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ЗМІСТ

CONTENTS

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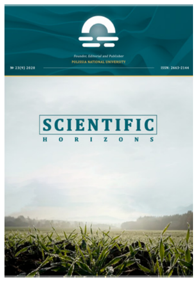
Scientific Horizons, 25(2), 9-15



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The Effect of Oral Administration of the Antibacterial Peptide MPX on Intestinal Inflammation of Mice in Experimental Infection with *Escherichia Coli* Strain O157: H7

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Abstract. *Escherichia coli* is a gram-negative bacterium, an intestinal pathogen that can cause intestinal inflammation. Antimicrobial peptides are a class of small molecule peptides, which has good antibacterial activity against a variety of gram-positive and negative bacteria. In this regard, the authors aimed to study the effect of the antimicrobial peptide MPX, which was administered orally, on the intestinal wall of mice infected with the intestinal barrier function, which were infected with *E. coli*. Synthesis and purification of the antimicrobial peptide MPX (H-INWKGIAAMAKKLL-NH2) was performed by Jier Sheng Hua (Shanghai, China). Mass spectrometry and liquid chromatography (HPLC) were used for this purpose. *Escherichia Coli* (O157: H7 ATCC 43889) was isolated from human faeces in which haemolytic uremic syndrome was reported. Solid LB agar (Solarbio, China) was used to isolate enterohemorrhagic *E. coli*. The culture was obtained from the Chinese Institute of Veterinary Drug Control (Beijing, China). The results of necropsy found that using of an orally administered MPX could alleviate the damage of *E. coli* to the liver, spleen, and the lungs were less affected. According to H&E results in case of an orally administered MPX group considerably relieved duodenum and organs on day 7 and day 28. qRT-PCR results showed orally administered MPX could reduce the inflammation-related factors in the mRNA expression of IL-2 and IL-6 and TNF-α on day 7 and day 28. In addition, orally administered MPX could significantly increase them RNA expression of tight junction proteins Occludin and Zo-1 on day 7 and day 28. The results of immune histochemistry further showed that an orally administered MPX could increase the mRNA expression of MUC2 in jejunum. The above results showed that orally administered MPX could alleviate the attack of *E. coli* on the intestinal tract of mice, relieve intestinal inflammation, and improve the intestinal barrier function. This study lays a theoretical foundation for adding antimicrobial peptides to food. In orally administered MPX authors can see reducing the mRNA expression of inflammation-related factors, thereby alleviating the intestinal inflammation caused by *E. coli* infection in mice. Authors can add that orally administered MPX shows an increase in mRNA expression of tight junction protein in intestines and improves the intestinal barrier function. This study lays the foundation for adding antimicrobial peptides to food to relieve inflammation and improve barrier function in clinical practices

Keywords: antimicrobial peptide MPX, enterohemorrhagic *E. coli*, inflammatory process, intestinal barrier, white mice

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INTRODUCTION

Escherichia coli is a bacterium whose colonies are registered in the lower intestine of mammals and birds. Under certain conditions, they are pathogenic and cause disease (Tran *et al*., 2021). Some bacteria can move with the help of flagella. On the surface of the cells there are fimbriae, saws. There are stationary strains. Disputes do not form (Nunayon *et al*., 2022). *Escherichia coli* is heat-resistant and can survive in the wild for several months (Lim *et al*., 2021). More than a hundred pathogenic serotypes of *Escherichia coli* that cause diseases in humans, animals, including birds have been systematised. *Escherichia coli* is resistant to antibiotics (Li *et al*., 2022). The emergence of antibiotic-resistant strains of *Escherichia coli* has caused economic losses to livestock (Khawaskar *et al*., 2021). At present, the resistance of *E. coli* to antibacterial drugs has become an increasingly serious global problem. Therefore, it is urgent to find drugs that can fight against *E. coli* infection and are not easy to develop drug resistance. Antimicrobial peptides have become a research hotspot and considered to be one of the most potential antibiotic substitutes.

Antimicrobial peptides are molecules made up of amino acids produced by the body, they are an important part of the body's immune system (Vimberg *et al*., 2022). Peptides have low molecular weight, broad antibacterial spectrum, and endurance to resistance (Lin *et al*., 2021). Peptide molecules consist of 12 to 100 amino acids (Sudadech *et al*., 2021). Both gram-positive (G+) and gram-negative (G-) bacteria have an inhibitory effect, most antimicrobial peptides have bactericidal activity, and their mode of action is specific to cellular targets (Peng *et al*., 2019). With the expansion of research, people gradually discovered antimicrobial peptide have a wide range of effects and have attracted much attention in anti-inflammatory and intestinal barrier function. The earlier study has found that intraperitoneal injection MPX could alleviate the damage of *E. coli* to the intestines of mice, reduce the mRNAexpression of inflammation-related factors and improve the intestinal barrier function of mice (Zhao *et al*., 2021). However, whether orally administered MPX can also relieve intestinal inflammation and improve intestinal barrier function in mice infected with *E. coli* is still unknown.

The purpose of this study was to explore the effect of orally administered MPX on intestinal inflammation and intestinal barrier function in mice infected with *E. coli*.

MATERIAL AND METHODS

Ethics statement. BALB/c mice (6 to 8 weeks old, female) were bought from Zhengzhou University. Animal studies were conducted per the principles of humane treatment of animals according to the International Guidelines for Biotic Standards and the requirements of the International Science Committee and the Animal Ethics Committee of the Henan Institute of Science and Technology (June 1, 2021).

Antimicrobial peptide synthesis. MPX (H-INWKGIAAMAKKLL-NH2) was synthesised and purified by Jiershenghua (Shanghai, China). High-performance liquid chromatography (HPLC) and mass spectrometry were used to purify MPX. The purity of MPX was greater than 98 %. MPX was dissolved in dd H_2O and stored at -20°C.

E. coli ***strain culture***. *Escherichia coli* (enterohemorrhagic *Escherichia coli* O157: H7ATCC43889) were isolated from faeces of patients who with symptoms of diarrhoea and intestinal inflammation and obtained from the China Institute of Veterinary Drug Control (Beijing, China). LB (Solarbio, China) solid agar was used to obtain isolated pure *E. coli* colonies. Single *E. coli* colonies were seeded in 5 mL LB liquid medium with inoculation rings in an aseptic operation room. Next, the cultures were placed on a shake (Thermo, USA) at 180 rpm for 10 h at 37°C. Then, 1 mL of *E. coli*-containing liquid was replaced in a 1.5 mL centrifuge tube, then centrifuged at 8000 rpm for 5 min, and then resuspended in phosphate buffer (pH=7.4). After diluting, the bacteria were smeared on an LB solid plate for colony counting. Then, the LB plates were placed in a 37°C incubator for 12 h and counted after the growth of visible single bacterial colonies. Authors first set up three *E. coli* gradients of 4.5×10^8 CFU/mice; 4.5×10^7 CFU/mice and 4.5×10^6 CFU/mice for preliminary experiments. According to the results, authors ultimately found that the dose of 4.5×10^6 CFU/mice of *E. coli* infection. Finally, the bacteria were administered to mice at 4.5×10^6 CFU/mice in the experiment.

Animal experiment. A total of 48 BALB/c mice (aged 6-8 weeks, 18-20 g, female) were randomly divided into 4 experimental groups (control, MPX, *E. coli*, and MPX+*E. coli*; 12 mice per group, 6 mice at separate times). The mice had ad libitum access to food and water. The MPX group and MPX+*E. coli* group mice orally administered MPX at a concentration of 100 μg/mL (200 μL/mouse) every day for 7 consecutive days. The control group was intragastrically administered 200 μL of normal saline for 7 days. Authors challenged mice with *E. coli* at 24 h after an orally administered MPX. The *E. coli* and MPX+*E. coli* groups were processed with *E. coli* via oral administration at 4.5×10^6 CFU/mouse. Mice showed diarrhoea, decreased appetite, and were prone to gathering after *E. coli* infection.

Necropsy observation. Mice were euthanised via CO_2 inhalation at different time points. After the mice were killed by anaesthesia, the liver, lungs, and spleens of mice were collected a septically with forceps, and pathological observations were performed. Aseptic operation was performed to observe the pathological changes of the liver, spleen and lungs of the mice after *E. coli* infection. The main pathological changes after *E. coli* infection in mice.

H&E ***staining observation***. Autopsy was performed on dead mice after infection to observe the pathological changes of mice organs. The lung, liver, spleen, and intestines of mice were taken out with scissors, wipe them clean with alcohol cotton, and put them in a 15 mL centrifuge tube. Selected organs and intestines were fixed in 4 % paraformaldehyde, then paraffin-embedded, sections were made, H&E was stained, and pathological changes were determined (Su *et al*., 2021).

qRT-PCR. 0.1 g of jejunum tissue was weighed and placed in liquid nitrogen for grinding. The ground jejunum powder was placed in a 1.5 mL centrifuge tube. 1 mL RNA was added to each well for 10 min, 200 μL of chloroform was added to each well. Shaked on the instrument for 15 s, placed it on ice for 2~3 min, centrifuged at 12000 rpm, 4°C for 10 min, slowly aspirated the supernatant, added 500 μL of isopropanol and mixed well, centrifuged at 12000 rpm, 4°C for 10 min, discarded the supernatant, added 1 mL of 75 % ethanol to each tube, centrifuged at 12000 rpm, 4°C for 5 min, slowly discarded the supernatant, and allowed the RNA to dry naturally for 10 min. Added a proper amount of DEPC water, generally 20~30 μL, and the RNA concentration was determined by NanoDrop 2000 spectrophotometer (Thermo Fisher Scientific, United States). 2 μg of total RNA was converted into cDNA. A reverse transcription kit (Thermo Scientific, USA) was used for this purpose. The reaction volume was 10 μl and included 5 μl of SYBR Green Master Mix (QuantiNova, China), 0.5 μl of reverse primer (10 μM), 0.5 μl of direct primer (10 μM), 0.5 μl of cDNA and 3, 5 μl of ddH2O. The reaction of the thermocycler took place for 2 min at 95°C and included 40 cycles at 95°C for 20 s and at 60°C for 30 s, considering the melt curves by fluorescence quantitative instrument (ABI7900, America). The primer sequences of IL-2, IL-6, TNF-α, ZO-1, Claudin-1, Occludin as bellow: IL-2, F:5'-CCTGAGCAGGATGGAGAATTACA-3', R:5'-TCCAGAACATGCCGCAGAG-3'; IL-6, F:5'-CTCTGGCGGAGCTATTGAGA-3', R:5'-AAGTCTCCTGCGTGGAGAAA-3'; TNF-α, F:5'-CTCATGCACCACCATCAAGG-3', R:5'-ACCTGACCACTCTCCCTTTG-3'; ZO-1, F:5'-ACCCGAAACTGATGCTGTGGATAG-3', R:5'-AAATGGCCGGGCAGAACTTGTGTA-3'; Claudin-1, F:5'-AGCTGCCTGTTCCATGTACT-3', R:5'-CTCCCATTTGTCTGCTGCTC-3'; Occludin, F:5'-ACGGACCCTGACCACTATGA-3', R:5'-TCAGCAGCAGCCATGTACTC-3'.

RESULTS

MPX relieves the pathological damage of E. coli to the organs of mice

The results of necropsy found that *E. coli* infection caused pathological changes in the liver and spleen of the mice, such as congestion and necrosis, and the pathological changes on day 7 were more serious than that on day 28 (Fig. 1A). There was no obvious pathological change in the lungs. Compared to *E. coli* group, the liver, lungs, and spleen of the negative control mice did not show the above adverse symptoms and orally administered MPX can effectively alleviate the above symptoms. Furthermore, H&E results found that the liver, spleen, and lungs of the mice in the control group had no lesions (Fig. 1B, C, D). *E. coli* infection leads to necrosis in the liver, caseous necrosis in the spleen, and insignificant pathological changes in the lungs. Orally administered MPX could relieve liver and spleen damage. The above results showed that orally administered MPX can effectively alleviate the pathological damage of *E. coli* to the organs of mice.

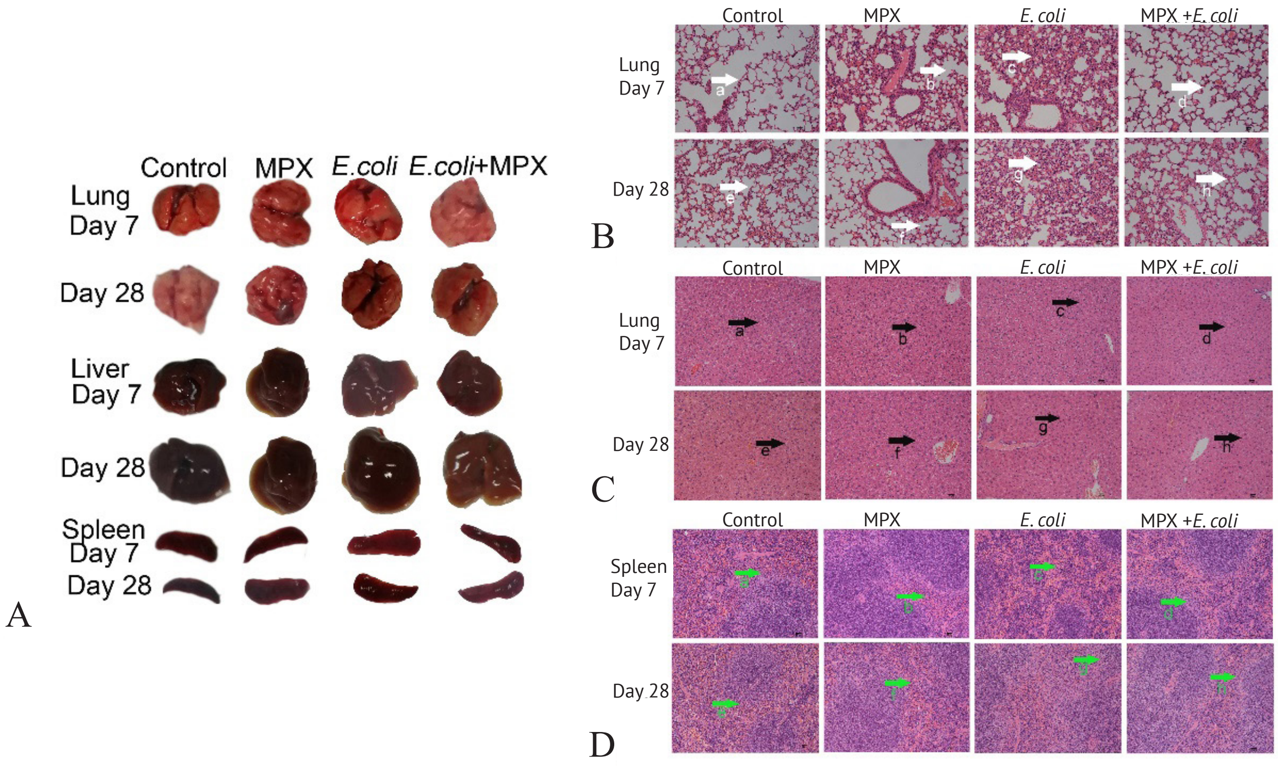

Figure 1. *The results of necropsy and H&E staining of mice infected with E. coli after orally administered MPX. A: Observation of autopsy results of liver, lung, and spleen of mice; B-D: Observation the results of H&E staining of liver, lung, and spleen of mice. Lung, liver, and spleen are highlighted respectively by white arrows, black arrows and green arrows to indicate lesions or normal parts. In addition, separate groups are indicated by different lowercase letters.*

MPX can effectively alleviate the intestinal morphology

As shown in Fig. 2, H&E staining of the duodenum showed that the control group intestinal villi were arranged neatly and there was no villi loss. *E. coli* infection in mice causes damage to the structure of the duodenum, the intestinal villi fall off, the arrangement is uneven, the depth of the intestinal crypts increases, and the intestinal villi become shorter. The orally administered MPX group significantly relieved the above symptoms on day 7 and day 28. The above results show that orally administered MPX can effectively alleviate the intestinal damage caused by *E. coli* infection.

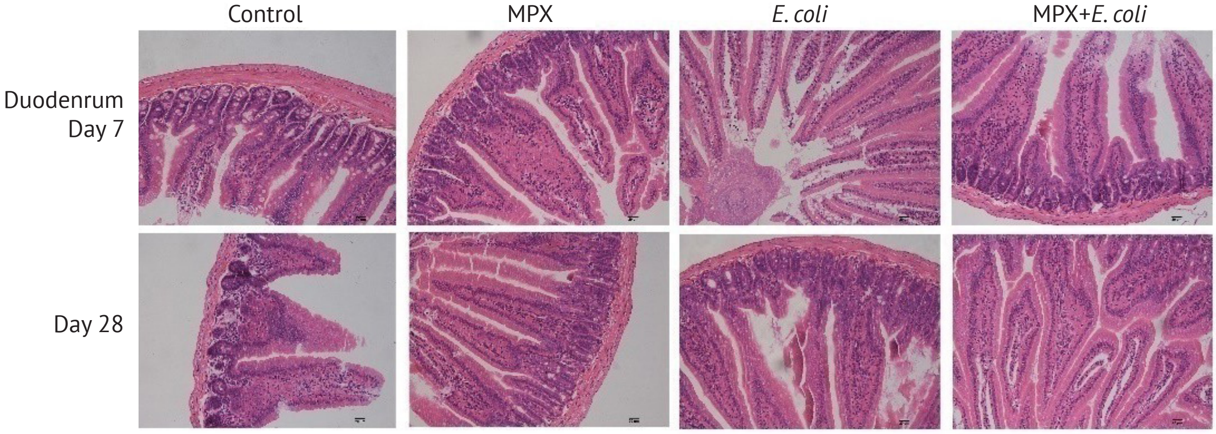

Figure 2. *Observation of the H&E staining pathological results in duodenum of E. coli infected mice after orally administered MPX*

Orally administered MPX reduces the expression of inflammation-related factors in duodenum

To study the effect of an orally administered MPX on duodenum inflammation-related factors in mice, RT-qPCR was used for detection of the effect of MPX on the mRNA expression ofIL-2, IL-6, and TNF-α in duodenum (Fig. 3A, B, C). The results showed that the mRNA levels of inflammation-related factors IL-2, IL-6, and TNF-α increased significantly on day 7 and day 28 after *E. coli* infection. Orally administered MPX can inhibit the mRNA levels of inflammation-related factors in the jejunum infected with *E. coli*. This result shows that orally administered MPX can reduce the mRNA expression of inflammation-related factors and relieve intestinal inflammation.

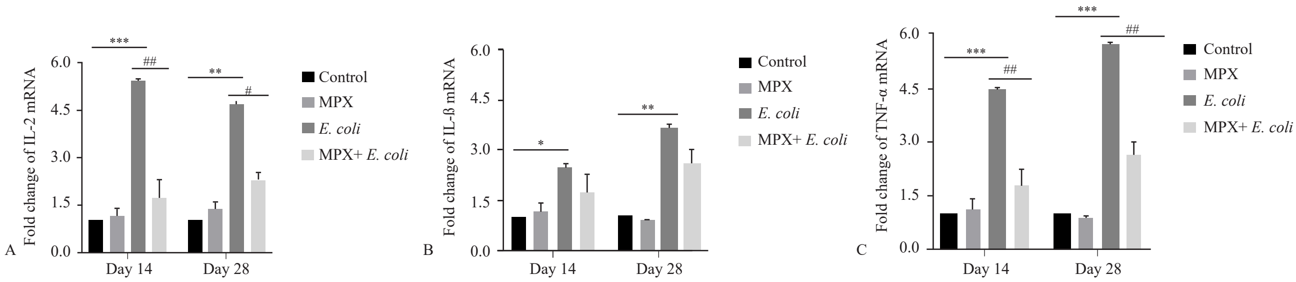

Figure 3. *The effect of an orally administered MPX on the mRNA expression of inflammatory factor in the duodenum infected with E. coli*

Orally administered MPX improves intestinal barrier function

To study the effect of orally administered MPX on the intestinal barrier function of mice. The mRNA expression of tight junction proteins Occludin, Claudin-1, ZO-1 were detected by RT-qPCR (Fig. 4A, B, C). Compared to control group, *E. coli* infection resulted in decreased mRNA expression of tight junction protein in the duodenum of mice. While orally administered MPX could significantly increase the mRNA level of intestinal tight junction proteins, thereby improving the intestinal barrier function of mice.

