1+N₁₆P₄₀K₆₀;
- B6–D+P3:1+N_{68,8};
- B7–D+P4:1.

Innovative results from the introduction of a mixture of digestate and wood ash were noted according to the norms A1 – 5 t/ha, A2 – 10 t/ha and A3 – 20 t/ha.

The chemical composition of the digestate and wood ash mixture is shown in Table 1, according to which the amount of nutrients applied with each fertilizer mixture and the rate can be calculated.

Table 1. Nutrient content in digestate and wood ash mixtures

Nutrients	Content in dry matter, %				
	D	D+P1:1	D+P2:1	D+P3:1	D+P4:1
Nitrogen in a natural sample (N)	0.29	0.27	0.30	0.51	0.34
Ammonium nitrogen (N/NH ₄), g/kg	1.20	0.43	0.40	0.76	0.37
Phosphorus (P)	0.74	0.90	0.89	0.83	0.83
Potassium (K)	1.70	2.90	2.92	2.73	2.64
Calcium (Ca)	2.41	13.44	13.55	10.48	10.86
pH	9.27	12.19	11.84	11.22	10.91

Note: D – digestate from cattle manure; P – wood ash

Source: author's development

As a control, unfertilized plots of winter rape and different application rates of digestate from cattle manure (D) were used. Variants in two-factor studies were randomized in three replications. In total, 66 sites were laid in the experiment, the area of each site was 30 m².

Winter wheat (*Triticum aestivum* L.) was the predecessor of winter rape. To prepare the experimental plots, plowing was carried out to a depth of 22 cm, and before sowing, pre-prepared mixtures of digestate and wood ash and mineral fertilizers were applied in option 5–D+P3:1+N₁₆P₄₀K₆₀ kg/ha.

Fertilizers were spread on the prepared plots of winter rapeseed, which were wrapped in the soil with the unit of pre-sowing soil treatment – the universal rotary harrow Zirkon 8. It is characterized by positive qualities. So, with the help of the optional DUAL-Shift gearbox, it is possible to change the rotation of the rotors from 300 to 400. If necessary, the direction of their rotation is also changed – from aggressive to gentle, moreover, without tools.

For sowing, the Visby winter rapeseed variety was used with a sowing rate of 80 similar seeds per m². Winter

rapeseed was sown to a depth of 1.5-2 cm. In the spring, when plant vegetation was recovering, N 68.8 kg/ha of ammonium nitrate was applied to the plots of the experimental variant A6. Harvesting from each plot was carried out separately with a small-sized "Sampo" harvester.

After the test plots were harvested, the harvest from each plot was weighed and cleaned using a PFEUFFER SLN3 automatic sample cleaner. This sample cleaning complex is capable of weighing the initial seed sample (approx. 1.5 liters) in one cycle, running the SLN3 sample cleaner, removing the coarse fiber, opening and closing the bottom to remove the coarse fiber, performing a time-controlled cleaning and automatically weighing two fractions - fine grain and quality grain, i.e. cleaned sample. Available modern software allows you to view the obtained masses and their corresponding percentage ratios on the display. Then, average samples were taken from each version of the two-fold repetition for chemical analysis. Analyzes were carried out in the accredited scientific laboratory of biotechnology of the Latvian University of Natural Sciences and Technologies (LBTU BZL). Using standard methods, dry matter content (%), total protein (%), seed oil content (%), seed volume weight (g/l) and weight of 1000 seeds were determined.

According to the obtained results, the yield (t/ha) and the amount of oil (t/ha) were calculated at standard humidity (8%) and full (100%) purity of the samples. Data processing was carried out with the help of

two-factor variance analysis of computer programs Microsoft Excel and R-Studio.

RESULTS AND DISCUSSION

Tips for applying fertilizers for rape are quite diverse. Thus, in the experiments of V. Parkhuts (2015), conducted in the conditions of typical chernozem of the Khmelnytsky region, it was established that the highest yield of rapeseed (3.94 t/ha), on average over three years of research, was formed under the model of the main application of mineral fertilizers with the rate of $N_{60}P_{80}K_{130}$ with the following by feeding plants N_{60} . The yield increase under the specified model was 2.10 t/ha (or 114.1%).

In Latvia, four-year research by O. Balodis & Z. Gaile (2011) proved the significant dependence of plant growth and development, in particular the germination of winter rape seeds, on precipitation and air temperature.