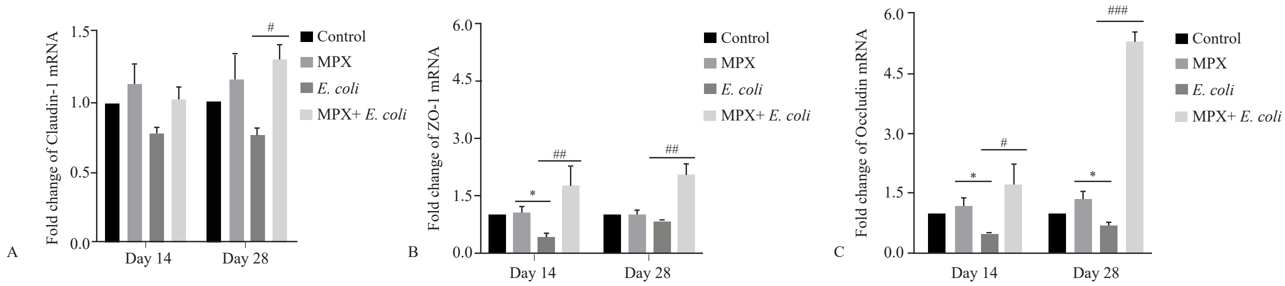

Figure 4. *The effect of orally administered MPX on the mRNA expression of tight junction protein of mice infected with E. coli*

Orally administered MPX increases MUC2 protein in mouse jejunum

In case of study the effect of an orally administered MPX on MUC2 in jejunum, authors have used immunohistochemistry for detection of the effect of an orally administered MPX on the intestinal barrier function of mice. As shown in Figure 5, compared to control group, the mRNA expression of MUC2 decreased in the jejunum after *E. coli* infection, and orally administered MPX can effectively alleviate the decreased MUC2 mRNA expression caused by *E. coli* infection. Authors' results showed that via an orally administered MPX can considerably increase MUC2 mRNA expression caused by *E. coli* infection in mice.

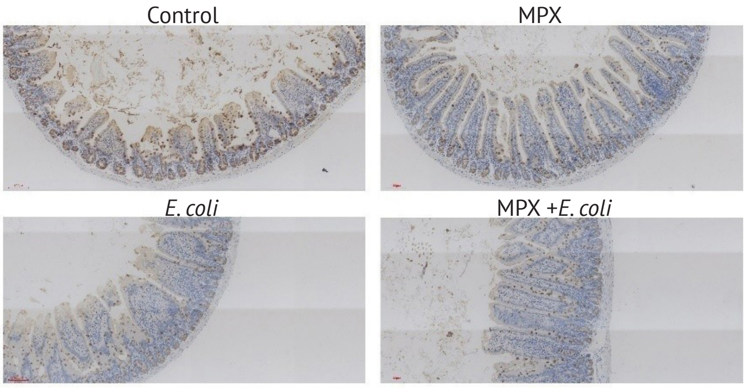

Figure 5. *Immunohistochemical detection of MUC2 protein level in jejunum of mice*

DISCUSSION

This study found that after infecting mice with *E. coli*, it caused organ damage, and orally administered MPX could effectively alleviate the above symptoms. *E. coli* infection in mice leads to increased expression of inflammation-related factors, and orally administered MPX could effectively reduce jejunum inflammation-related factors. In addition, *E. coli*-infected mice disrupted the mouse's intestinal barrier function and reduced tight junction protein and mucin levels, while orally administered MPX can increase tight junction protein and mucin levels. This study lays the foundation for the use of antimicrobial peptides as feed additives to prevent the occurrence of diseases in the clinic.

Many studies have reported that antimicrobial peptides are closely related to inflammation. The antimicrobial peptides Cathelicidin have been shown to reduce the increased expression of anti-inflammatory cytokines in the intestines of mice caused by LPS, comparable results were obtained in experiments on porcine macrophages (Fijalkowska *et al.*, 2021; Ting *et al.*, 2021). The anti-inflammatory effect of LL-37 peptide has been most thoroughly studied (Vera-Cruz *et al.*, 2021). LL-37 can alleviate the inflammation caused by pathogenic bacteria, LPS or other TLR agonists through a variety of signalling pathways. Studies have found that antimicrobial peptide LL-37 not only has anti-inflammatory effects, but also increases the expression of pro-inflammatory factors under certain conditions. For example, the expression of IL-8 in macrophages and IL-6 in dendritic cells may be enhanced by the peptide LL-37 (Mohanty *et al.*, 2021). Peptides such as defensins, LFP-20 inhibits the NF-κB signalling pathway and reduces inflammation (Rodriguez-Carlos *et al.*, 2021; Zong *et al.*, 2015). Therefore, antimicrobial peptides may have the function of selectively regulating inflammation, thereby supporting the balance of the body's immune system. The results of this study found that the orally administered MPX can effectively reduce the mRNA expression of inflammation-related IL-2, IL-6 and TNF-α in the intestinal, thereby alleviating the inflammation of the jejunum caused by *E. coli* infection in mice.

Antimicrobial peptides have abilities to increase the expression of tight junction of proteins. Antimicrobial peptides C-BF and LFP-20 reduce damage to dense compounds, increase protein expression and protect the physical barrier function of the intestine (Feng *et al.*, 2020; Han *et al.*, 2013). Snake-derived antimicrobial peptide C-BF may increase the expression of tight junction proteins Occlud in and ZO-1 in porcine jejunal epithelial cells IPEC-J2through the MAPK signalling pathway, and enhance the epithelial barrier function (Feng *et al.*, 2020). At the same time, studies have found that the porcine antimicrobial peptide PR-39 enhances the transmembrane resistance of small intestinal epithelial cells, increases the expression of tight junction proteins, and enhances the intestinal physical barrier function. The mechanism may be through up-regulation of the Rho-Rac 1 signalling pathway (Haiwen *et al.*, 2019). Authors' results found that via an orally administered MPX expression of tight junction of protein can increase in the intestine after *E. coli* infection in mice. The above results showed that antimicrobial peptides can regulate the intestinal barrier function.

CONCLUSIONS

In summary, in this study, necropsy and H&E staining results showed that oral antimicrobial peptide MPX could effectively alleviate the pathological damage of *E. coli* in the intestine, liver, spleen and lung of mice. RT-qPCR results showed that orally administered MPX can reduce the expression levels of inflammation-related factors IL-2, IL-6 and TNF-α mRNA, thereby alleviating the intestinal inflammation caused by *E. coli* infection in mice. In addition, orally administered MPX could increase the expression levels of tight junction protein Claudin-1, ZO-1 and Occlud in mRNA and improve the barrier function in the intestine. Furthermore, jejunum immune histochemistry results showed that oral administration antimicrobial peptide MPX could effectively increase the mucin MUC2 protein expression levels in the jejunum. The above results show that oral antimicrobial peptide MPX could effectively alleviate intestinal inflammation and enhance the intestinal barrier function of mice caused by *E. coli* infection. This study lays the foundation for adding antimicrobial peptides in feed to relieve inflammation and improve barrier function in clinical.

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Вплив орального застосування антибактеріального пептиду MPX на запалення кишечника мишей при експериментальній інфекції *Escherichia coli* штаму O157:H7

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Анотація. *Escherichia coli* – це грамнегативна бактерія, кишковий патоген, який може викликати запалення кишечника.Антимікробні пептиди – це клас пептидів з невеликою молекулою,які мають хорошу антибактеріальну активність проти різноманітних грампозитивних і негативних бактерій. Метою цієї роботи було дослідити вплив перорального введення антимікробного пептиду MPX на запалення кишечника та функцію кишкового бар'єру у мишей, інфікованих *E.coli*. MPX(H-INWKGIAAMAKKLL-NH2) був синтезований та очищений компанією Ji er Sheng Hua (Шанхай, Китай). Для очищення MPX використовували високоефективну рідинну хроматографію (ВЕРХ) і мас-спектрометрію. Кишкова паличка (ентерогеморагічна *Escherichia coli* O157:H7ATCC43889) була виділена з фекалій пацієнта з гемолітико-уремічним синдромом та отримана з Китайського інституту ветеринарного контролю над лікарськими засобами (Пекін, Китай). Для отримання ізольованих чистих *E.coli* культур використовували агар LB (Solarbio, Китай). Результати розтину показали, що пероральне введення MPX може полегшити ураження кишковою паличкою печінки, селезінки та легень, ці органи менш постраждали. Результати H&E показали, що застосування MPX при пероральному введенні значно полегшує вплив *E. coli* на дванадцятипалу кишку та органи на 7-й та 28-й день. qRT-PCR результати показали, що пероральне введення MPX може зменшити фактори, пов'язані із запаленням, експресію мРНКIL-2,IL-6 і TNF-α на 7 і28 день. Крім того, пероральне введення MPX може значно збільшити експресію мРНК білків щільного з'єднання Occludin і Zo-1 на 7 і 28 день. Результати імуногістохімії також показали, що пероральне введення MPX може збільшити експресію мРНКMUC2 в порожній кишці. Наведені вище результати показали, що пероральний прийом MPX може послабити вплив кишкової палички на кишковий тракт мишей,зменшити кишкове запалення та покращити функцію кишкового бар'єру. Це дослідження закладає теоретичну основу для додавання антимікробних пептидів до кормів. Пероральний прийом MPX може зменшити експресію мРНК факторів, пов'язаних із запаленням, тим самим полегшуючи кишкове запалення, викликане інфекцією *E. coli* у мишей. Крім того, пероральне введення MPX може збільшити експресію мРНК білка щільного з'єднання в кишечникута покращити бар'єрну функцію кишечника. Це дослідження закладає основу для додавання антимікробних пептидів у корм для зняття запалення та покращення бар'єрної функції в клінічній практиці

Ключові слова: антимікробний пептид MPX, ентерогеморагічна *E. coli,* процес запалення, кишковий бар'єр, білі миші

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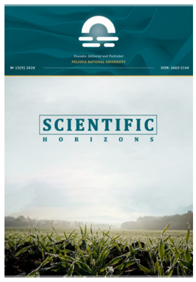

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Study of the Content of Essential Mineral Elements in the Feed of Dairy Cows Against the Background of Increased Concentrations of Toxic Metals Cd and Pb in Plants

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Abstract. Uncontrolled entry of pollutants – heavy metals into the environment creates obstacles to the production of environmentally safe, biologically complete cow's milk. The accumulation of pollutants in the soil reduces the supply of essential mineral elements to plants, which are necessary to ensure the full feeding of animals. In such environmental situations, it is important to analyse feed rations for the content of essential and non-essential mineral elements. Samples of feed included in the main diet were taken on four experimental farms specialising in the production of cow's milk, the agroecosystems of which were located around the industrial centre and near environmentally unfavourable objects – roads, enterprises for the extraction (processing) of gas condensate, etc. The samples were analysed for the content of mineral elements by atomic adsorption spectrophotometry. Statistical data processing – STATISTICA software suite version 10.0. The feed was found to exceed the permissible level for cadmium by an average of 2.1-3.2 times, lead – 2.4-5.7 times, copper – 1.4-2.3 times, zinc – 1.2-2.4 times. In cereal and legume hay, the concentration of cadmium and lead exceeded permissible levels by 3.2 and 5.7 times, respectively. Against this background, there is a deficiency of calcium in various types of diets of cows from 1.4% to 47.5%, phosphorus – from 1.5% to 62.3%, magnesium – from 2.7% to 64.4%, potassium – from 0.8 % to 37.9 %, sulphur – from 2.3% to 48.8%, among trace elements, iron – from 2.3 % to 48.8%, cobalt – from 5.0% to 80.0%, iodine – from 4.0% to 60.7%. The reason for the deficiency of vital mineral elements in plants (feed) is different, including changes in soil pH, but mainly antagonism between mobile forms of toxic elements and essential elements. For the production of high-quality milk, it is necessary to normalise toxic metals in the diets of cows with different types of feeding and eliminate the lack of minerals with the help of specially developed feed additives (mineral and vitamin premixes), which will prevent elementosis in cows, which is a pressing issue in many countries of the world. Future studies will be aimed at monitoring the concentration of mineral elements in animal feed kept in the forest-steppe and steppe zone and Donetska oblast of Ukraine

Keywords: heavy metals, lead, trace elements, macronutrients, calcium, phosphorus

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INTRODUCTION

Contamination of agroecosystems with heavy metals, especially cadmium and lead, is a major concern in various countries around the world. Under various conditions of agricultural production, the influence of abiotic and biotic environmental factors, pollutants that have accumulated in the soil easily migrate through the root system of the plant, accumulating in it in quantities that often exceed the established permissible levels (Bigalke *et al*., 2017; Borah *et al*., 2018). Further, plants are added by specialists to animal diets and affect the physiological state, productivity, quality, and environmental safety of products. They get into the manure, and as an organic fertiliser, back into the soil. The high concentration of heavy metals in livestock manure is also a concern. Researchers from China (Xu *et al*., 2021) prove that manure can pollute agricultural land when animals are fed large amounts of mineral feed additives. China recently issued new regulations restricting the use of high doses of mineral feed additives. To reduce environmental pollution and increase the competitiveness of industrial enterprises in the market, researchers highlight the importance of understanding the characteristics of heavy metals in animal feed, in this case, pigs, with an intent to develop some alternative and more efficient approaches in conducting technological processes. To do this, scientists analyse a large number of research papers over the past twenty years. They found that copper and zinc exceed the existing standards established for feed used in feeding pigs. Researchers suggest that organic and new inorganic mineral feed additives can effectively replace high doses of inorganic minerals, which, in turn, will reduce cases of diarrhoea in piglets, improve animal productivity, growth and development, and reduce pollution. The concentration of Zn and Cu in pig manure will decrease by 8.21×10^7 and 3.23×10^7 kg, respectively, per year. In addition, the quality and economic efficiency of production will improve, and the income of breeding enterprises will increase by USD 1.28×10^{10} per year (Xu *et al*., 2021).

Researchers from Germany (Schöne *et al*., 2017) also indicate that milk can be a source of iodine intake in the human body, but its value directly depends on the iodine content in cow feed. The researchers focused their attention on investigating the concentration of this essential mineral element in cow feed and milk in the German practice of animal feeding. The results obtained were compared with the results of previous monitoring of milk and experiments to investigate the dependence of the iodine content in the diet and its content in the milk of dairy cows. 73 samples of various feeds were analysed, including 41 samples of concentrated feed, 32 samples of silage made from green corn or grasses (haylage), 83 samples of vitamin and mineral premixes and feed additives for iodine content, the daily intake with the diet of animals of this trace element was determined. Grains of cereals and legumes had a low iodine content. In silage, the element content was slightly higher than in concentrated feed. In general, researchers report the need for the additional introduction of this mineral element into the diets of cows in Germany, if there is a shortage of it in feed, which will support the health of animals and ensure the production of milk with iodine content, increase the intake of the essential element in the human body with the product. Studies of the mineral composition of feed were also conducted by researchers from England (Nicholson *et al*., 1999). They analysed 183 samples of animal feed and 85 samples of animal manure from commercial farms in England and Wales. The concentration of zinc, copper, lead, nickel, cadmium, arsenic, chromium, mercury and other essential and non-essential elements was determined. Zinc and copper concentrations ranged from 150-2,920 mg Zn/kg dm (dry matter) and 18-217 mg Cu/kg dm in pig feeds, depending on the age of the pigs. In poultry feeds, concentrations ranged from 28-4,030 mg Zn/kg dm and 5-234 mg Cu/kg dm, with laying hen feeds generally having higher heavy metal contents than broiler feeds. Pig manures typically contained c.500 mg Zn/kg dm and c.360 mg Cu/kg dm, reflecting metal concentrations in the feeds. Typical concentrations in poultry manures were c.400 mg Zn/kg dm and c.80 mg Cu/kg dm, and in cattle manures c.180 mg Zn/kg dm and c.50 mg Cu/kg dm.

Thus, against the background of the problem of accumulation of heavy metals in plants (feed), including toxic ones, there is a problem of low content of essential mineral elements for the animal body, for example, iodine, etc. The reasons for the lack of mineral elements in feed can be any, not only caused by the content of an increased concentration of antagonist elements in the soil, which block the flow of iodine, calcium, and phosphorus through the root system. To ensure the normal physiological state of a dairy cow, seven mineral elements such as calcium, phosphorus, magnesium, sodium, potassium, chlorine, and sulphur must be present in the diet in very large amounts every day (Goff, 2018). R.J. Van Saun (2022) lists nine mineral elements: chromium, cobalt, copper, iodine, iron, manganese, selenium, and zinc, which play a significant biological and metabolic role in the body of dairy animals. Researchers (Séboussi *et al*., 2016) in an experiment on dairy cows prove the positive role of diets with the addition of selenium. In the experimental groups of cows, the content of somatic cells in milk was significantly lower than in the control groups of animals. Another group of researchers also highlights the important role of calcium and phosphorus in the diet of lactating cows (Moreira *et al*., 2009), because a lack of elements in the diet leads to hypocalcemia and hypophosphatemia. Absorption of elements in the intestine occurs mainly due to passive diffusion, when animals receive a diet with a sufficient amount of minerals. Calcium and phosphorus deficiency in the feed, and accordingly, in the diet, will lead to resorption of elements from the bones. This mechanism was studied at the southeastern research station of the agricultural centre of the University of Louisiana, located in Franklington, Louisiana.

The nutritional value of feed included in the diet of productive animals depends on their physiological state, quality and environmental safety of the milk produced. A lack or excess of any mineral element can negatively affect the homeostasis of the animal's body, its productivity.

Originality of the study. For the first time, the content of essential mineral elements in plants (fodder), included in different types of diets of dairy cows in farms located around the industrial centre, where agroecosystems have an increased anthropogenic load with heavy metals, was analysed.

The purpose of the study is to analyse the concentration of essential and non-essential mineral elements in various feeding rations of silage and root crops, silage and hay, silage and haylage, and silage-haylage-concentrate feeding types in agroecosystems located around the industrial centre of farms and near sources of anthropogenic pollution to assess new technological methods for the production of environmentally safe, pollutant-free cow's milk.

MATERIALS AND METHODS

Testing of new technological methods for the production of pollutant-free cow's milk using special antitoxic mineral and vitamin premixes requires a deep analysis of the nutritional value of animal feed, especially with respect to the content of essential and non-essential mineral elements. For this purpose, average samples of various feeds were selected, which were included in the diets of dairy cows in four experimental farms: the first – "Druzhba" specialised agricultural enterprise with silage and root crop type of feeding cows; the second – "Khoroshkivsky" agricultural production cooperative-silage and hay; the third – agricultural limited liability company "Svitanok" – silage and haylage; the fourth – agricultural limited liability company "Uday" – silage-haylage-concentrate feeding type. The rations included such feed as alfalfa hay and legumes, wheat straw, corn silage, alfalfa haylage, fodder beet, and various types of stock feed: barley, pea, and corn. Structure of diets of experimental cows in animals with silage-haylage-concentrate feeding type: hay and straw – 17.7%, silage and haylage – 53.5%, concentrates – 28.8%; with silage and hay type: hay and straw – 23%, silage and haylage – 44%, root crops – 17%, concentrates – 16%; with silage and root crops type: hay and straw – 19.8%, silage and haylage – 41%, root crops – 22.8 %, concentrates – 16.4%; with silage and haylage type: hay and straw – 22%, silage and haylage – 60.8%, concentrates – 17.2%. Agroecosystems of farms are located around the industrial city, near the Kyiv – Kharkiv – Dovzhanskyi highway (Ukraine), where there is a high traffic intensity, as well as near natural gas production fields and gas condensate enterprises, asphalt concrete production enterprises, main oil and gas pipelines, etc. Feed analysis and economic experiments on animals to balance animal feeding with a special mineral and vitamin premix MP-A together with subcutaneous injection of the biologically active drug BP-9 of plant origin were conducted in Poltavska oblast during 2000-2007. In the experiment, we were able to test new technological methods for feeding a specially developed mineral and vitamin premix MP-A in combination with subcutaneous injection of the biologically active drug BP-9 for the production of pollutant-free milk. The role of premix was to introduce mineral elements of heavy metal antagonists into its composition to prevent the absorption of pollutants in the gastrointestinal tract, essential elements to restore their balance in the body, and vitamins, which are extremely important for an intoxicated body. A biological product is developed from an extract of 9 medicinal herbs. The role of herbal preparation is to enhance the elimination of toxic metals that have been absorbed into the blood and block their harmful effects at the cellular level, at the level of organs and systems of the body. The drug has a hepatoprotective function, increases the excretion of cadmium and lead through the kidneys in the urine, and has a rich mineral composition – partially contributes to the restoration of the deficiency of essential elements in the animal body caused by a lack of plant feed diets. For the experiment, three groups of animals were formed in each farm. First – control, second and third – experimental groups. In the second experimental group, premix MP-A was fed as part of the diet, and in the third – premix MP-A were fed along with the subcutaneous injection of the biologically active drug BP-9.

The analysis of selected feed samples for the content of mineral elements, including heavy metals, was carried out by atomic absorption spectrophotometry (AAS-30 spectrophotometer) (Praice, 1972). The deficiency of macro- and microelements in feed was established relative to the average nutritional value of feed, defined in detailed standards (Kalashnikov *et al.*, 1985), and considering the maximum permissible concentrations of heavy metals established by the mandatory list of raw materials, products of animal and plant origin, mixed feed raw materials, mixed feed, vitamin preparations, etc., which should be carried out in state laboratories of veterinary medicine and according to the results of which a veterinary certificate (F-2) is issued (Mandatory minimum list..., 1998).

Statistical data processing was performed in the STATISTICA software suite version 10.0 for the Windows 7 operating system.

RESULTS AND DISCUSSION

Content of mineral elements belonging to the category of heavy metals in the main diet

It is established that the permissible concentrations of mineral elements belonging to the category of heavy metals in the diet of cows are exceeded. In particular, the concentration of cadmium in the diet of animals of the first experimental farm exceeded the permissible levels by an average of 2.1-3.2 times, lead – 2.4-5.7 times, copper – 1.4-2.3 times, zinc – 1.2-2.4 times, respectively. Cereal and legume hay had the highest concentration of toxic metals – cadmium and lead, which exceeded permissible levels by 3.2 and 5.7 times, respectively. Copper is a heavy metal, which belongs to the category of essential mineral elements, the maximum accumulation was recorded in corn stock feed with an excess of the norm by 2.3 times. Wheat straw accumulated an excess of zinc, which exceeded the permissible level by 2.4 times.

The influence of various environmental factors, including anthropogenic ones – various pollutants and different distances to the industrial centre, natural gas production sites, transport highway, gas condensate enterprise; the use of agrochemicals, in particular, mineral fertilisers – significantly affected the content of mobile forms of chemical elements in the soils where plants were grown, which went to feed farm animals, since the content of heavy metals in the feed of other experimental farms fluctuated. In the diet of cows of the second experimental farm, an excess of cadmium, lead, copper, and zinc in fodder beet was found by 2.5, 3.4, 3.8, 4.1 times, respectively. As it turned out, of all the feeds in the diet, fodder beets had the highest content of heavy metals, in particular, including toxic ones such as cadmium and lead.

The diet of animals of the third experimental farm exceeded the permissible concentration of cadmium, lead, copper, and zinc. In comparison with the analysis of feed from other farms, a high concentration of zinc was recorded in oats and peas, which on average exceeded permissible levels by 6.3-6.8 times. Pea stock feed was characterised by the highest accumulation of cadmium and lead, and cereal and legume hay accumulated the most copper, which exceeded the permissible level by 3.9 times.

The lead accumulation in the diet of dairy cows was highest at the fourth experimental farm. The content of the element exceeded permissible levels by 7.3 times, which is due to the location of agricultural land actually along the highway with heavy traffic Kyiv – Kharkiv – Dovzhanskyi. The concentration of zinc exceeded permissible levels by 7.8 times, copper – 4.1 times, respectively. At the same time, the feed of this farm had the lowest level of contamination with cadmium. Among the feed of the diet, hay and legumes had the highest content of Cd, Pb, Cu, and Zn. However, the last essential element accumulated the most in corn grain.

Among the studied mineral elements in feed, cadmium and lead are not essential, unlike copper and zinc. The ingress of cadmium and lead from the soil into plants – animal feed, and then into the body and milk – leads to the content of pollutants in products that are consumed by humans. Cadmium and lead can cause disruption of the body's enzymatic, hormonal, and other systems. Milk containing cadmium and lead is dangerous for humans. Copper and zinc are essential, vital mineral elements for the body, although they are heavy metals. In the appropriate normalised amount, they must necessarily enter the body of both animals and humans. To develop new technological methods for the production of environmentally safe cow's milk, it is necessary to investigate not only the content of such ecocidal mineral elements as cadmium and lead, but also the concentration of essential mineral elements in the main diet of animals, because such mineral elements as calcium, phosphorus, magnesium, potassium, iron, sulphur, cobalt, manganese, iodine, etc. have an antagonistic effect on the absorption of toxic metals in the gastrointestinal tract. The availability of detailed information about the content of essential macro- and microelements in the diet will allow specialists to develop appropriate effective feed additives, premixes, etc. – to balance the diet to ensure intensive removal of harmful elements from the body and support its vital physiological functions against the background of intoxication.

Content of essential mineral elements in the animal feed

The lowest calcium content was found: in fodder beet (47.5%) and wheat straw (31.4%) – in the first experimental farm; in wheat straw (38.6%) and alfalfa hay (22.6%) – in the second farm; corn stock feed (36%) – in the fourth; pea stock feed (12.5%) – in the third experimental farm; the rest of the feed had an average calcium content of 1.4-31.4% lower than the average for nutritional value (Fig. 1).

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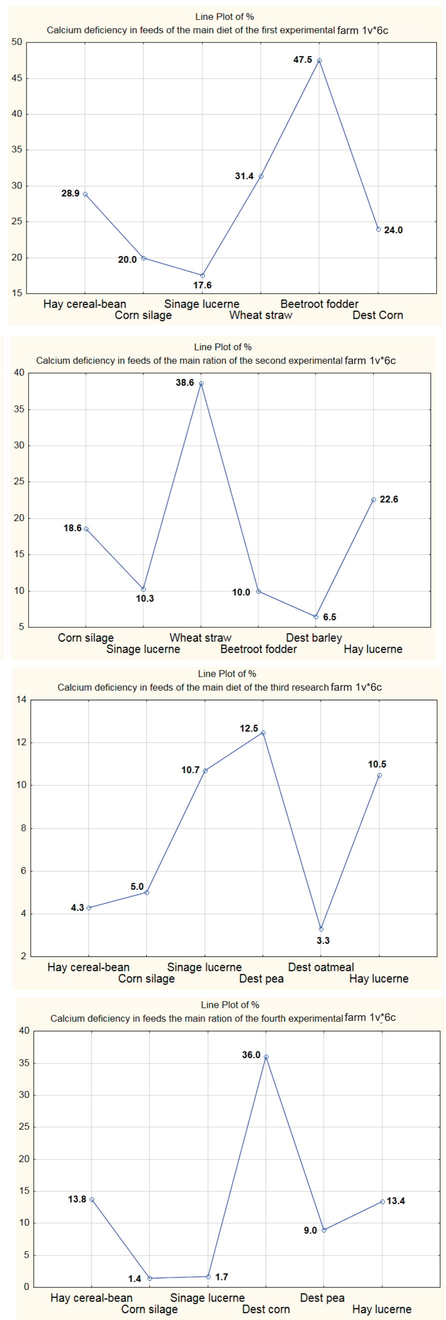

Figure 1. *Calcium deficiency in the diet: 1 – first experimental farm; 2 – second experimental farm; 3 – third experimental farm; 4 – fourth experimental farm*

The content of another mineral element phosphorus in the lowest concentration was found: in alfalfa hay 62.3% and oat stock feed (46.2%) – in the third farm; in alfalfa haylage (45%) – in the fourth and 31% – in the first experimental farm; in corn silage (42.5%) – in the second and (22.5%) – in the third farm; the rest of the feed had a phosphorus content of 1.5-22.3% lower than average (Fig. 2).

Magnesium deficiency was observed in wheat straw (51.3%) in the first farm, the most scarce relative to this macronutrient was alfalfa haylage, which was in the diet of cows of all four experimental farms. In the second experimental farm, a significant magnesium deficiency was observed in barley stock feed – 34%, the rest of the feed had a magnesium deficiency on average from 2.7% to 27.1% (Fig. 3).

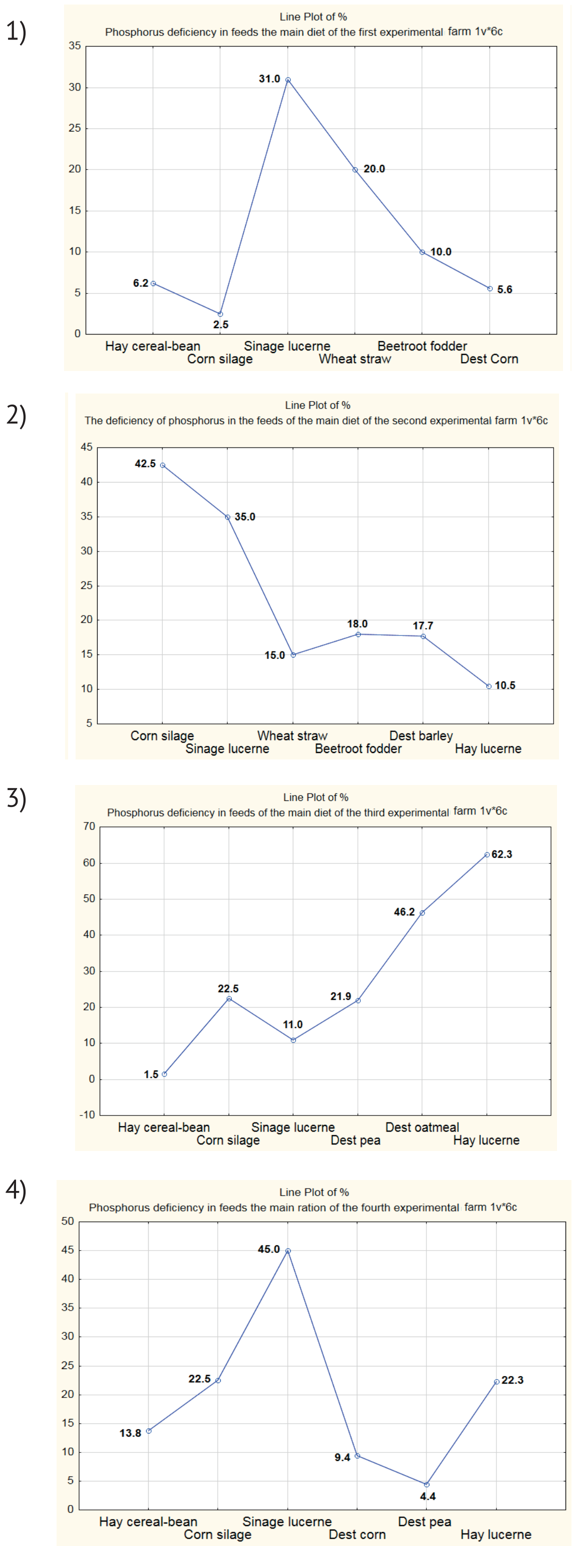

Figure 2. *Phosphorus deficiency in the diet:*
1 – first experimental farm; 2 – second experimental farm;
3 – third experimental farm; 4 – fourth experimental farm

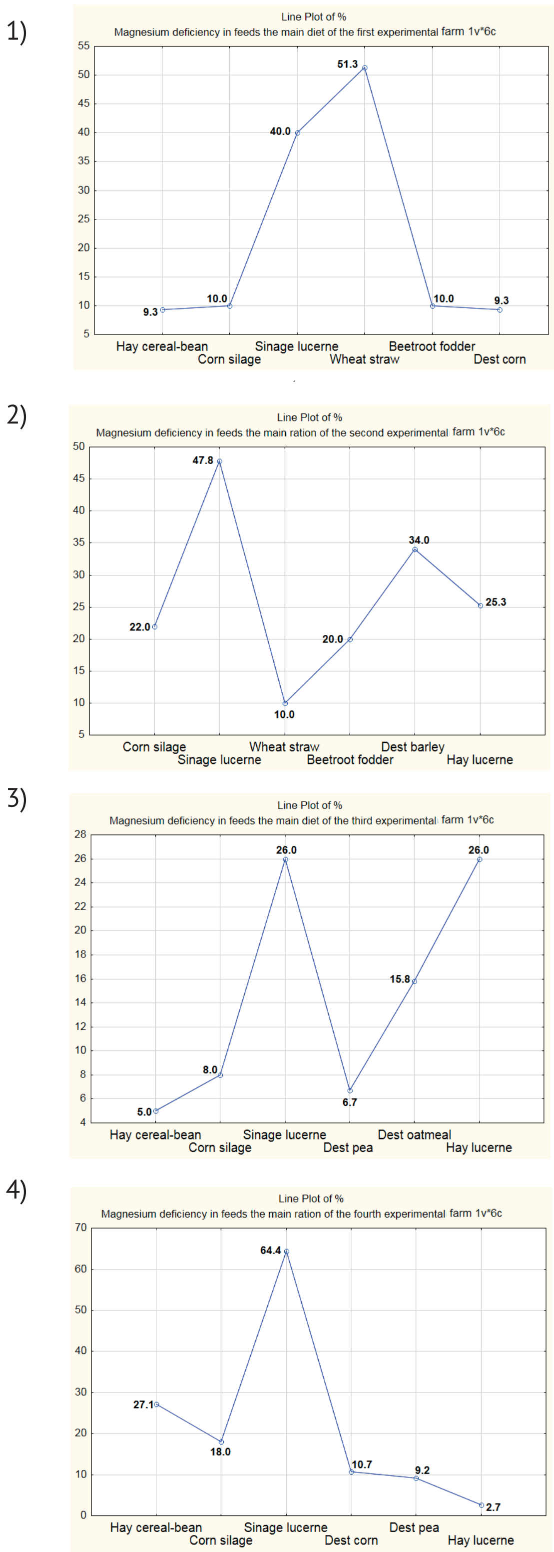

Figure 3. *Magnesium deficiency in the diet:*
1 – first experimental farm; 2 – second experimental farm;
3 – third experimental farm; 4 – fourth experimental farm

Potassium deficiency in the largest amount of 37.9% was found in wheat straw and 26.8% in fodder beet of the first farm; 33.5% in alfalfa haylage and 31.2% in alfalfa hay of the fourth experimental farm; 25% in alfalfa haylage in the second agricultural enterprise, other feeds had a potassium deficiency of 0.8-18.5% (Fig. 4).

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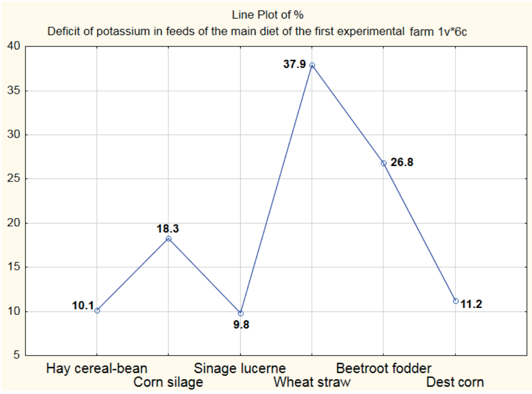

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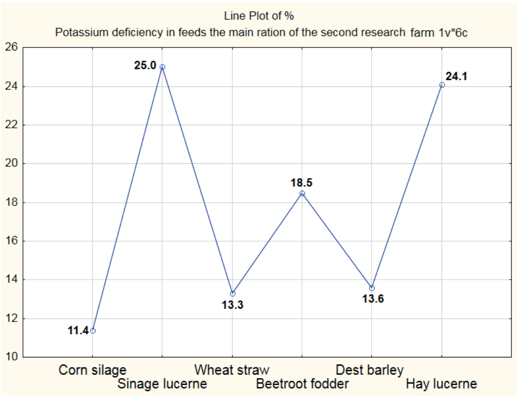

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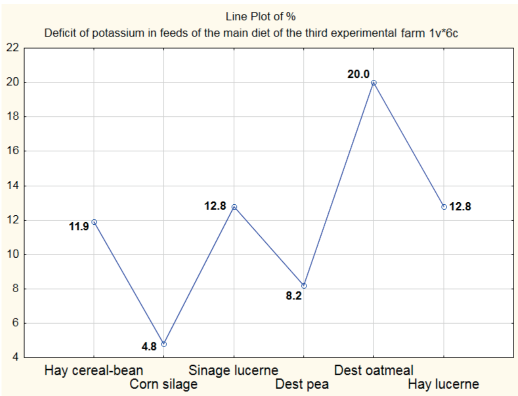

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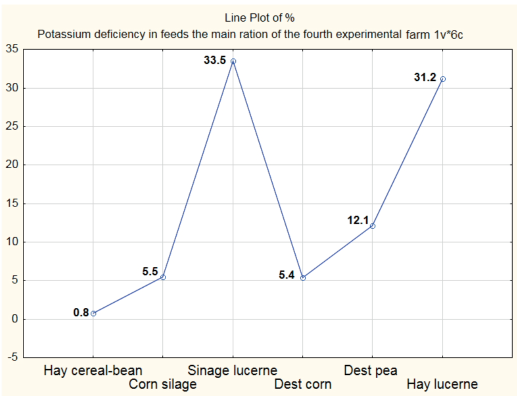

Figure 4. *Potassium deficiency in the diet:*
1 – first experimental farm; 2 – second experimental farm; 3 – third experimental farm; 4 – fourth experimental farm

Sulphur in the feed of all farms was also at a low level on average – from 2.3 to 48.8% (Fig. 5).