The average yield of winter rape in the experimental plots was relatively low (1.97-2.48 t/ha) compared to the potential of the variety. This was caused by dry and hot weather conditions during the emergence of seedlings and the beginning of vegetation. It is described in the literature that abiotic stress - drought reduces the diameter and length of the rape stem and negatively affects the seed yield (Sangtarash *et al.*, 2009).

In the study, the lowest winter rape yield of 1.97 t/ha was obtained directly from control field plots (Table 2).

Table 2. The influence of different rates of fertilizers from mixtures of digestate and wood ash on the yield of winter rapeseed, t/ha

Fertilizer rate (F_A)	The ratio of digestate and wood ash in the mixture (F_B)							(FA)p=0.003 LSD _{0.05} =0.149
	D	D+P1:1	D+P2:1	D+P3:1	D+P3:1+NPK	D+P3:1+N	D+P4:1	
Control				1.97				1.97
5 t/ha	1.85	2.21	1.94	2.24	2.12	1.77	2.30	2.05
10 t/ha	2.76	2.47	2.45	2.24	2.53	2.06	2.66	2.45
20 t/ha	2.26	2.67	2.13	2.03	2.11	2.25	2.50	2.28
On average p=0.046 LSD _{0.05} (B)=0.230 LSD _{0.05} (AB)=0.393	2.29	2.45	2.17	2.17	2.26	2.03	2.48	*

Note: D – digestate from cattle manure; P – wood ash

Source: author's development

Significantly higher ($p < 0.05$) average yields of winter rapeseed were obtained when applying fertilizer rates of 10 and 20 t/ha. At the lowest fertilizer rate of 5 t/ha, a lower yield was formed in variants D, D+P2:1 and D+P3:1+N than in the control variants; however, the differences were significant ($p > 0.05$). The variants D, D+P1:1, D+P3:1+NPK, D+P4:1 had significantly higher ($p < 0.05$) average yields of winter rape, of which the highest yields were obtained from fertilizer in variants D+P1:1 and D+P4:1.

Research by M. Koszel *et al.* (2020) also showed that the use of liquid digestate, at least 25,000 l/ha as fertilizer, can significantly ($p < 0.05$) to increase the yield of rapeseed, and due to the increase in digestate rates, the yield increases.

The use of organic fertilizers such as digestate can lead to the formation of small anaerobic zones in the soil. Thus, the use of digestate can increase N_2O emissions compared to the use of mineral fertilizers (Jones *et al.*, 2007).

The cultivation of rapeseed during the winter is closely related to the problems of N_2O emissions arising from the use of nitrogen fertilizers in the cultivation of rapeseed. Nitrification is one of the main sources of N_2O formation in soil (Hoefnagels *et al.*, 2010).

D. Figueiro *et al.* (2009) found that the application of organic fertilizers with nitrification inhibitors increases nitrogen use efficiency and increases yield.

In the study, compared to the control, the use of digestate alone increased the average yield of winter

canola at a fertilizer rate of 10 t/ha in all mixed fertilizer treatments, indicating that nutrient deficiency was not a yield-limiting factor in the test years. The observed conclusion is also supported by the fact that the average increase in seed yield when using a mixture of digestate and wood ash with the addition of nitrogen fertilizers only slightly increased the yield.

It should be noted that there are conclusions in the literature according to which an increase in nitrogen fertilizers up to 60 kg/ha also led to a significant increase in the yield of winter barley, regardless of the trial year (Litke, 2019).

One of the main indicators of the quality of winter rapeseed is the oil content of its seeds.

The analysis of the results showed that significantly higher ($p=0.07$) average oil content in winter rapeseed was obtained at the rate of 5 t/ha of digestate and ash mixture. Between the average values of all variants of fertilizer mixtures, the oil content is significantly higher ($p=0.001$) in the variants D+P1:1, D+P2:1, D+P3:1, D+P3:1+NPK; while a significantly lower ($p=0.001$) oil content was obtained in variants where ammonium nitrate was additionally used for feeding (Table 3).