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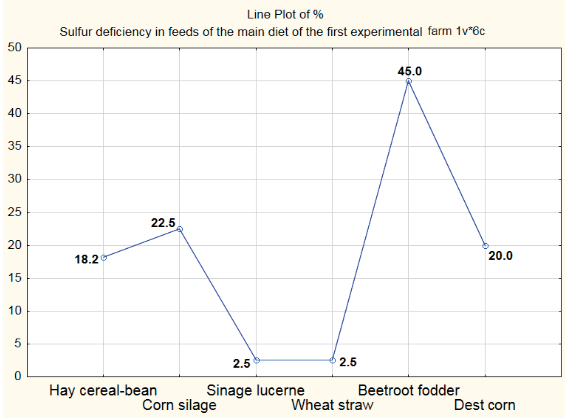

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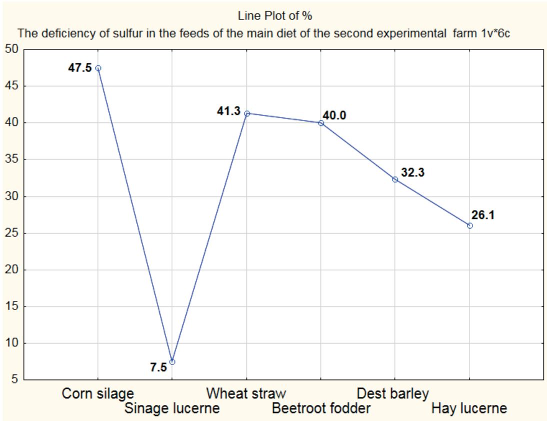

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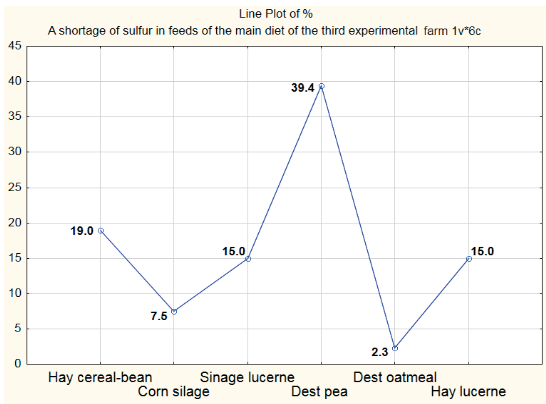

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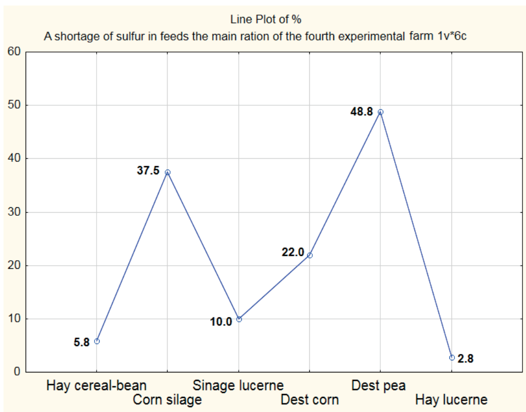

Figure 5. *Sulphur deficiency in the diet:*
1 – first experimental farm; 2 – second experimental farm; 3 – third experimental farm; 4 – fourth experimental farm

Sulphur is a fairly important trace element in case of intoxication of the body with heavy metals, especially cadmium and lead, as it is a part of sulphur-containing amino acids (methionine, cystine, cysteine) and sulfhydryl groups that form chelated compounds with toxicants. The content of sulphur in feed is very important, since its deficiency can lead to a deficiency of trace elements in the diet, which will be more dangerous for the health of cows and all the more affect the quality and safety of milk.

The reason for the low iron content in animal feed, and especially in the plants from which it is made, is the antagonism between Fe and Mn, Fe and Cu in the soil. A significant role in this is played by the increased concentration of mobile forms of copper in the soils of farms. Iron deficiency in feed is observed, which averaged 2-29.2% (Fig. 6).

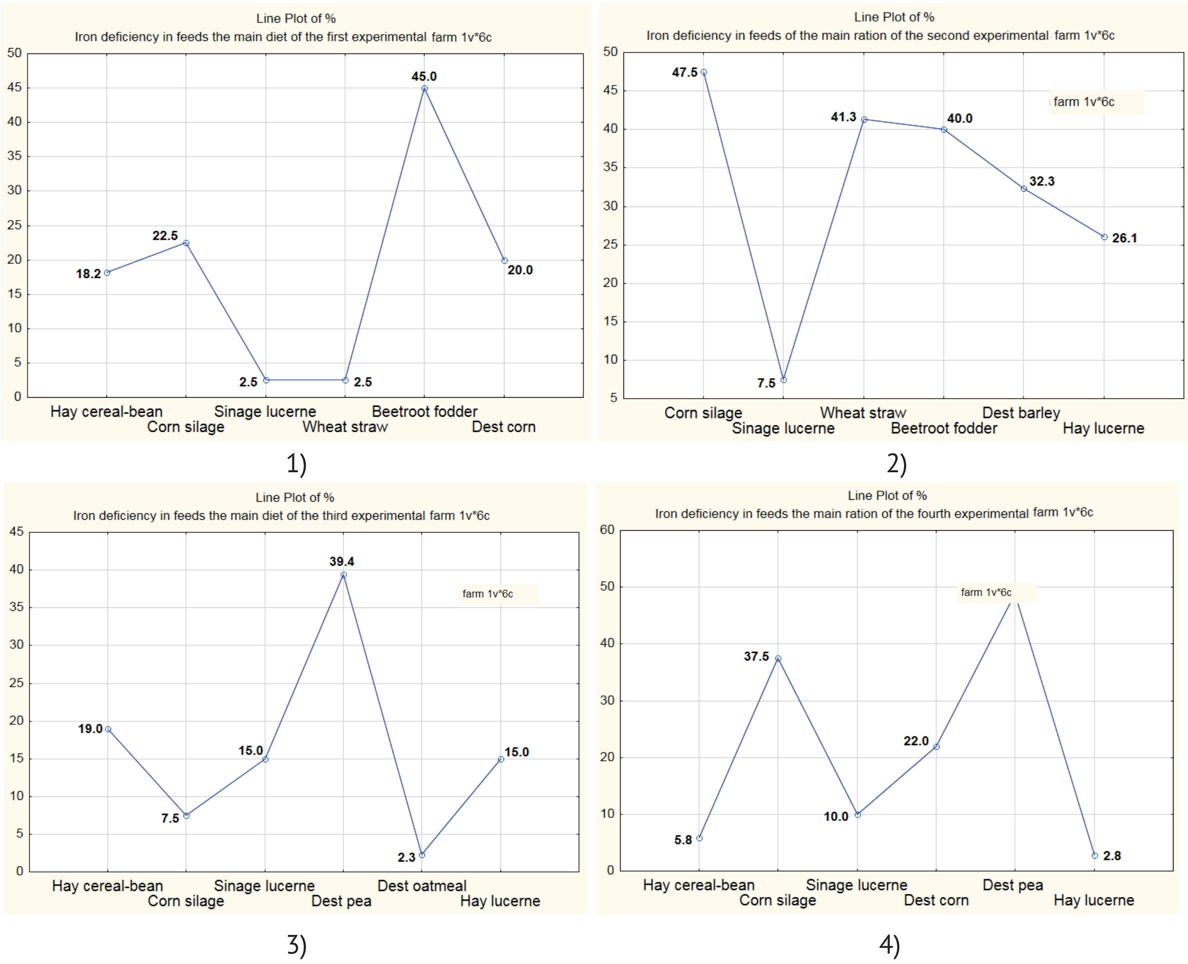

Figure 6. *Iron deficiency in the diet:*
1 – first experimental farm; 2 – second experimental farm; 3 – third experimental farm;
4 – fourth experimental farm

The absence of cobalt in feed may be conditioned by their cultivation in wetlands and the presence in the soil of a high concentration of cobalt antagonist elements, which include cadmium and lead. Applying phosphorous fertilisers to the soil can increase the supply of cobalt to plants. Cobalt deficiency can affect its deficiency not only in feed, but also in the diet, which will pose a danger of increased intoxication with cadmium and lead, and the death of the animal is also possible (the paradox is starvation with a sufficient amount of feed). The shortage of cobalt in feed is quite high (Fig. 7).

The lowest deficiency was found in cereal and legume hay (5%) — in the fourth experimental farm; in other feed — at least 11.5% in barley feed of the second farm, and beyond 15%, 20%, 40%, 50% and even 80% in alfalfa haylage in the first farm. In such a situation, a lack of cobalt in the diet and, as a result, in milk is very likely. In the ruminant's body there is a struggle for cobalt between rumen micro-organisms and enzyme systems. This element is used for the synthesis of vitamin B_{12} in the body. The presence of this vitamin in milk under such conditions is unlikely, which was confirmed by the study. Content of vitamin B_{12} in the milk of cows of all control groups was at the level of "traces".

The manganese deficiency in feed was relatively insignificant and on average ranged from 2.2% to 11.7%, 22.5%, and 29%. But the greatest manganese deficiency was distinguished by corn stock feed in the first and fourth experimental farms, where it was 35.6% and 29%, respectively. Under certain pH conditions in the soil, manganese can show antagonism to cadmium, lead, cobalt, and iron. Excessive amounts of mobile forms of cadmium and lead in the soil affected a decrease in the absorption of manganese by the root system of plants (Fig. 8).

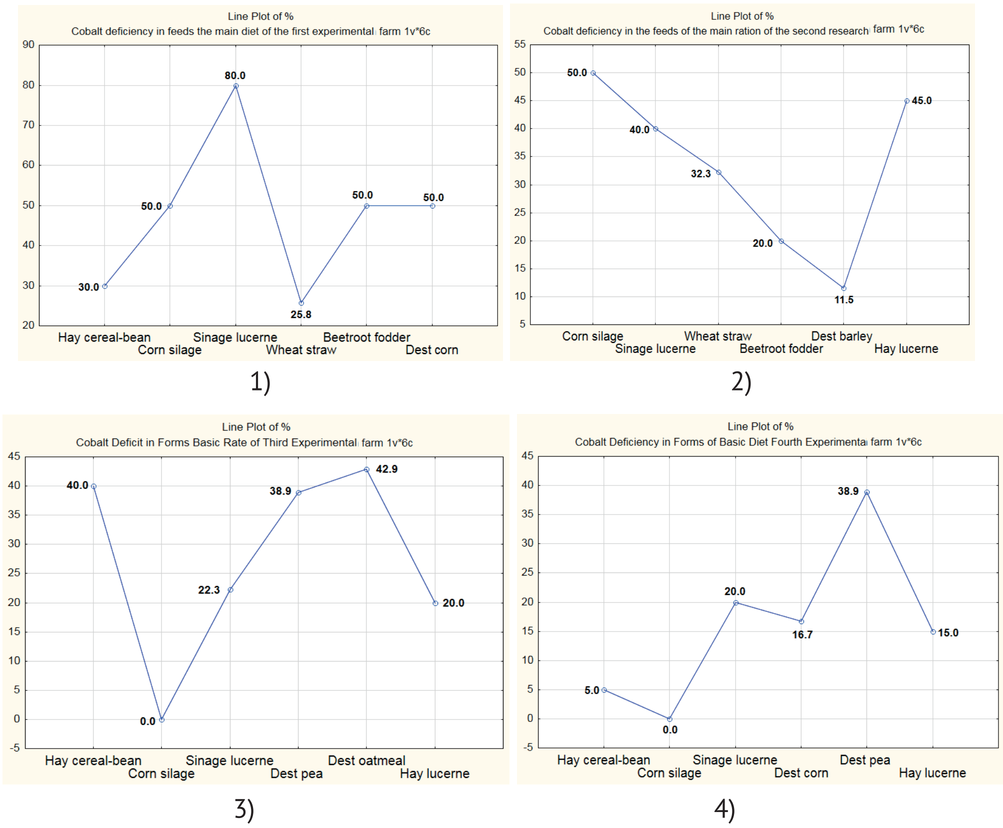

Figure 7. *Cobalt deficiency in the diet*
1 – first experimental farm; 2 – second experimental farm; 3 – third experimental farm; 4 – fourth experimental farm

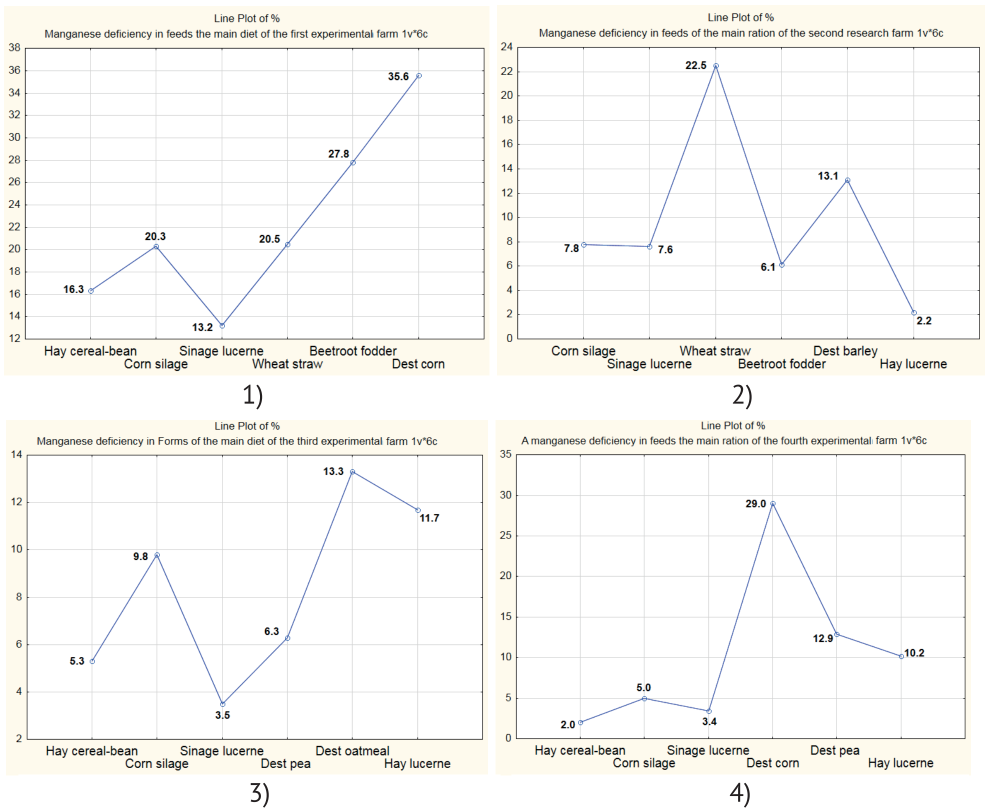

Figure 8. *Manganese deficiency in the diet:*
1 – first experimental farm; 2 – second experimental farm; 3 – third experimental farm; 4 – fourth experimental farm

Iodine deficiency in feed is caused by the presence of its antagonists in the soil – lead. Moreover, this element is part of the thyroid hormones, in particular, tetraiodothyronine (thyroxine) and triiodothyronine, which regulate the main types of metabolism in the body, growth and development of the animal. Iodine deficiency in feed from 4% to 60.7% (Fig. 9) leads to a lack of it in the diet, and consequently, in milk. Milk without iodine is not the best raw milk.

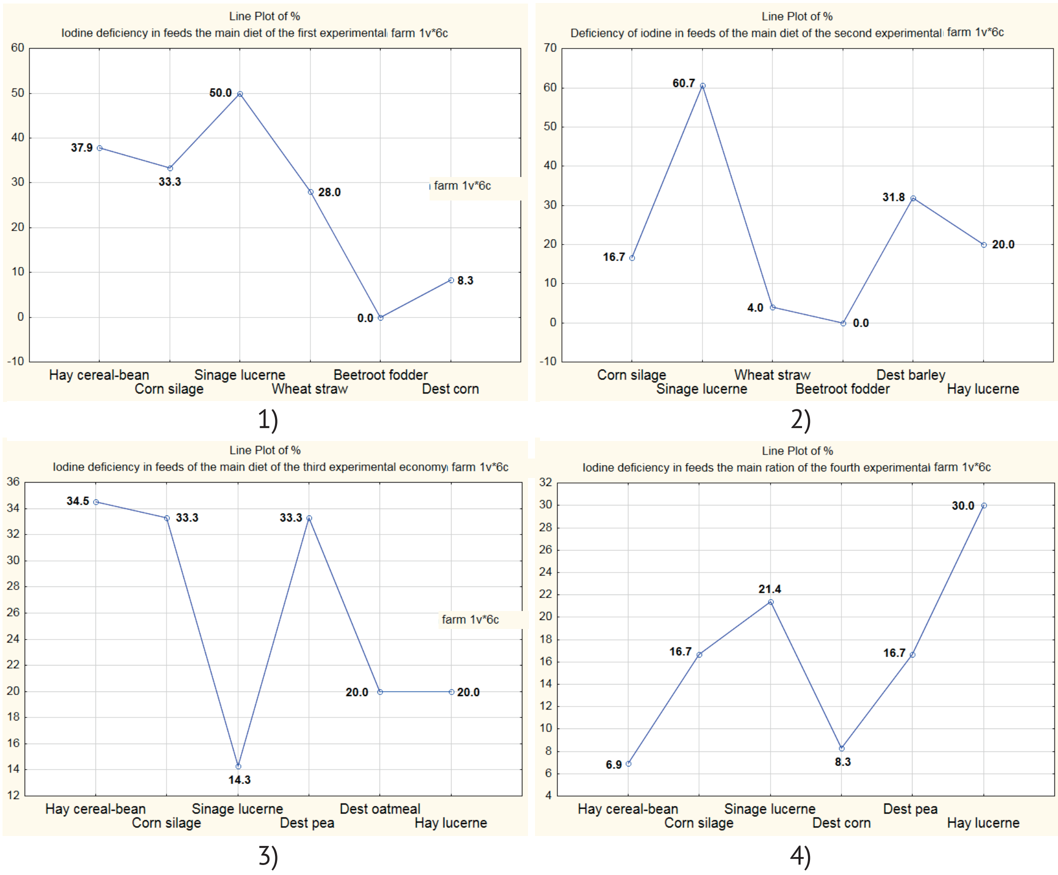

Figure 9. *Iodine deficiency in the diet:*
1 – first experimental farm; 2 – second experimental farm; 3 – third experimental farm;
4 – fourth experimental farm

The chemical analysis of feed showed not only an excess of heavy metals, but also a low content of essential macro- and microelements in plants – antagonists of cadmium, lead, copper, and zinc (Fig. 1-9). At the same time, there was a significant fluctuation in the content of macro- and microelements both in different feeds and in different experimental farms, which is natural. The problem is that the content of these elements did not correspond to the average nutritional values according to the detailed animal feeding standards. The results of laboratory analysis of feed from all experimental farms showed a characteristic low content of essential macro – and microelements against the background of an excess of dangerous heavy metals, especially cadmium and lead. In such circumstances, rationing and balancing rations becomes more difficult. There is a problem with the production of environmentally safe high-quality milk with the content of heavy metals within the permissible levels provided for by the standards, and with the content of essential elements important for the human body: calcium, phosphorus, potassium, magnesium, sulphur, iron, iodine, cobalt, etc., which bring dairy raw materials into the category of biologically complete and functional products.

Microelements are necessary for the plant in small amounts for normal development, unlike macronutrients (Castro *et al.*, 2018). They are not directly incorporated into the plant structure, but are involved in various enzymatic reactions, for example, as catalysts for chemical reactions in living systems. The concentration of iron in plants is insignificant and its physiological role in plant life is that it is a part of enzymes, participates in the synthesis of chlorophyll and metabolism. It plays an important role in the process of plant respiration, since it is an integral part of respiratory enzymes. Without iron, plant respiration is simply impossible. Since iron can pass from an oxidising form to a nitrous one and vice versa, it is involved in the redox processes that occur in plants. The problem of low iron content in plants may be related to pH problems. Iron is better absorbed at lower pH values of 5.5-6.0, and at higher pH levels, especially above 7.0, it is usually blocked. The introduction of mineral fertilisers into the soil, which reduce the pH, in farms should not have caused a deficiency of the element in plants – obviously, the antagonism between iron and other elements, including heavy metals, affected the iron intake in plants more. Excess copper in the soil can lead to iron deficiency in plants. During this study, there was a slight excess of copper in the soil and during migration in plants, in particular, in corn, the excess of the norm was 2.3 times. Similarly, iron deficiency can cause problems with calcium and magnesium. Calcium deficiency in plants (feed) of the first experimental farm ranged from 17.6% to 47.5%, the second – from 6.5% to 38.6%, the third – from 3.3% to 12.5%, the fourth – from 1.4% to 36.0 %, the situation was similar in terms of magnesium content– 9.3-51.3%, 10.0-47.8%, 5.0-26.0%, and 2.7-64.4%, respectively. No external visible signs of iron deficiency were observed on the plants. Bird droppings can increase the pH of the soil, but on farms, cattle manure is mainly used as organic fertiliser. Excess iron in plants is very rare, and the growth and development of the root system can stop. The leaves can die off and fall off without any visible changes.