Table 3. The influence of different rates of fertilizers from mixtures of digestate and wood ash on the oil content of winter rapeseed, %

Fertilizer application rate, t/ha (factor A)	The ratio of digestate and wood ash in the mixture (factor B)							On average (factor A) $p=0.007$ $LSD_{0.05}=0.295$
	D	D+P1:1	D+P2:1	D+P3:1	D+P3:1+NPK	D+P3:1+N	D+P4:1	
Control				47.3				47.3
5 t/ha	47.70	48.03	48.06	48.06	48.03	46.27	47.27	47.63
10 t/ha	47.23	47.50	47.70	47.63	47.57	45.87	47.40	47.27
20 t/ha	47.43	47.73	47.76	47.93	47.87	46.37	48.06	47.59
On average $LSD_{0.05}(B)=0.390$ $LSD_{0.05}(AB)=0.781$	47.45	47.75	47.84	47.87	47.82	46.17	47.58	×

Note: D – digestate from cattle manure; P – wood ash

Source: author's development

This trend was also observed in other studies, where increasing the rate of nitrogen fertilizers significantly reduced the oil content of winter rapeseed (Farahbakhsh *et al.*, 2006). In a trial (Kesenheimer *et al.*, 2021) conducted in Germany, N_2O emissions were investigated when digestate fertilizers with and without nitrification inhibitors were used in rapeseed cultivation. The studies did not reveal a positive effect of nitrification inhibitors on the yield of winter rape, as well as the yield of oil from 1 ha. The yield of rapeseed varied from 2.8 to 5.7 t/ha, and the yield of oil varied from 1.2 to 2.7 t/ha, depending on the location of the experiment and the year. These results were probably influenced by the high rate of fertilizer application (180 kg $NH_4\pm N$ ha⁻¹ per year) when using liquid digestate.

At the same time, in the experiments of J. Beres *et al.* (2019), it was established that the effect of fertilizer on oiliness and weight of 1000 seeds was statistically insignificant. And according to V.V. Bazalii *et al.* (2015), the application of mineral fertilizers in the calculated dose and feeding with Rostkonzentrate led to the formation of the largest mass of 1000 winter rape seeds, an increase in the content of fat, protein, fiber and raw ash.

Studies show that the use of a mixture of wood ash and digestate as fertilizer did not have a significant effect ($p=0.334$) on the average oil content of rapeseed. But, on the other hand, increasing the rate of fertilizers to 10 and 20 t/ha led to an increase ($p=0.004$) in the collection of oil of the studied crop (Table 4).

Table 4. The influence of different rates of fertilizers from mixtures of digestate and wood ash on the collection of winter rapeseed oil, t/ha

Fertilizer application rate, t/ha (factor A)	The ratio of digestate and wood ash in the mixture (factor B)							On average (factor A) $p=0.004$ $LSD_{0.05}=0.128$
	D	D+P1:1	D+P2:1	D+P3:1	D+P3:1+NPK	D+P3:1+N	D+P4:1	
Control				0.93				0.93
5 t/ha	0.88	1.06	0.93	1.07	1.02	0.80	1.11	0.98
10 t/ha	1.30	1.17	1.17	1.07	1.21	0.94	1.26	1.16
20 t/ha	1.07	1.28	1.02	0.97	1.01	1.04	1.18	1.08
On average $p=0.334$	1.08	1.17	1.04	1.04	1.08	0.93	1.18	×

Note: D – digestate from cattle manure; P – wood ash

Source: author's development

An important indicator of seed quality is the nature of the grain (volumetric mass). This is the mass of seeds in a volume of 1 liter. The higher this indicator is, the higher the seed quality.

The analysis of changes in the volumetric weight of winter rape seeds showed that increased rates of fertilizers from mixtures of wood ash and digestate

significantly ($p=0.001$) reduce this indicator compared to the control. A comparison of the mixture variants showed a significantly greater ($p=0.001$) volume mass with the additional introduction of ammonium nitrate. In this variant, a bulk density of 679.6 g/l was achieved, which is similar to the control variant (Table 5).

Table 5. The effect of fertilizer rates from mixtures of digestate and wood ash on the volumetric weight of winter rapeseed, g/l

Fertilizer application rate, t/ha (factor A)	The ratio of digestate and wood ash in the mixture (factor B)							On average (FA)
	D	D+P1:1	D+P2:1	D+P3:1	D+P3:1+NPK	D+P3:1+N	D+P4:1	$p=0.001$ $LSD_{0.05}=1.62$
Control	679.3							
5 t/ha	671.0	673.3	672.7	672.0	672.0	680.3	673.3	673.5
10 t/ha	671.7	668.3	675.0	671.7	669.3	679.3	675.0	672.9
20 t/ha	671.3	671.3	669.7	672.3	672.0	679.3	672.3	672.6
On average $p = 0.001$								
$LSD_{0.05}(B) = 2.1$	671.3	671.0	672.5	672.0	671.1	679.6	673.5	×
$LSD_{0.05}(AB) = 4.3$								

Note: D – digestate from cattle manure; P – wood ash

Source: author's development

The experiment evaluated the effect of a mixture of wood ash and digestate on the weight of 1000 winter rape seeds. The average weight of 1000 seeds of the samples ranged from 4.37 to 4.79 g. Small differences between fertilizer treatments were observed, but they were significant ($p=0.671$).