Manganese activates more than 35 enzymes and participates in various reactions, including nitrogen metabolism. In this regard, plants that are deficient in the element have difficulty using nitrates as a source of nitrogen nutrition. Manganese is involved in the synthesis of vitamin C, regulates the water regime, increases resistance to adverse factors in the plant. Manganese, like iron, is better absorbed at lower temperatures with a pH of 5.5-6.0. If the pH level is very high in the soil, it can lead to a deficiency of the element in plants (Orynyk, *et al*., 2020). For all the years of research, the pH of soils in all farms ranged from 6.0 to 6.7. Therefore, the reason for the low content of manganese in plants (feed) is obviously different and most likely conditioned by the excessive amount of mobile forms of manganese antagonist elements in the soil. Excess manganese can lead to interstitial chlorosis, signs similar to those with a significant lack of magnesium, but no visible signs of this were observed. In the plants (feed) under study, the manganese deficiency ranged from 13.2% to 35.6% on the first farm, 2.2-22.5% on the second, 3.5-13.3% on the third, and 2.0-29.0% on the fourth farm, respectively.

Low soil pH, emissions of pollutants, and the use of agrochemicals affected the accumulation of heavy metals copper and zinc in plants (feed), including toxic cadmium and lead. Cadmium can affect the redistribution of calcium in the structural elements of the plant (leaves, stem), which is important for forage harvesting, for example, hay, straw, silage or haylage, and grain feed. Other studies (Morina & Küpper, 2020) found that cadmium mainly accumulates in the veins and limits the distribution of iron and zinc in the plant, and the concentration of potassium increases throughout the leaves. Cadmium did not affect the distribution of calcium, but reduced its content in the leaves. This toxic element disrupted the processes of photosynthesis, in part, it may be the result of a selective violation of the homeostasis of leaf nutrients.

Researchers from China (Zhao *et al*., 2020) point to the global problem of mineral element deficiency in plants, which can negatively affect human health. Scientists focused on maintaining the proper concentration of mineral elements in the corn grain. In 2017, a field survey of four main areas of China's corn production was conducted. 980 pairs of soil and grain samples were taken from farm fields, and geospatial fluctuations in the concentration of zinc, iron, manganese, and copper in the grain were also investigated. Zinc and iron concentrations were 18-89% lower. Top dressing of the soil with nitrogen fertilisers increased the concentration of copper and zinc in the grain, and phosphorous fertilisers reduced the content of zinc and iron. A decrease in the pH of the soil and an increase in the content of organic substances, according to researchers, can lead to an increase in the accumulation of iron andmanganese in the grain.

Another problem that affects the level of mineral elements in plants can be the pollination. Researchers from Brazil (Porto *et al*., 2021) note that half of the nutrients in plants and, accordingly, in animal feed and human food depend on pollination. Concentrations of lipids, vitamin B_9, and potassium are higher in pollinated plants. Reducing the number of pollinators can lead to a loss of 7.9-29.5% of nutrients. The researchers investigated the relative differences in nutrient concentrations of 45 major crops grown in Brazil. Of the 45 crops, some were classified as pollinator-dependent; some, on the contrary, were independent. Researchers estimate that reducing the number of pollinators can lead to total nutrient losses of 4% to 18% for all macronutrients, 6.8-26.2% for all minerals, and 2.4-31.5% for all vitamins. Scientists emphasise the importance of maintaining the number of pollinators, ensuring sustainable agricultural development and food security of the country.

Excess of mobile forms of heavy metals in the soil Cd, Pb, Cu, Zn, which are antagonists of essential elements: Ca, P, Mg, K, S, Fe, Co, Mn, I, affects their transformation into forms inaccessible to assimilation by plants, which causes a lack of data on macro- and microelements in them, which was revealed by US during laboratory analysis of fodder.

A lack of essential elements in feed in the amount of more than 50% can lead to a loss not only of milk quality, but also to a decrease in cow productivity and deterioration of animal health (Roche & Satter, 2022). With a low intake of calcium and phosphorus in the animal's body, a disease develops – osteomalacia; a low intake of potassium – allotriophagia; cobalt – pining (anemia-acobaltosis), this element also participates in haematopoiesis, is part of vitamin B_{12}; copper – anemia; sulphur deficiency causes a violation of ether-sulphur compounds formed in the liver as a result of neutralisation of certain toxic substances contained in the blood and urine in the form of inorganic sulphates; magnesium activates many enzymatic systems including those that catalyse synthesis reactions associated with adenosine triphosphoric acid, which is important in intoxication of the body with heavy metals; iron – its most important physiological function is that it is part of haemoglobin and some respiratory enzymes, in the lungs easily combines with oxygen to form oxyhaemoglobin; manganese – takes part in tissue respiration affects the metabolism of carbohydrates when there is a lack in the body slows down the growth of the animal and worsens the skeletal development; iodine – lack of it significantly affects the function of the thyroid gland, which produces the thyroxine hormone, which includes iodine, and this, in turn, affects the calcium and phosphorus metabolism in the body.

The low content of essential elements and an excess of heavy metals in the studied conditions could have been caused by a violation of the timing and types of mineral fertilisers applied. At all experimental farms, approximately 70-80% of mineral fertilisers are applied to the soil in the spring due to various production and economic reasons, instead of being applied with the main tillage. Nitrogen fertilisers were mainly applied. This creates not only organisational tension in spring field work, but also reduces the effectiveness of fertilisers to a certain extent. Studies (Vyrliev, 1986) have established that the untimely application of fertilisers and their uneven distribution reduces the efficiency of nitrogen by 35-40%, phosphorus — by 20-25%, potassium — by 15-20%, complex fertilisers — by 30-35%.

Anthropogenic pollution of the natural environment around industrial centres leads to a violation of the cycle of substances, a decrease in the nutritional value of feed, which makes it almost impossible to produce high-quality environmentally safe milk and the raw materials for the production of dairy products, without the use of appropriate science-based technologies for the restoration of the balance of mineral elements both in the animal's body itself and in products. All the studied feeds were included in the main diets with different types of feeding of dairy cows.

CONCLUSIONS

In conditions of local contamination of agroecosystems with heavy metals, especially cadmium and lead, it is unacceptable to balance the main diets of dairy cows without considering the actual nutritional value of feed. The production of environmentally safe, high-quality cow's milk is much more complicated without rationing the content of heavy metals of cadmium, lead, copper, and zinc in the feed that exceeds the permissible level of pollutants and has a deficiency of essential mineral elements, such as calcium, phosphorus, magnesium, potassium, sulphur, and among the trace elements of iron, cobalt, manganese, iodine. The development of special mineral and vitamin premixes or other new feed additives specifically adapted to such diets will reduce the negative impact of toxic trace elements and compensate for the lack of biologically important elements in the body of highly productive animals, which will ensure the production of pollutant-free milk and dairy raw materials with a sufficient content of iodine, cobalt, iron. Such feed additives would help to improve the health of cows and prevent the occurrence of hypocalcemia, hypophosphatemia, and other diseases characteristic of lactating animals.

Further study will be aimed at environmental monitoring of the content of essential and non-essential mineral elements, including heavy metals, in plants (feed) of various farms of the forest-steppe, steppe regions of Ukraine and Donetska oblast, where dairy cows are kept.

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Дослідження вмісту ессенціальних мінеральних елементів у кормах раціонів дійних корів на фоні підвищеної концентрації в рослинах токсичних металів Cd та Pb

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Анотація. Неконтрольоване надходження у довкілля забруднюючих речовин – важких металів, створює перешкоди для виробництва екологічно безпечного, біологічно повноцінного коров'ячого молока. Акумуляція полютантів у грунті зменшує надходження в рослини ессенціальних мінеральних елементів, необхідних для забезпечення повноцінної годівлі тварин. У таких екологічних ситуаціях важливе значення має аналіз кормів раціонів на вміст ессенціальних і неессенціальних мінеральних елементів. У чотирьох дослідних господарствах, які спеціалізуються на виробництві коров'ячого молока, агроекосистеми розміщені навколо промислового центру і поблизу екологічно несприятливих об'єктів – автошляхи, підприємства з видобутку (переробки) газоконденсату тощо, відібрано зразки кормів, що входили до основного раціону. Методом атомно-адсорбційної спектрофотометрії проведено аналіз їх на вміст мінеральних елементів. Статистична обробка даних – STATISTICA версії 10.0. У кормах встановлено перевищення допустимої норми по кадмію у середньому в 2,1–3,2 рази, свинцю – 2,4–5,7 рази, міді – 1,4–2,3 рази, цинку – 1,2–2,4 рази. У сіні злаково-бобовому концентрація кадмію, свинцю перевищувала норму у 3,2 і 5,7 рази відповідно. На цьому фоні встановлено дефіцит кальцію в кормах раціонів різних типів годівлі корів від 1,4 % до 47,5 %, фосфору – від 1,5 % до 62,3 %, магнію – від 2,7 % до 64,4 %, калію – від 0,8 % до 37,9 %, сірки – від 2,3 % до 48,8 %, серед мікроелементів, заліза – від 2,3 % до 48,8 %, кобальту – від 5,0 % до 80,0 %, йоду – від 4,0 % до 60,7 %. Причина дефіциту в рослинах (кормах) життєво важливих мінеральних елементів носить різний характер, що включає зміни pH грунту, але переважно – антагонізм між рухомими формами токсичних елементів та ессенціальними елементами. Для виробництва високоякісного молока необхідно здійснювати нормування токсичних металів у раціонах корів з різними типами годівлі, ліквідувати дефіцит мінералів за допомогою спеціально розроблених кормових добавок (мінерально-вітамінних преміксів), що дозволить забезпечити профілактику елементозів корів, які є проблемними в різних країнах світу. Майбутні дослідження спрямовані на моніторинг концентрації мінеральних елементів в кормах тварин, які утримуються в Лісостеповій і Степовій зоні та Донецькому регіоні України

Ключові слова: важкі метали, свинець, мікроелементи, макроелементи, кальцій, фосфор

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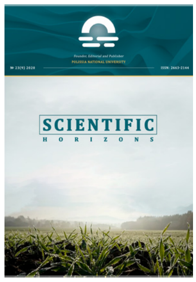

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Fractional Composition of Mineral Phosphates of Podzolized Chernozem after Prolonged Use of Fertilisers in Field Crop Rotation

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Abstract. The phosphate state of the soil is an important factor in forming its fertility. In this regard, the study of the phosphate state of different soil subtypes in different agrocenoses is relevant. Experimental data on changes in the content of gross phosphorus and its fractional composition in podzolized chernozem under the influence of long-term fertilisation are important for the effective use of fertilisers in the right-bank forest-steppe of Ukraine, determine its potential for providing plants with phosphorus, and are the theoretical basis for clarifying the standards for the rational use of high-cost phosphorous fertilisers. The purpose of the study was to investigate changes in the fractional composition of mineral phosphates of podzolized chernozem compared to fallow after the use of various fertiliser systems in the field crop rotation of the right-bank forest-steppe. In the soil from a layer of 0-20 cm, the content of mineral phosphates was determined by the Chang and Jackson method modified by Ginzburg-Lebedeva with photo colourimetric determination of phosphorus by the Denigs method modified by Truog-Mayer. Studies have shown that the loessial podzolized heavy loam chernozem has significant reserves of phosphorus potentially available for plant nutrition. After 55 years in the field crop rotation, depending on the characteristics of fertiliser, its content in the soil changed from 921 mg/kg to 2,565 mg/kg P_2O_5 (content of 1,008 mg/kg under fallow). The content of mineral phosphate fractions in podzolized chernozem is arranged in the following sequence: $Ca\text{-}P_{II}$>$Ca\text{-}P_{III}$>$Ca\text{-}P_{I}$>Fe-P>Al-P. The use of manure and mineral fertilisers increases the phosphorus content in all fractions of mineral phosphates. First of all, the share of active forms – $Ca\text{-}P_I$ and $Ca\text{-}P_{II}$ is growing up to 66-72% (with 64% content in fallow). According to the organo-mineral fertiliser system (option Manure 13.5 t + $N_{68}P_{101}K_{54}$), phosphorus between the fractions of mineral phosphates is distributed in the following ratio,%: $Ca\text{-}P_I$-7; $Ca\text{-}P_{II}$-40; $Ca\text{-}P_{III}$-28; Al-P-11; Fe-P-14. Phosphate mobility estimated by the indicator ($Ca\text{-}P_I$+ $Ca\text{-}P_{II}$): $Ca\text{-}P_{III}$ depends more on fertiliser doses than on fertiliser systems. High content of $Ca\text{-}P_{III}$ fraction in podzolized chernozem indicates the need to clarify the optimal content of mobile phosphorus compounds

Keywords: soil, fertiliser systems, gross phosphorus, calcium phosphates, aluminium phosphates, iron phosphates

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INTRODUCTION

The soils of Ukraine have an average ability to provide plants with phosphorus. Therefore, one of the important tasks of modern agricultural production is to restore and gradually increase its content in soils to create an optimal phosphate regime that ensures high and sustainable crop yields (Soltangheisi *et al.*, 2020; Ginzburg, 1981). In the forest-steppe, the area of chernozems is podzolized by about 16% and they are most common on the Right Bank. Their profile is characterised by a combination of genetic traits inherent in chernozems typical of dark grey forest soils. The main processes of chernozem formation are: sod-forming process and migration of calcium bicarbonates along the profile. These processes remain leading, but in ploughed chernozems, they are quantitatively changed, because after ploughing, the sod-forming process is significantly inhibited due to a sharp decrease in the intake of plant residues (Bulygin *et al.*, 2016). This leads to a weakening of the humus accumulation process and, accordingly, to the loss of humus by soils. According to H.M. Hospodarenko *et al.* (2018) the humus content in podzolized chernozem depends on the intensity of fertiliser use in the field crop rotation. With prolonged use of optimal fertiliser systems, its agrochemical state gradually stabilises.

In the chernozem zone, the effective fertility of soils and the effect of fertilisers are most affected by the supply of phosphorus to plants (Baluik *et al.*, 2018). Even D.N. Prianishnikov (1952) believed that in order to revive the chernozems depleted by centuries-old agriculture, it is necessary to add phosphorus. The problem of phosphorus in agriculture is still quite important today. The phosphate level of soils is one of the important signs of their fertility (Vasbieva *et al.*, 2021; Miroshnichenko *et al.*, 2021; Nosko, 2017). Plants' assimilation of the optimal amount of phosphorus to produce a high yield depends on its soil reserves, mobility, and a number of conditions that affect its absorption (Marschner, 2012).

Experimental data on changes in the content of gross phosphorus and its fractional composition in podzolized chernozem under the influence of long-term fertilisation is the theoretical basis for the effective use of fertilisers in the right-bank forest-steppe of Ukraine, and the potential capabilities of this type of soil to provide plants with phosphorus is the theoretical basis for creating new standards for the rational use of high-cost phosphorous fertilisers on a regional scale.

The phosphate state of the soil largely reflects its genetic characteristics. The total phosphorus content, the nature of the profile distribution, the proportion of mineral compounds and their forms, and other indicators determine the type of soil development and the degree of soil cultivation (Menezes-Blackburn *et al.*, 2018). This is conditioned by the peculiarities of interaction of phosphorus compounds with individual soil components (cations of soil solution, free iron and aluminium oxides, exchange bases of the soil absorption complex) with the establishment of stable hard-to-dissolve compounds. The content of phosphorus and its distribution by forms in soils has a zonal and subzonal character and is associated with both geological processes and anthropogenic transformation of modern soils under the influence of various factors (Baliuk *et al.*, 2018; Schneider *et al.*, 2019). In this regard, the study of the phosphate regime of podzolized chernozem under long-term application of different doses of fertilisers and fertiliser systems in the field rotation is relevant.

The main source of phosphorus in the process of soil development is the parent rock. Due to bio-displacement by plants, most of it accumulates in the upper layers of the soil profile. Phosphorus has a number of chemical properties that determine its versatile interaction with soil components, which contributes to the formation of a large number of compounds. This makes it difficult to develop methods for assessing the ability of soils to provide agricultural crops with phosphorus (Nosko, 2017; Kristenko, 2019). In phosphorus agrochemistry, the most important issue is the absorption of fertiliser phosphates by the soil, the level of which and the strength of the bond depends on the supply of plants with this element. Phosphorous fertilisers introduced into the soil undergo various transformations with the formation of organic and mineral phosphates. The ability of plants to absorb phosphorus from fertilisers does not depend on those compounds that were introduced, but on those that were formed in the soil. Therefore, to evaluate a particular phosphorous fertiliser and outline its rational use, i.e., the dose, method, and time of application, it is necessary to know what transformations it undergoes during interaction with the soil and what phosphates are formed in this case (Teicher *et al.*, 2018). B.S. Nosko (2019) found that fertiliser phosphorus is distributed among phosphate fractions in the same way as their distribution in virgin soil, but this cannot be traced in all soils. For example, in chernozems, newly formed phosphates form a structure of the phosphate fund that is not identical to its natural counterparts (Nunes *et al.*, 2020). It has been shown that the features of phosphorus conversion of organic and mineral fertilisers, the properties of newly formed phosphates depend on the mineralogical composition of the soil, the content of organic compounds (Kyrychenko, 2015; Lisoval *et al.*, 1984), fertiliser doses and forms, soil cultivation, but the main factor in these transformations is the acidity of the soil environment (GInzburg, 1981; Vasbieva, 2021; Sheil *et al.*, 2016).

According to R.S. Truskavetsky & Yu.L. Tsapko (2016), the use of mineral fertilisers increases the content of potentially available phosphates in the soil. Residual phosphates of applied fertilisers are more mobile than natural compounds. In a long-term experiment, the degree of provision of carbonate phosphates to chernozem and changes in their group (qualitative) composition depended on the doses and duration of fertiliser application. At low doses of phosphorous fertilisers, changes are usually insignificant, since doses that exceed the removal of phosphorus by crops accumulate in all soil residues, which are distributed among all fractions of soil phosphates (Volkogon *et al*., 2019; Zagorcha, 1990). Consequently, the features of the distribution of phosphorus between them during fertiliser application remain rather neglected and require further investigation.

The purpose of the study was to identify and theoretically substantiate the nature and line of changes in the phosphate fund of podzolized chernozem after the prolonged application of fertilisers in crop rotation. The main task of the research is to characterise the phosphate state of podzolized chernozem by identifying patterns of changes under the influence of mineral, organic, and organo-mineral fertiliser systems; to assess the fractional composition of mineral phosphates in agrocenosis with different fertiliser systems in crop rotation.

MATERIALS AND METHODS

The study was conducted in a stationary experiment (NAAS Certificate No. 88), laid in the experimental field of the Uman National University of Horticulture (Zaryshniak *et al*., 2014), which is located in the Mankivskyi natural and agricultural area of the right-bank forest-steppe, which is based on a 10-field crop rotation with a typical set of field crops for the region, deployed in all fields (Table 1) (Zaryshniak *et al*., 2014).

***Table 1**. Fertiliser distribution scheme for crops in a field crop rotation in a stationary experiment (manure, t/ha; mineral fertiliser, kg/ha)*

Experiment variant	Fertiliser option	Clover	Winter wheat	Sugar beet	Corn	Peas	Winter wheat	Corn for silage	Winter wheat	Sugar beet	Spring barley + Clover
Control (without fertilisers)	–	–	–	–	–	–	–	–	–	–	–
$N_{45}P_{45}K_{45}$	N	–	45	90	50	10	45	50	45	90	25
	P_2O_5	–	45	90	50	10	45	50	45	90	25
	K_2O	–	45	90	50	10	45	50	45	90	25
$N_{90}P_{90}K_{90}$	N	80	90	135	100	30	90	100	90	135	50
	P_2O_5	80	90	135	100	30	90	100	90	135	50
	K_2O	80	90	135	100	30	90	100	90	135	50
$N_{135}P_{45}K_{45}$	N	50	135	180	200	60	135	200	135	180	75
	P_2O_5	50	135	180	200	60	135	200	135	180	75
	K_2O	50	135	180	200	60	135	200	135	180	75
Manure 9	Manure	–	–	30	–	–	30	–	–	30	–
Manure 13.5	Manure	–	–	45	–	–	45	–	–	45	–
Manure 18	Manure	–	–	60	–	–	60	–	–	60	–
Manure 4.5 t+$N_{22}P_{34}K_{18}$	N	–	22.5	30	50	–	22.5	22.5	22.5	30	25
	P_2O_5	–	22.5	67.5	50	10	22.5	50	22.5	67.5	25
	K_2O	–	22.5	15	47.5	10	22.5	–	22.5	15	25
	Manure	–	–	15	–	–		15	–	15	–
Manure 9 t+$N_{45}P_{68}K_{36}$	N	–	45	60	100	20	45	50	45	60	25
	P_2O_5	25	45	135	100	20	45	50	45	135	75
	K_2O	20	45	30	100	20	45	–	45	30	25
	Manure	–	–	30	–	–	–	30	–	30	–
Manure 13.5 t+$N_{68}P_{101}K_{54}$	N	–	67.5	90	150	20	67.5	75	67.5	90	47.5
	P_2O_5	50	67.5	202.5	150	30	67.5	100	67.5	202.5	75
	K_2O	17.5	67.5	45	150	30	67.5	–	67.5	45	50
	Manure	–	–	45	–	–	–	45	–	45	–

The soil is classified as loessial podzolized heavy loamy chernozem. Before laying the experiment in 1964, a humus content according to the Tyurin method (DSTU 4289:2004, 2005) was 3.31%; pH_{KCl} – 6.2; nitrogen content of easily hydrolysed compounds according to the Tyurin-Kononova (Tyurin & Kononova, 1934) – 48 mg/kg; mobile compounds of phosphorus (122 mg/kg) and potassium (135 mg/kg) according to the Chirikov (DSTU 4115:2002, 2003). The experiment uses organic, mineral, and organo-mineral fertiliser systems with single, double, and triple levels of saturation with the main elements of nutrition of the crop rotation area. Single-dose of mineral fertilisers – $N_{45}P_{45}K_{45}$, organic – 4.5 tonnes of manure per 1 ha of crop rotation area. According to the organo-mineral fertiliser system, the doses of the main nutrients are equal to the corresponding variants of the mineral system. The area of the experimental site of the experiment variant – 180 m^2, length – 18 m, and width – 10 m. Semi-rotted cattle manure, ammonium nitrate, granulated superphosphate, and potassium chloride were used in the experiment. Since long-term cultivation processes do not allow monitoring changes in the soil from the natural state to the one that has developed during land use, the method of comparison with the natural analogue – the fallow near the site was used for comparison.

For analytical studies, in 2020, soil samples were selected from 0-20 cm layer in accordance with the requirements of DSTU 4287:2004 and DSTU ISO 11464:2007. The gross phosphorus content was determined in accordance with DSTU 4290 (DSTU 4290:2004, 2005). Mineral phosphates were determined by the Chang and Jackson method in the Ginzburg & Lebedeva modification (Ginzburg & Lebedeva, 1971), the essence of which is to treat soil samples with various solvents in the following sequence – 1% solution of ammonium sulphate and 0.25% ammonium molybdate, 0.5% acetic acid and 0.25 % am-monium molybdate, 0.5% solution of ammonium fluoride, 0.1 % solution of caustic acid sodium, 0.5 % sulphuric acid. Phosphorus determination was performed photocolourimet-rically using the Denigs method modified by Truog-Mayer (Tyurin & Kononova, 1934).

Statistical processing of the research results contained was carried out using the Microsoft Office and STATISTICA 12 software suites.

RESULTS AND DISCUSSION

Studies have shown that the use of manure and mineral fertilisers causes changes in phosphorus reserves in the soil (Fig. 1).

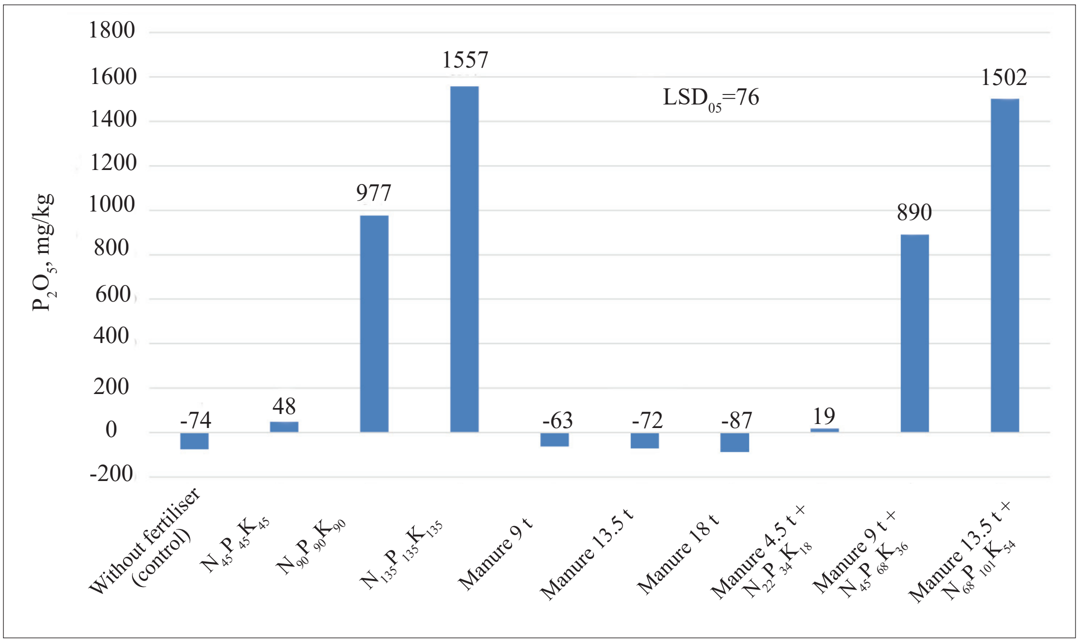

Figure 1. *Changes in gross phosphorus content in 0-20 cm soil layer after long-term (55 years) use of fertilisers in crop rotation compared to fallow (1,008 mg/kg)*

The phosphorus content in the soil varies depending on the doses of fertilisers and fertiliser systems. There is a very strong correlation between its content and the doses of phosphorus introduced (r=0.99). This is explained both by the removal of phosphorus by crops, and by its movement along the soil profile mechanically during its cultivation and in the forms of complex organo-mineral compounds.

Mineral phosphates in the 0-20 cm layer of fallow make up 61% of the gross phosphorus content, or 615 mg/kg. In this case, phosphorus is distributed between the fractions in the following ratio, %: Ca-P_I-5; Ca-P_{II}-42; Ca-P_{III}-36; Al-P-9; Fe-P-8 (Fig. 2). High-base calcium phosphates occupy the main share of mineral phosphate compounds. The fertiliser does not affect the structure of mineral phosphates. It mostly depends on the acidity of the soil solution and the content of carbonates in it (Ginzburg, 1981; Kristenko, 2019; Truskavetsky &Tsapko, 2016). O.A. Biriukova *et al.* (2010) found that the amount of phosphorus absorbed by plants depends on the ratio of calcium exchange to the amount of total carbonates in the soil. There is a certain equilibrium between the exchange calcium and the total content of carbonates of various nature in these soils, the displacement of which reduces the availability of phosphorus. This is explained by the formation of hard-to-dissolve calcium phosphates.

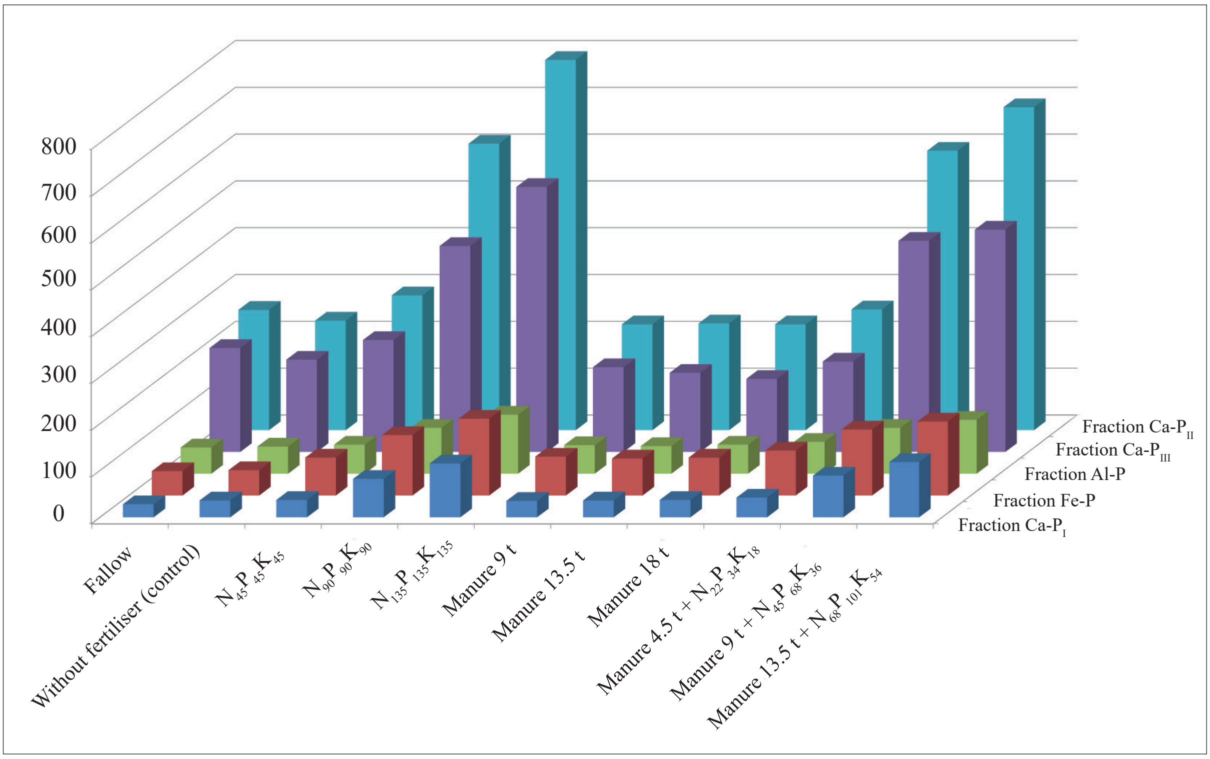

Figure 2. *Fractional composition of mineral phosphates in 0-20 cm soil layer after long-term (55 years) use of fertilisers in crop rotation, mg/kg*

Long-term cultivation of crops without the use of fertilisers did not significantly affect both the content of mineral phosphates and their distribution between fractions. This can be explained by the bio-displacement of phosphorus from the lower soil layers by plant root systems (Karengina *et al.*, 2020). The phosphate content of the fraction Ca-P$_{I}$ which is represented by phosphates of alkaline and alkaline earth metals, is 28-118 mg/kg of soil, depending on the experimental variant and depends on the content of gross phosphorus in the soil (r=0.98). The content of dissimilar calcium phosphates (Ca-P$_{II}$), which is less accessible to plants, is much larger – 226-791 mg/kg. A significant proportion of the amount of mineral phosphates is occupied by three substituted calcium phosphates (Ca-P$_{III}$) – 28-36%, depending on the experiment variant. There is a close correlation between the content of gross phosphorus in the soil and its distribution in different fractions of mineral phosphates (r=0.89-0.99).

The use of organic and mineral fertilisers increases the phosphorus content in all fractions of mineral phosphates. First of all, there is an accumulation of phosphates of the fraction Ca-P$_{I}$, which is the most valuable for phosphorous nutrition**,** and also in the faction Ca-P$_{II}$, which is its immediate reserve. According to (Menezes-Blackburn *et al.*, 2018), the intake of organic substances into the soil with both organic fertilisers and plant residues, improves the water-physical properties of the soil, increases their biological activity, and stabilises the nitrogen state. At the same time, the intensity of transformation processes of mineral and organic phosphates in the soil changes accordingly, which contributes to their better assimilation by plants.

Attention is drawn to the almost identical content of Al-P and Fe-P fractions on the fallow and the increase in the content of the latter with prolonged use of fertilisers, especially mineral ones. This can be explained by an increase in the binding of phosphate ions to iron and a decrease in aluminium with the acidification of the soil medium (Rosso *et al.*, 1995). Notably, aluminium-bound phosphorus is 1-6 times more accessible to plants than iron phosphates, and iron phosphates are 8-18 times more accessible than calcium phosphates (Sheil *et al.*, 2016). This also explains the change in the content of the fraction Ca-P$_{III}$. Despite the increase in the content of this fraction in the soil at high doses of fertilisers of the mineral and organo-mineral systems to 440-566 mg/kg (with a content of 222 mg/kg on fallow), in the composition of mineral phosphates, their content respectively decreased from 36 to 28-34 %. At the same time, for example, according to the organo-mineral fertiliser system (option Manure 13.5 t + $N_{68}P_{101}K_{54}$), phosphorus between the fractions of mineral phosphates is distributed in the following ratio, %: Ca-P$_{I}$-7; Ca-P$_{II}$-40; Ca-P$_{III}$-28; Al-P-11; Fe-P-14. That is, in comparison with the fallow and plots without fertilisers, the share of phosphorus in active forms has increased. Similar data were obtained on carbonate chernozem (Zagorcha, 1990). Long-term systematic use of mineral fertilisers and their combination with organic ones contributes to an increase in the amount of mineral phosphates – in some variants of the experiment ($N_{90}P_{90}K_{90}$, $N_{135}P_{135}K_{135}$, Manure 9 t+$N_{45}P_{68}K_{36}$, Manure 13.5 t+$N_{68}P_{101}K_{54}$) up to 1,361-1,762 mg/kg with content in fallow of 615 mg/kg (Table 2).

***Table 2**. Distribution by fractions of mineral phosphates in the soil layer 0-20 cm after long-term fertilisation in crop rotation, 2020*

Experiment variant	Amount, mg/kg of soil				$\frac{Ca-PI + Ca-PII}{Ca-PIII}$	$\frac{\Sigma\, Ca-P}{Al-P + Fe-P}$
	Mineral phosphates	Active forms	Ca-P	Al-P+Fe-P		
Fallow	615	393	507	108	1.28	4.69
No fertiliser (control)	579	382	467	112	1.37	4.17
$N_{45}P_{45}K_{45}$	707	468	564	143	1.36	3.94
$N_{90}P_{90}K_{90}$	1,361	921	1,134	227	1.58	5.00
$N_{135}P_{135}K_{135}$	1,762	1,196	1,472	290	1.60	5.08
Manure 9 t	586	405	442	144	1.44	3.07
Manure 13.5 t	571	402	433	138	1.56	3.14
Manure 18 t	562	406	419	143	1.69	2.93
Manure 4.5 t + $N_{22}P_{34}K_{18}$	657	464	493	164	1.55	3.01
Manure 9 t + $N_{45}P_{68}K_{36}$	1,376	925	1,137	239	1.61	4.76
Manure 13.5 t + $N_{68}P_{101}K_{54}$	1,586	1,081	1,283	273	1.70	4.69

However, relative to the gross phosphorus content, their number has changed less significantly – only at the second and third levels of the mineral and organo-mineral fertiliser systems, their content is 62-69%, while the content on fallow – 61%. Fertiliser systems and fertiliser doses have only a small effect on the distribution of phosphorus between mineral phosphate fractions. First of all, it is necessary to note an increase in the number of active forms in the composition of mineral phosphates – from 64% on the transfer to 66-72%, depending on the characteristics of the fertiliser. This is mainly conditioned by the fractions Ca-P_I and Fe-P. Thus, according to the organo-mineral fertiliser system, the content of phosphates of the fraction Ca-P_I increased by 14-90, and Fe-P – by 44-106 mg/kg of soil compared to untilled virgin land. An increase in these fractions in the composition of mineral phosphates was also observed in other subtypes of chernozems (Soltangheisi *et al.*, 2020; Vasbieva, 2021).

The sum of active forms of phosphates in areas without fertilisation, under the organic fertiliser system and at the first levels of the mineral and organo-mineral fertiliser system almost did not change and was in the range of 382-468 mg/kg (with the content of fallow of 393 mg/kg). This can be explained by the negative balance of phosphorus and its bio-displacement by the root systems of agricultural crops. The increase in the content of calcium phosphates in the soil was slower than the sum of aluminium and iron phosphates (Al-P+Fe-P). However, the mobility of phosphates estimated by the indicator (Ca-P_I+Ca-P_{II}): Ca-P_{III}, significantly depended on fertiliser doses and less on fertiliser systems. The highest rate of their mobility – 1.70 – was formed by applying 13.5 t/ha of manure + $N_{68}P_{101}K_{54}$ per 1 ha of crop rotation area. For fallow areas and areas without fertilisers, this indicator is significantly lower – 1.28 and 1.37, respectively.

With a negative balance of phosphorus in the soil of crop rotation, the content of calcium phosphates available to plants (Ca-P_I+ Ca-P_{II}) decreases, as do phosphates of sesquioxides (Al-P+Fe-P) (Khristenko, 2019; Hospodarenko, 2002; Sheudzhen, 2018). In the test soil, most phosphorus accumulates in the form of calcium phosphate, which is 3-5 times more, depending on the experimental variant, than in other phosphates. Therefore, the study of the fractional composition of podzolized chernozem shows that with long-term cultivation of field crops, there is an increase in the content of mineral phosphates in the soil regardless of the systems and levels of fertiliser application. Due to Fertilisers, the proportion of active forms in their composition increases, primarily fractions Ca-P_I and Fe-P. The increase in the content of the Fe-P fraction is explained by the acidification of the soil. The application of phosphorous fertilisers in doses exceeding the extraction of phosphorus from the soil affects all fractions of its phosphate fund.

It is worth noting that podzolic chernozem fallow contains only 65 mg/kg of mobile forms of phosphorus, which indicates a possible high efficiency of using phosphorous fertilisers. In the soils of the forest-steppe zone, agricultural crops react to phosphorous fertilisers with the content of mobile forms of phosphorus up to 250 mg/kg (Kristenko, 2019). This is conditioned by the high content of the Ca-P_{III} fraction in the soil. However, these phosphates have a low degree of mobility – 0.095 mg P_2O_5/l and do not take a direct part in plant nutrition, but pass into 0.5 m acetate extract in large quantities. Therefore, based on the obtained experimental data, it can be concluded that the optimal content of mobile phosphates (150 mg/kg) accepted for the podzolized chernozem of the right-bank forest-steppe is underestimated and needs to be clarified.

CONCLUSIONS

1. Podzolized chernozem of the right-bank forest- steppe has high potential capabilities in terms of the ability to provide field crops with phosphorus. After 55 years of applying various doses of fertilisers and fertiliser systems, the gross phosphorus content is 0.09-0.27% P_2O_5 (according to the content on fallow – 0.10%).

2. Fertiliser systems and fertiliser doses have little effect on the distribution of phosphorus between mineral phosphate fractions. At the same time, the share of active forms increases – from 64% on the transfer to 66-72%, depending on the characteristics of the fertiliser. This is mainly conditioned by the fractions $Ca\text{-}P_I$ and Fe-P. According to the organo-mineral fertiliser system, the content of phosphates of the fraction $Ca\text{-}P_I$ increased by 14-90, and Fe-P – by 44-106 mg/kg of soil compared to untilled virgin land.

3. The content and mobility of phosphorus compounds in the soil significantly depend on the fertiliser systems. Thus, in the organic fertiliser system, mineral phosphates make up 61-62%, in the organo-mineral system – 64-72, and in the mineral system – 67-69% of the gross phosphorus content.

4. Calcium phosphates predominate in the composition of soil mineral phosphates. By content, mineral phosphates make up the following series: $Ca\text{-}P_{II}>Ca\text{-}P_{III}>Ca\text{-}P_I>Fe\text{-}P>Al\text{-}P$.

5. The phosphate level of podzolized chernozem can be significantly improved by creating a positive balance of phosphorus due to the introduction of organic and mineral fertilisers. This is facilitated by a number of factors: the preservation of phosphorus in compounds potentially available to plants and the absence of migration along the soil profile.