At the same time, V. Parkhuts (2015) claims that the highest indicators of the structure of the winter rapeseed crop (number of pods – 99.7 pcs./plant, seeds in a pod – 20.0 pcs./plant, number of seeds – 1994 pcs./plant, weight 1000 of seeds – 3.49 g, weight of seeds from 1 plant – 7.0 g) was noted in the version of the experiment for the application of mineral fertilizers at the rate of $N_{60}P_{80}K_{130}$ followed by N_{60} plant feeding, which led to a higher yield under this model of fertilization.

Also, no significant differences ($p=0.095$) were found between the samples of winter rape according to the introduced norms of fat mixture. The relatively low 1000-seed weight values obtained in the trial can be explained by the dry conditions of the season, which prevented development in the spring and caused heat stress in the plants at the end of flowering before full maturity of canola.

L. Shkarivska et al. (2021), scientists of the NSC “Institute of Agriculture of the National Academy of Sciences of Ukraine” also assure that it is possible to use digestates as fertilizers, but it is necessary to control the presence of heavy metals and trace elements in them, because thanks to the agrochemical examination of digestates and their by-product (liquid fraction) a high their nutrient content.

Some laboratory studies have confirmed significant reductions in N_2O emissions when using nitrification inhibitors in the digestate (Wolf et al., 2014; Severin et al., 2016).

Digestate, depending on the source and type of materials used, can also contain heavy metals, which can significantly affect its use in food production (Kupper et al., 2014; Govasmark et al., 2011). It may contain compounds that stimulate or inhibit microbiological soil activity (Risberg et al., 2017).

When analyzing the content of heavy metals in rapeseed and soil after three years of using the digestate, their increase was not detected. The content of heavy metals in the soil, as well as in rapeseed, met EU standards (Rozylo et al., 2019).

H. Riedel & C. Marb (2008) conducted a comparison of composts obtained by different methods for the content of heavy metals in them. Composted digestate from food waste was analyzed, as well as compost obtained from the same waste. They found that there was no difference between the two samples in terms of heavy metal content for almost all indicators. Both composts met German quality requirements.

The impact may be different in groundwater conservation zones, where farmers must reduce nitrogen application rates. Overall, research findings show that the use of organic fertilizers such as digestate can help reduce greenhouse gas emissions during the industrial production of synthetic nitrogen fertilizers (Kesenheimer et al., 2021).

A. Comparetti et al. (2013) note that the production of agricultural products must be carried out in accordance with the requirements of environmental protection. It is important to support the safe use of fertilizers in the agricultural environment, especially nitrogen fertilizers. The nutrients contained in the digestate are in a form that is convenient for plants and is a suitable

fertilizer for them. The organic matter contained in the digestate has a positive effect on the physical and chemical properties of the soil and its fertility in general.

Therefore, the results of research indicate the possibility of replacing high-value mineral fertilizers with non-traditional fertilizers. In addition, it is common knowledge that mineral fertilizers are assimilated by only 30-50%, and biofertilizers – almost completely, simultaneously increasing the yield of agricultural crops, in particular, winter rapeseed.

CONCLUSIONS

It has been established that under modern farming conditions, a large amount of organic waste is accumulated in the form of cattle manure and wood shavings, which causes the need for their disposal. These wastes are mostly used for the production of heat and energy by biogas cogeneration plants and various solid fuel boilers. By-products of these enterprises are digestate and wood ash.

According to the results of the conducted research, it was established that using a mixture of wood ash and digestate as alternative fertilizers, it is possible to obtain good crops of winter rape even without the use of mineral fertilizers.

A higher yield of winter rapeseed – 2.45 t/ha was obtained in variants treated with fertilizers at the rate of 10 t/ha, while in the control (without fertilizers) this indicator was 1.97 t/ha, or 24.4% less.