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Фракційний склад мінеральних фосфатів чорнозему опідзоленого після тривалого застосування добрив у польовій сівозміні

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Анотація. Фосфатний стан ґрунту є важливим чинником формування його родючості. У зв'язку з цими дослідження фосфатного стану різних підтипів ґрунтів у різних агроценозах є актуальним. Експериментальні дані про зміни вмісту валового фосфору та його фракційний склад у чорноземі опідзоленому під впливом тривалого удобрення мають важливе значення для ефективного використання добрив у Правобережному Лісостепу України, визначають потенційні його можливості щодо забезпечення рослин фосфором і є теоретичною основою уточнення нормативів раціонального застосування високовартісних фосфорних добрив.Метою досліджень стало вивчення зміни фракційного складу мінеральних фосфатівчорнозему опідзоленогопорівняно з перелогом після застосування різних систем удобрення в польовій сівозміні Правобережного Лісостепу. У ґрунті з шару 0–20 смвизначали вміст мінеральних фосфатів методом Чанга та Джексона у модифікації Гінзбург-Лебедєвої з фото колориметричним визначенням фосфору за методом Деніже модифікованим Труог-Майєр. Дослідження показали, що чорнозем опідзолений важкосуглинковий на лесі має значні запаси потенційно доступного для живлення рослин фосфору. Через 55 років у польовій сівозмінізалежно від особливостей удобрення вміст його у ґрунті змінився від 921 мг/кг до 2565 мг/кг P_2O_5 (за вміступід перелогом 1008 мг/кг).Вміст фракцій мінеральних фосфатів у чорноземі опідзоленому розміщується у такій послідовності: $Ca\text{-}P_{II}>Ca\text{-}P_{III}>Ca\text{-}P_{I}>Fe\text{-}P>Al\text{-}P$. Застосування гною і мінеральних добрив сприяє збільшенню вмісту фосфору в усіх фракціях мінеральних фосфатів. Насамперед зростає частка активних форм – $Ca\text{-}P_I$ і $Ca\text{-}P_{II}$ до 66–72 % (за вмісту на перелозі 64 %). За органо-мінеральної системи удобрення (варіант Гній 13,5 т + $N_{68}P_{101}K_{54}$) фосфор між фракціями мінеральних фосфатів розподіляється в такому відношенні, %: Ca-PI-7; $Ca\text{-}P_{II}$-40; $Ca\text{-}P_{III}$-28; Al-P-11 і Fe-P-14. Рухливість фосфатів, оцінена за показником($Ca\text{-}P_I$+$Ca\text{-}P_{II}$): $Ca\text{-}P_{III}$ більше залежить від доз добрив, ніж від систем удобрення. Високий вміст у чорноземі опідзоленому фракції $Ca\text{-}P_{III}$ вказує на необхідність уточнення оптимального вмісту рухомих сполук фосфору

Ключові слова: ґрунт, системи удобрення, валовий фосфор, фосфати кальцію, фосфати алюмінію, фосфати заліза

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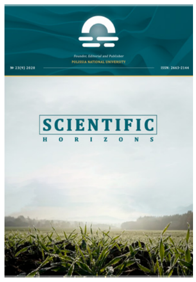

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Influence of Weather Conditions on the Duration of Interphysical Periods and Yield of Durum Winter Wheat

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Abstract. Despite the high genetic potential of productivity of new varieties, the yield of durum winter wheat remains low. One of the reasons for this is non-compliance with the recommended cultivation technologies, which would take into account the genetic characteristics of different varieties, their adaptation to the climatic conditions of the region. Due to insufficient scientific studies of the impact of weather conditions on the productivity of durum winter wheat, taking into account the main strategy of agricultural adaptation to negative climate changes in the southern steppe of Ukraine, the research topic is relevant. The aim of the work was to determine the degree of influence of changes in weather and climatic conditions in the main interphase periods on the growth and development and yield of winter durum wheat grain, depending on the varietal composition. Field studies were conducted during 2014-2020 yrs in the experimental field of the MNAU training, research and practical center with four varieties of winter durum wheat. In the course of the study, generally accepted methods were used: system approach and systems analysis, monographic, analysis and synthesis, field research and statistical mathematical, etc. Its predecessor was black steam, the sowing period was October 1st. According to the results of research, it was determined that the formation of winter durum wheat grain yield was significantly influenced by the duration of interphase and vegetations and the amount of precipitation. The weather conditions of 2014, 2016 and 2019 were more favorable for the germination of winter durum wheat seeds, when the plants reached the sum of effective temperatures of 70.0-89.1°C, the duration of the interphase period "sowing-seedlings" was only 11-12 days. In favorable yields in 2016 and 2019 yrs the duration of the vegetation of plants was the longest – 296 and 288 days, respectively, with the amount of precipitation for the reporting period – 358.5-402.0 mm, and in unfavorable years in 2018 and 2020 yrs the vegetation was 272 and 276 days with the amount of precipitation 256.9 and 308.9 mm. The highest average yield of winter durum wheat grain by variety was formed in 2016 yr as 7.24 t/ha, which was by 8.3-43.5% higher than in other years studied

Keywords: durum wheat, varieties, interphase period, sum of effective temperatures, sum of precipitation, grain yield

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INTRODUCTION

Modern agricultural production is threatened by climate change, which is characterised by rising temperatures, changes in precipitation patterns, and frequent extreme weather events (Arora, 2019; Ivanyuta *et al.*, 2020). The consequences of global climate change are becoming more and more noticeable in Ukraine. Analysis of the frequency of extreme weather conditions, namely droughts, shows an alarming trend of their increase. Over the past 20 years, the average annual temperature has increased by another 0.8°C, and the average temperature in January and February – by 1-2°C. The duration of the growing season with a minimum threshold of 10°C over the past 30 years in Ukraine has increased by 16 days, which has already led to changes in the rhythm of seasonal phenomena – spring floods, the beginning of plant flowering in winter, snowfall in spring or autumn, etc. (Pisarenko *et al.*, 2020).

According to the researchers, by 2070, wheat yields in the steppe zone may decrease to 5.5 cent./ha, so measures to develop effective adaptation should focus on preparing this region for the expected climate changes (Balabukh *et al.*, 2017).

The Food and Agriculture Organization of the United Nations proposes a "Save and grow" agriculture intensification model to reduce the impact of climate change on wheat production, which consists in a sustainable increase in yields on existing agricultural land (Graziano da Silva, 2016).

Durum wheat is of interest to the global grain industry primarily as a raw material for pasta, baby food products, and baking (Pompa *et al.*, 2021; Peressini *et al.*, 2020). Compared to soft wheat, hard wheat has significant advantages – it is less affected by diseases and pests, does not crumble, is more resistant to lodging, is more resistant to air drought, and provides stable yields on a high agricultural background (Steiner *et al.*, 2019; Korkhova, 2020). However, due to increased requirements for agroclimatic conditions, its acreage in the world ranges from 16 to 18 million hectares, which provides up to 8.0-10.0% of global wheat grain production (De Vita & Taranto, 2019).

In Ukraine, the acreage of durum wheat is about 500 thousand hectares, although, the soil and climatic conditions are favourable for growing and obtaining high yields, especially the winter crop (Franchesko, 2013). Modern varieties of durum winter wheat have a fairly high genetic potential for productivity and quality, as evidenced by the studies (Giunta *et al.*, 2019; Stefanova-Dobreva & Muhova, 2020). However, the yield of this crop remains low due to abiotic and biotic stress factors, which negatively affect photosynthesis and, as a result, limit plant growth.

There is evidence that climate changes, namely rising air temperatures and changes in humidification during the growing season, negatively affect wheat yields in many regions of the world (Raza *et al.*, 2019; Kucher, 2017; Sabella *et al.*, 2020). Especially in recent years, there has been an increase in temperature in the autumn and winter period, the duration of the autumn vegetation of winter crops is gradually reduced. Often in winter, there is a long-term restoration of vegetation, and the final restoration of spring vegetation occurs two to three weeks earlier than long-term periods, which leads to a significant reduction in the winter dormancy period. An increase in air and soil temperature in winter contributes to better overwintering of winter durum wheat plants. In this regard, in the zone of the southern steppe of Ukraine, it is necessary to grow crops that can adapt to the climatic realities of today in the conditions of rainfall farming, which includes winter durum wheat (Balabukh's, 2018; Ostapenko & Kostyrya, 2020).

It is possible to balance the negative impact of weather and climatic conditions by strictly observing the recommended technologies for growing durum winter wheat, which would take into account the genetic characteristics of different varieties (Mereu, 2021; Kahiluoto *et al.*, 2019). The relevance of the subject matter is conditioned by the fact that the choice of a variety adapted to the climatic conditions of the region is the main strategy for adapting agriculture to negative climate changes, especially in the south of Ukraine. Currently, Ukraine pays considerable attention to the investigation of the productivity of spring durum wheat, while the influence of weather conditions of the year on the yield of winter durum wheat varieties has not been sufficiently studied. The use of durum wheat varieties that are resistant to drought and unfavourable winter conditions can effectively increase grain productivity (Mengistu, 2019).

The purpose of the study was to determine the degree of influence of changes in weather and climatic conditions in the main interstage periods on the growth and yield of winter durum wheat grain, depending on the varietal composition.

LITERATURE REVIEW

Many researchers have proven that the yield of winter durum wheat depends on weather conditions [16]. V. Lubich & I. Polyanetska (2021) in the Right-bank forest-steppe of Ukraine, have determined that the yield of winter durum wheat varied from 3.74 to 5.46 t/ha for the Kontinent variety and from 4.63 to 7.99 t/ha for the Linkor variety, depending on the year of study.

N.E. Samofalova *et al.* (2019) prove that the temperature regime plays a crucial role in the yield of winter durum wheat, and its productivity depends not on the total amount of precipitation, but on their distribution, the presence of moisture in the soil, and temperature. However, these studies were conducted in different soil and climatic conditions, which differ from the southern steppe of Ukraine.

The seed germination phase is important in timely obtaining full-sized seedlings, forming the density of crops, and the future harvest of durum winter wheat (Poltoretsky, 2020). Predicting the emergence of seedlings and determining the duration of the "sowing-germination" interstage period is important in agricultural practice, because late shoots of winter wheat often lead to liquefaction of crops, weak tillering and plant development, which significantly reduces crop productivity. Long-term studies have determined that with timely receipt of full-sized shoots of winter wheat, plants develop well from autumn and create a secondary root system, which contributes to overwintering and increases plant resistance to drought (Zaiets, 2019; Zapisotska, 2021).

Based on the findings of A. Kovalenko *et al.* (2020), conducted in the southern steppe zone of Ukraine, under conditions of optimal soil moisture, the duration of the "sowing-germination" period when growing winter wheat on black fallow was 11 days, and in dry autumn, shoots appeared on 47th day.

The growth and development of winter durum wheat plants in the autumn period depend not only on the timely emergence of seedlings but also on the date of termination of the autumn vegetation. Too early or late termination of the autumn vegetation of plants is not favourable for sowing crops in the autumn-winter period (Mostipan, 2019).

M. Mostipan *et al.* (2021) claim that the highest yield of winter wheat (5.67 t/ha) for black fallow is formed in years with the cessation of autumn vegetation in the third decade of November.

Many studies have determined that the duration of the autumn vegetation of winter wheat plants should be from 40 to 60 days. During this period, plants should have time to gain the sum of effective temperatures from 300 to 350°C, which will ensure the accumulation of a sufficient amount of plastic substances in the tillering nodes and contribute to better overwintering of wheat plants and their resistance to adverse conditions of the spring-summer growing season (Gulyanov *et al.*, 2021).

The growth and development of winter wheat also depend on the time of resumption of the spring growing season (Miroshnychenko *et al.*, 2021). In recent years, due to the warming climate, the average date of vegetation resumption has somewhat shifted. In recent years, in Ukraine, in particular in Mykolaivska oblast, at the latest (April 6), the restoration of vegetation of winter grain crops was observed in 2003, which led to a significant shortage of crops (Ministry of Agrarian Policy and Food of Ukraine, 2022).

MATERIALS AND METHODS

Experimental studies were conducted over six agricultural years (2014/2015-2019/2020) in the experimental field of the MSAU Educational, Scientific, and Practical Centre, which belongs to the southern steppe zone of Ukraine. Agricultural technology in the experiment was generally accepted, namely: the predecessor – black fallow, the sowing period – October 1, the seeding rate – 5 million pcs/ha. The experiment included 4 variants (varieties), which were placed randomly in four repetitions. The area of the accounting plot – 25 m².

The soil of the experimental field is typical for southern chernozem residual-slightly alkalinised heavy loamy on loess soil with a humus content (0-30 cm) from 3.1 to 3.3 % and a neutral reaction of the soil solution (pH – 6.8-7.2). The arable soil layer contained an average of 15-25 mobile forms of nitrates (according to Grandval-Lajoux), mobile phosphorus – 41-46 (according to Machigin) and 389-425 mg/kg of exchange potassium (on a semi-lamp photometer).

The material for the research was durum wheat varieties Linkor, Kreiser, Bosfor, and Havan owned by the Plant Breeding and Genetics Institute – National Centre of Seed and Cultivar Investigation (PBGI – NCSCI), which are registered in the state register of plant varieties suitable for distribution in Ukraine in 2010-2011 (Ministry of Agrarian Policy and Food of Ukraine, 2022; Gadzalo *et al.*, 2021).

The analysis of agroclimatic conditions was carried out according to the Austrian-made PessIInstruments (iMETOS) weather station, which provides not only high-precision local meteorological data, but also a high-precision weather forecast for 6 days. The weather station is equipped with sensors that determine such indicators as: precipitation, air and soil temperature; humidity level of air, soil, and leaf; wind speed, etc.

Phenological observations were carried out in the main phases of plant growth and development according to the "Methodology of state variety control of agricultural crops" (Tkachuk *et al.*, 2017). The beginning of the phase was recorded when it occurred in 10% of plants and full – in 75% of plants. The interstage period was calculated as the time interval from the full previous phase to the beginning of the next phase; the duration of the growing season of the variety was calculated from the date of full germination to the date of waxy (economic) ripeness.

Winter durum wheat was harvested using a Sampo-500 combine. After threshing each site, the threshing machine of the combine was turned off, the collected grain was weighed separately and transferred to standard humidity (14%) and purity (100%).

The obtained results in the form of analytical digital material were subjected to statistical and mathematical processing performed by the method of variance and correlation analysis using Microsoft Excel and Agrostat software suites with the method of variation, correlation, and variance analysis.

The years of research differed significantly in weather conditions. Thus, the 2014/2015 and 2015/2016 agricultural years were medium-wet, with 337.5 and 358.5 mm of precipitation falling during the growing season, respectively, while in 2016/2017 – 159 mm; 2017/2018 – 256.9 mm, 2018/2019 – 402.0 mm, and 2019/2020 – 308.9 mm. Consequently, 2018/2019 was more favourable in terms of weather conditions, and 2016/2017 was less favourable. Such contrasting conditions allowed investigating the influence of weather conditions on the duration of interstage periods and the yield of durum winter wheat.

RESULTS AND DISCUSSION

The first stage of organogenesis of winter wheat is crucial for the development of crop density and plant yield. Timely full-sized shoots are the key to good growth and development of plants in the autumn period, and weak and sparse crops almost always form low productivity. Thus, the duration of the interstage period "sowing-germination" is very important, since plants that have time to form a powerful root system before the onset of dormancy, as a rule, have better resistance to overwintering and provide a high grain yield even with insufficient precipitation in the summer months.

It is known that the duration of germination of winter wheat seeds depends on the average daily air temperature. Therefore, the minimum temperature for germination of winter wheat seeds is +1-2°C, and the optimal temperature is 12-18°C. However, in addition to the air temperature, the humidity of the sown soil layer during the sowing of winter wheat is important, especially in the zone of risky agriculture, which includes Mykolaivska oblast. Winter wheat seeds can germinate quickly only if there is 10-15 mm of moisture in the sown soil layer. In recent years, especially in the steppe regions of Ukraine, soil drought is increasingly observed, which delays seed germination, so shoots can appear during thaws in winter, or even in spring, which does not allow plants to open up and leads to a significant decrease in grain yield.

Studies by V.F. Petrychenko *et al.* (2021) show that winter wheat plants should accumulate the sum of effective temperatures of 116-139°C from sowing to full germination. However, this issue requires additional investigation due to global warming and the emergence of varieties with a short period of vernalisation. In the years of research, the average air temperature for the "sowing-germination" period ranged from 7.2°C in 2016/2017 to 12.5°C in 2018/2019 (Table 1).

***Table 1**. Hydrothermal characteristics of the interstage period "sowing-germination" of durum winter wheat*

Indicators	Year						Average 2014-2020
	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	
Duration of the interstage period, days	11	31	12	24	24	12	18.8
Average temperature (°C)	+10.8	+9.5	+7.2	+11.7	+12.5	+12.4	+10.8
Sum of effective temperatures, °C	70.0	158.0	86.6	176.0	176.0	89.1	113.4
Precipitation, mm	0.0	13.0	0.5	23.0	14.0	31.0	14.0
Soil moisture, %	15.0	12.0	11.7	18.2	12.5	20.0	14.9

More precipitation during the interstage period "sowing-germination" (31.0 mm) fell in the 2019/2020 agricultural year. In 2014/2015 and 2016/2017, moisture supply was worse – 0.0 and 0.5 mm for the reporting period.

The air temperature and humidity of the sown soil layer significantly affected the duration of the "sowing-germination" period, which ranged from 11 days (2014/2015) to 31 days (2015/2016). Plants have accumulated the sum of effective temperatures from 70.0 to 176.0°C. Thus, the most favourable weather conditions for the germination of winter durum wheat seeds were in 2014/2015, 2016/2017, and 2019/2020, when seedlings were obtained in the shortest period (11-12 days), while the plants managed to accumulate the sum of effective temperatures of 70.0, 86.6, and 89.1°C.

On average, for 2014/2015-2019/2020, the duration of the reporting period was 18.8 days, the average air temperature was +10.8°C, the sum of effective temperatures was 113.4°C with a humidity of the sown soil layer of 14.9%.

According to the obtained data, it is established that between the duration of the interfacial period "sowing-germination", the average daily air temperature and the sum of effective temperatures, there is a direct relationship with the average indicators of the correlation coefficient (<0.5), while between the duration of the interstage period from sowing to germination and precipitation, this relationship is with high indicators of the correlation coefficient (>0.5). That is, of the studied factors, the greatest influence on the duration of the interstage period "sowing-germination" of durum winter wheat is the amount of precipitation.

Further growth and development of plants depend on the date of termination of the autumn growing season. With the late termination of the autumn vegetation, plants outgrow, are affected by diseases and pests, and become less resistant to adverse wintering conditions. In years with an early cessation of autumn vegetation, plants can enter the winter unopened.

In 2016/2017, the termination of autumn vegetation occurred 1-2 weeks earlier than the long-term average – November 14. Close to the long-term average were 2014/2015 and 2019/2020, when the date of termination of the autumn growing season of winter wheat occurred within the long-term average period – November 21 and 24, respectively (Table 2).

***Table 2**. Dates of termination of autumn and resumption of spring vegetation of winter durum wheat, 2014-2020*

Years of research	Date of termination of the autumn vegetation	Date of resumption of spring vegetation
2014/2015	November 21	March 6
2015/2016	December 29	February 28
2016/2017	November 14	March 4
2017/2018	January 12, 2018	March 31
2018/2019	November 17	March 6
2019/2020	November 24	February 18

The autumn-winter period of 2017/2018 was abnormal in temperature, winter wheat plants temporarily stopped growing several times, and the average monthly air temperature in December was +5.2°C, which is 5.0-5.8°C higher than normal. The final cessation of vegetation of winter durum wheat plants occurred 3-4 weeks later than the long-term average – January 12. The autumn vegetation of winter wheat should last 40-60 days, while plants should gain the sum of effective temperatures of 300-350°C from sowing to a stable temperature transition through 5°C, which contributes to the accumulation of a sufficient amount of plastic substances by crops.