The highest oil content of winter rapeseed was also formed on variants treated with a norm of 10 t/ha of fat mixture (1.16 t/ha), while on the control (without fertilizers) this indicator was noted at the level of 0.93 t/ha, or 24.7% less. Significantly lower oil content was obtained in variants where ammonium nitrate was additionally used for feeding. A higher average oil content in the seeds of the studied crop was obtained by

applying 5 t/ha of a mixture of digestate and ash. The volumetric weight of winter rape seeds in the investigated variants was slightly higher at 670 g/l. No significant difference between the studied options was found.

Applying a digestate mixture of cattle manure and wood ash to optimize nutrition for winter rape, instead of a large amount of mineral fertilizers, can be expected to reduce the risk of environmental pollution by production waste, which includes heavy metals, radionuclides, and organic pollutants.

The use of mixtures of digestate from cattle manure and wood ash contributes to the processing of the above-mentioned biomass and the return of organic matter to the soil to preserve or even increase its fertility, therefore it is advisable to use mixtures of wood ash and digestate to optimize the nutrition of winter rapeseed in agro-formations. It is quite important to determine the specific benefit from them, the impact on the surrounding natural environment, in which terms it is better to apply the studied mixtures, which will be the goal of further research.

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CONFLICT OF INTEREST

The authors declare that the study was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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Нетрадиційні добрива для оптимізації живлення ріпаку озимого

Олександр Михайлович Адамович

Доктор сільськогосподарських наук, професор
Латвійський університет природничих наук і технологій
LV-3001, вул. Ліела, 2, м. Єлгава, Латвія
<https://orcid.org/0000-0003-1725-4421>

Ріхард Марисович Беркіс

Магістр сільськогосподарських наук
Латвійський університет природничих наук і технологій
LV-3001, вул. Ліела, 2, м. Єлгава, Латвія
<https://orcid.org/0000-0003-3029-3935>

Лідія Климівна Антипова

Доктор сільськогосподарських наук, професор
Миколаївський національний аграрний університет
54000, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0003-2609-0801>

Анотація. Актуальність теми обумовлена необхідністю оптимізації живлення ріпаку озимого (*Brassica napus* L.), у тому числі й із застосуванням нетрадиційних добрив, враховуючи обмежену кількість мінеральних туків з низькою вартістю. Метою досліджень було вивчити вплив суміші побічних продуктів виробництва (деревної золи та дигестату) на врожайність та якість насіння ріпаку озимого. Проведено польові дослідження в навчально-дослідному господарстві "Peterlauki" (Латвія). У сільському господарстві як деревна зола, так і дигестат біомаси використовуються окремо як матеріали для вапнування та добрива, тоді як із їх суміші можна отримати високоякісне добриво. Авторами оцінені суміші з дигестату гною великої рогатої худоби та деревної золи у різних співвідношеннях. Використані аналізи із груп системних, статистичних та порівняльних. Застосовано наступні методи дослідження: загальноприйняті в рослинництві польовий та лабораторний – для з'ясування взаємодії об'єкта досліджень з агротехнічними та природними абіотичними факторами; розрахунково-ваговий – для визначення продуктивності посівів; розрахунково-порівняльний; математично-статистичний (дисперсійний) – з метою оцінки ймовірності результатів досліджень. Визначено, що, використовуючи суміші деревної золи та дигестату, можна отримувати відповідні врожаї ріпаку озимого без застосування мінеральних добрив. Вищу врожайність цієї культури – 2.45 т/га було отримано у випадках, де для підживлення використовували норми добрив 10 т/га. Насіння ріпаку озимого мало більший вміст олії у варіантах із застосуванням удобреної суміші 5 т/га, але без аміачної селітри. Об'ємна маса (натура) насіння ріпаку озимого в досліджуваних варіантах трохи перевищувала 670 г/л. Наукова новизна полягає в тому, що оцінено вплив суміші дигестату та деревної золи на продуктивність, у тому числі олійність ріпаку озимого. Практична цінність полягає в удосконаленні технології вирощування досліджуваної культури шляхом правильно підібраної суміші для оптимізації живлення і отримання високоякісної олії

Ключові слова: *Brassica napus*; дигестат; деревна зола; врожайність; олійність; якість урожаю

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тел.: +38(0512) 70-93-54

E-mail: info@bsagriculture.com.ua

www: <https://bsagriculture.com.ua/uk>

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