In the studied conditions, the autumn growing season of durum wheat lasted from 23 days (2016/2017) to 80 days (2015/2016), while the plants accumulated the sum of effective temperatures from 4.6 to 223.5°C. More precipitation (69.0 mm) for the reporting period was recorded in 2017/2018, less (5.9 mm) in 2019/2020 and completely absent (0.0 mm) in 2016/2017 (Table 3).

***Table 3**. Hydrothermal characteristics of the interstage period "germination-termination of autumn vegetation" of winter durum wheat, 2014-2020*

Indicators	Year						Average 2014-2020
	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	
Duration of the interstage period, days	41	80	23	76	42	44	51
Average temperature (°C)	+6.9	+23.3	+2.3	+5.0	+9.4	+9.6	+9.4
Sum of effective temperatures, °C	133.0	159.0	4.6	101.0	200.0	223.5	136.9
Amount of precipitation for the interstage period, mm	47.0	49.0	0.0	69.0	17.0	5.9	31.3

Based on the observations, it was found that the best conditions for the growth and development of winter wheat plants in the autumn period were in 2014/2015 and 2018/2019, and the worst – in 2016/2017.

On average, for six years of research (2014/2015/2019/2020), the duration of the interstage period "germination-termination of autumn vegetation" of winter durum wheat was 51 days with an average daily air temperature of 9.4°C, the sum of effective temperatures – 136.9°C, and the sum of precipitation – 31.3 mm.

It is established that there is a high positive relationship (>0.5) between the duration of the interstage period of "germination-termination of autumn vegetation" of durum winter wheat and average daily temperatures and precipitation.

The duration of winter dormancy also affects the growth, development, and yield of durum wheat plants, which depends on the time of resumption of spring vegetation. Observations prove that the recovery time of spring vegetation significantly affects the growth and development, density, and grain yield of wheat plants. With the early resumption of vegetation on February 18, 2020 – plants grew more actively, but they bushed for a longer time and rooted more intensively, and in the years from late-March 31, 2018, there was a sharp transition from winter to summer.

Studies have determined that the duration of the winter dormancy period of plants on average for 2014/2015-2019/2020 was 97 days and ranged from 61 (2015/2016) to 110 days (2016/2017) (Fig. 1).

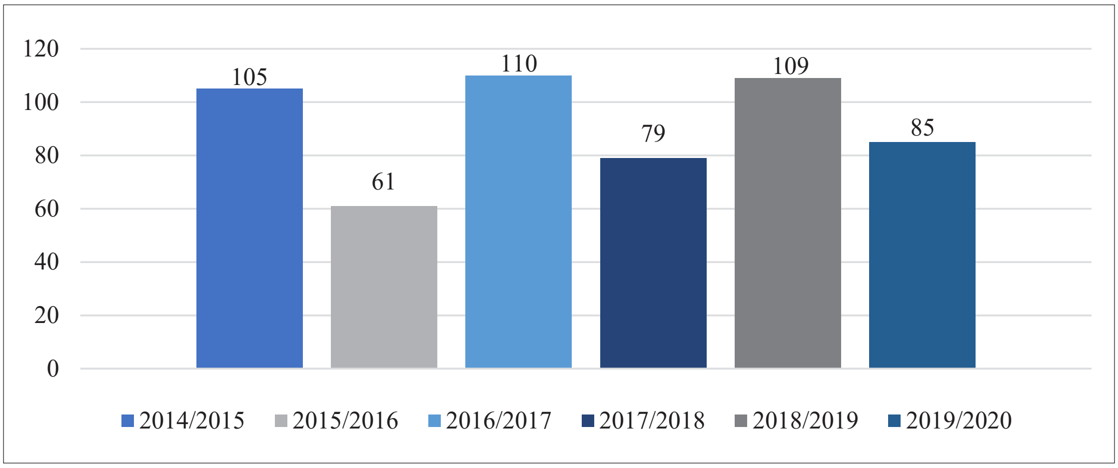

***Figure 1**. Duration of winter dormancy of durum winter wheat, days (2014/2015-2019/2020)*

During the interstage period of "termination of autumn-restoration of spring vegetation", the 2016/2017 agricultural year was drier over the years of research, when only 21.0 mm of precipitation fell in 110 days, while in 2014/2015 – 110.0 mm; 2015/2016 – 101.0 mm; 2017/2018 – 116.0 mm. The lowest average daily air temperature during this period (−2.1°C) was observed in 2018/2019, and the highest (+2.6°C) – in 2019/2020 (Fig. 2).

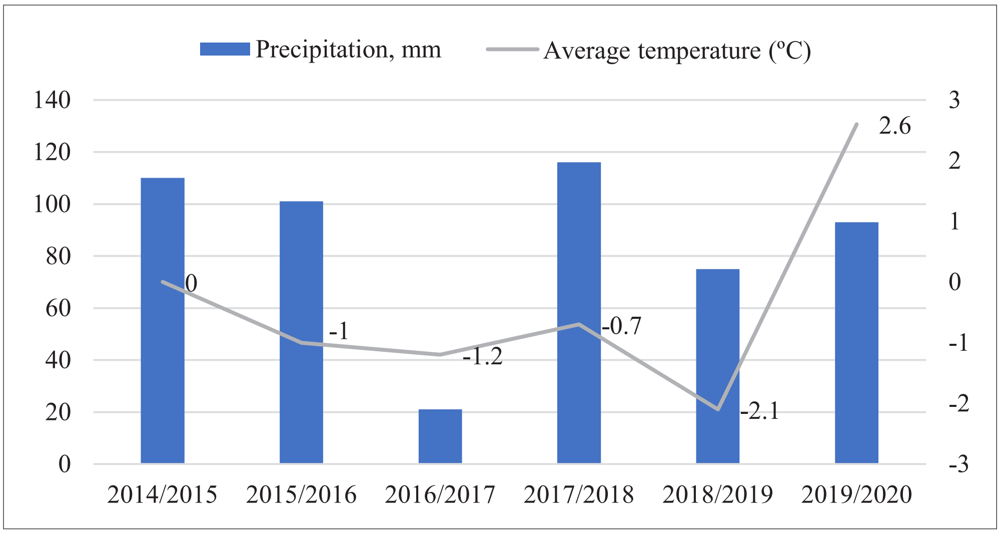

***Figure 2**. Average air temperature (°C) and precipitation amount (mm) for the interstage period "termination of autumn-restoration of spring vegetation" of winter durum wheat*

There is a low negative correlation between the duration of the dormant period of winter durum wheat plants and the average daily air temperature and precipitation (r=−0.27 and −0.20, respectively), that is, with an increase in the average daily temperature and precipitation, the duration of the dormant period decreases.

The period of "restoration of spring tillering-stem elongation" on average in Ukraine lasts 29-44 days. In the years of research, the average duration of the reporting period was 43 days with an average daily air temperature of +8.0°C, the sum of effective temperatures of 134.8°C, and the sum of precipitation of 41.6 mm (Table 4).

***Table 4**. Hydrothermal characteristics of the interstage period "restoration of spring vegetation-stem elongation" of winter durum wheat plants, 2014-2020*

Indicators	Years						Average 2014-2020
	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	
Duration of the interstage period, days	51	48	47	14	45	54	43
Average temperature (°C)	+7.1	+7.9	+7.9	+10.5	+7.5	+7.1	+8.0
Sum of effective temperatures, °C	125.5	148.2	135.9	130.5	125.2	143.6	134.8
Amount of precipitation, mm	117.0	33.5	21.0	0.0	52.0	21.0	40.8

The shortest duration (14 days) of the interstage period "restoration of spring vegetation-stem elongation" of winter durum wheat plants was recorded in 2017/2018, and the longest – 54 days in 2019/2020. In addition, in 2017/2018, there was no precipitation during this period, and the average daily temperature exceeded the long-term average, the sum of effective temperatures was within the long-term average. Thus, close to the optimal indicators for the reporting period was 2018/2019, the duration of vegetation was 45 days, with an average daily air temperature of +7.5°C with the sum of effective temperatures of 130.5°C and the sum of precipitation of 52.0 mm.

There is a high negative correlation (r=−0.98) between the duration of the interstage period "restoration of spring vegetation-stem elongation" and average daily temperatures, and the sum of effective temperatures and precipitation – a positive average (r=0.42 and r=0.49, respectively, the confidence level P=0.01). That is, the average daily temperature has the greatest influence on the duration of the study period of winter durum wheat.

It is known that the duration of the "stem elongation-earing" period is more affected by the air temperature. The higher the temperature, the shorter this period. With a reduced average daily air temperature, the interstage period "stem elongation-earing", on the contrary, is extended.

Analysing the interstage period "stem elongation-beginning of earing", it was found that its average duration in 2014/2015-2019/2020 is 34 days, with an average daily air temperature of +14.3°C, with the sum of effective temperatures of 303.9°C, and the sum of precipitation – 36.8 mm. This period was shorter (27 and 26 days) in 2014/2015 and 2018/2019, and longer (40 and 41 days) in 2019/2020 and 2016/2017, respectively (Table 5).

***Table 5**. Hydrothermal characteristics of the interstage period "stem elongation-beginning of earing" of winter durum wheat plants, 2014-2020*

Indicators	Years						Average 2014-2020
	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	
Duration of the interstage period, days	27	37	41	33	26	40	34
Average temperature (°C)	+15.7	+14.1	+13.6	+16.7	+13.0	+12.8	+14.3
Sum of effective temperatures, °C	295.5	313.7	334.5	377.6	197.2	306.9	303.9
Amount of precipitation, mm	28.0	78.0	62.5	5.8	19.0	27	36.8

It was found that in 2018/2019 there was a relatively low average daily air temperature (+13.0°C), so plants in a shorter period gained the sum of effective temperatures of 197.2°C, despite the fact that the amount of precipitation for this period was less than the average for the years of research. 2016/2017 was characterised by relatively low average daily temperatures, but the sum of effective temperatures for 41 days was 334.5°C with precipitation significantly higher than the average values for the years of research.

In 2017/2018, the highest sum of effective temperatures (377.6°C) and the highest average daily air temperature (+16.7°C) were observed with the lowest precipitation (5.8 mm), while the interstage period was close to average in duration.

There is a high positive correlation between the duration of the interstage period "stem elongation-beginning of earing" of winter durum wheat plants and the sum of effective temperatures and precipitation (r=0.54 and r=0.57, respectively), and the average negative correlation between the duration of the interstage period and the average daily temperature (r=−0.32).

Analysing the duration of the interstage period "earing-milk ripeness of grain" of winter durum wheat plants, it was found that its average duration over the years of research was 21 days with the sum of effective temperatures accumulated by plants – 276.5°C. This period was shorter (16 days) in 2014/2015 with the sum of effective temperatures – 214.0°C. The longest interstage period of "earing-milk ripeness of grain" was established in 2019/2020 (25 days), which significantly differed from the long-term average indicators (Table 6).

***Table 6**. Hydrothermal characteristics of the interstage period "earing-milk ripeness of grain" of winter durum wheat plants, 2014-2020*

Indicators	Years						Average 2014-2020
	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	
Duration of the interstage period, days	16	20	21	23	20	25	21
Average temperature (°C)	+20.4	+17.3	+17.3	+18.7	+20.0	+17.5	+18.5
Sum of effective temperatures, °C	214.0	253.5	307.7	291.5	294.4	298.0	276.5
Amount of precipitation, mm	20.0	49.0	21.0	30.0	49.0	53.0	37.0

The years of research also differed significantly in the average daily air temperature, which ranged from 17.3°C (2015/2016 and 2016/2017) to 20.4°C (2014/2015). A higher amount of precipitation (53 mm) for the reporting period "earing-milk ripeness of grain" was recorded in 2019/2020, which is 16 mm (30.2%) more than the average for the years of research, and the smallest 20.0 mm – in 2014/2015.

According to the results, it was found that between the duration of the interstage period "earing-milk ripeness" of winter durum wheat plants and the sum of effective temperatures, there is a high positive relationship (r=0.79), an average positive correlation for the duration of this interstage period with precipitation (r=0.48) and a high negative correlation with an average daily temperature (r=−0.62).

After analysing the duration of the interstage period "milk-wax ripeness of grain" of winter durum wheat plants for six years of research in the southern steppe zone of Ukraine, it was determined that the studied indicator ranged from 16 (2016/2017 and 2019/2020) to 23 days (2017/2018), which was affected by heterogeneous weather conditions in terms of temperature and precipitation. The average daily temperatures differed slightly from the average values of 22.7°C, and ranged from 21.2°C in 2016/2017 to 23.9°C in 2018/2019. The lowest values of the sum of effective temperatures (258.4°C) were accumulated by plants in 2016/2017, and the highest (419.0°C) in 2018/2019, which significantly distinguished them from the average values for all years of research (Table 7).

***Table 7**. Hydrothermal characteristics of the interstage period "milk-wax ripeness of grain" of winter durum wheat plants, 2014-2020*

Indicators	Years						Average 2014-2020
	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	
Duration of the interstage period, days	22	19	17	23	22	16	20
Average temperature (°C)	+21.6	+23.3	+21.2	+22.7	+23.9	+23.4	22.7
Sum of effective temperatures, °C	364.5	317.0	258.4	388.0	418.0	287.3	338.9
Amount of precipitation, mm	15.5	35.0	3.3	13.1	176.0	78	53.5

The southern steppe of Ukraine is characterised by a heterogeneous distribution of precipitation during the growing season, especially during the grain-filling period. Over the years of observations, the lowest amount of precipitation was recorded in 2016/2017, which was only 3.3 mm, and the highest – in 2018/2019, which reached 176 mm.

Thus, in 2017 and 2019, the sum of effective temperatures and precipitation during the interstage period "milk-wax ripeness of grain" had significant deviations.

Analysis of the results obtained shows that an average positive correlation was established between the duration of the interstage period "milk ripeness-wax ripeness of grain" of winter durum wheat plants and the average daily temperature and precipitation (r=0.39 and r=0.31, respectively). A high positive relationship was established between the duration of the interstage period and the sum of the effective temperatures (r=0.88).

Calculating the duration of the growing season of winter durum wheat, it was determined that on average for 2014-2020, this figure was 278 days and ranged from 261 days in 2016/2017 to 296 days in 2015/2016. During the entire growing season, plants accumulated the sum of effective temperatures of 1,202.5-1,464.6°C (Table 8).

***Table 8**. Hydrothermal characteristics of the growing season of winter durum wheat plants, 2014-2020*

Indicators	Year						Average 2014-2020
	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	
Duration of the growing season, days	273	296	261	272	288	276	278
Sum of effective temperatures, °C	1,202.5	1,349.4	1,127.7	1,464.6	1,410.8	1,348.4	1,317.2
Precipitation, mm	337.5	358.5	159.0	256.9	402.0	308.9	303.8

More precipitation for the reporting period fell in 2018/2019-402.0 mm, which is 32.3 % more than the long-term average. The driest growing season for all the years studied was 2016/2017, during which only 159.0 mm fell, which is 52.3 % less than the long-term average data.

According to the findings and observations, it was determined that the highest grain yield of the studied varieties of winter durum wheat (6.63-7.91 t/ha) was obtained in 2015/2016, which is 17.3-30.7 % higher than the long-term average yield (Fig. 3).

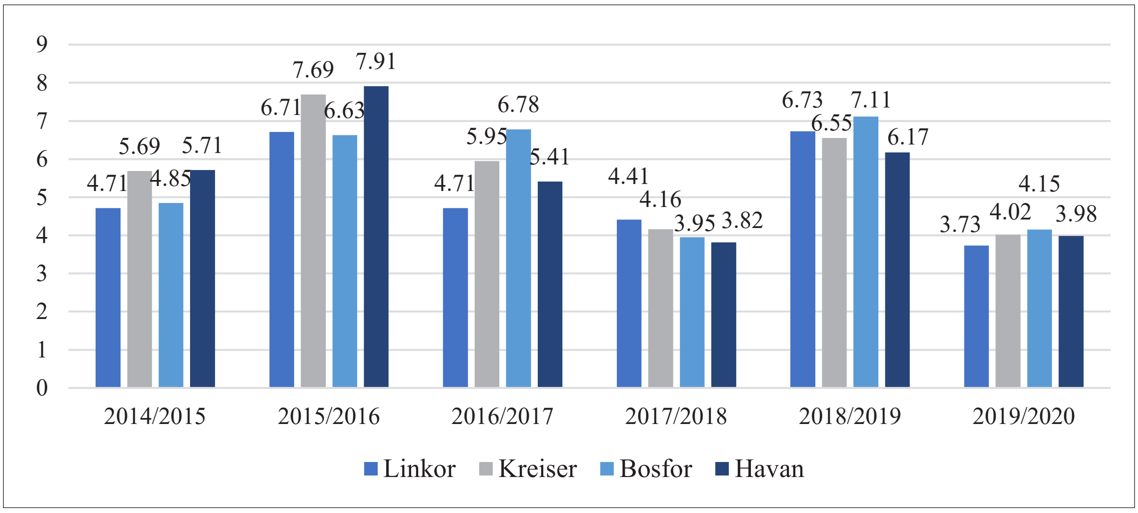

***Figure 3**. Winter durum wheat grain yield depending on the variety, 2014-2020*

***Note**: LSD_{05}=0.03 t/ha*

The yield of winter durum wheat in 2019/2020 was the smallest – 3.73-4.15 t/ha, which is 77.7-90.6 % less than in 2015/2016; 65.4-71.3 % less than in 2018/2019; 26.3-63 % more than in 2016/2017; 26.3-37.6 % more than in 2014/2015; 2.4-6.3 % more than in 2017/2018.

Among the studied varieties of durum winter wheat, the highest yield of grain (4.02-7.69 t/ha) was formed by the Kreiser variety, and the Linkor variety was less productive – 3.73-6.73 t/ha. In 2014/2015 and 2015/2016, a higher yield of winter durum wheat was obtained in the Havan variety – 5.71 and 7.91 t/ha, and a lower yield – 4.71 and 6.71 t/ha, respectively, in the Linkor variety. In 2016/2017 and 2019/2020, the Bosfor variety produced the highest grain yields – 6.78 and 4.15 t/ha, while in 2015/2016 and 2017/2018, the lowest – 6.63 and 3.95 t/ha, respectively. The Kreiser variety formed the highest yield indicators in 2014/2015 and 2015/2016-5.71 and 7.91 t/ha, while in 2017/2018 and 2018/2019, the lowest – 3.82 and 6.17 t/ha.

Similar results were obtained in the steppe zone during the state variety control. Thus, according to the economic and biological characteristics, the studied varieties of winter durum wheat belong to the medium-early ripeness group with a growing season duration of 270-273 days and an average grain yield of 4.71-6.00 t/ha (Gadzalo *et al.*, 2021; Ministry of Agrarian Policy and Food of Ukraine, 2022). In the years of research, when the duration of vegetation of plants of the studied crop was reduced to 272-276 days, the yield was obtained at the level of 3.73-5.71 t/ha. On the contrary, when the duration of the growing season increased to 288-296 days, the yield of durum wheat grain increased and reached the level of 6.17-7.91 t/ha, depending on the variety. Other researchers claim that the length of the growing season of winter durum wheat is almost independent of the weather conditions of the year (Lubich & Polyanetska, 2021).

CONCLUSIONS

Studies conducted in the conditions of the southern steppe of Ukraine with four varieties of durum winter wheat during 2014-2020 determined that weather conditions during the growing season of plants significantly affect the duration of interstage periods and crop development. The duration of the "sowing-germination" period is more influenced by the amount of precipitation. The duration of the interstage periods "germination-termination of vegetation", "stem elongation-beginning of earing" and "milk-wax ripeness" depended more on the sum of effective temperatures and precipitation. The average daily air temperature had a greater impact on the duration of the dormant period and "restoration of spring tillering-stem elongation".

The highest yield was obtained in 2015/2016 – 7.24 t/ha, the duration of the growing season was 296 days, and the amount of precipitation was 358.5 mm. This is 8.3% more than in 2018/2019; 21.1 % more than in 2016/2017; 27.6% more than in 2014/2015; 43.5 % more than in 2017/2018, and 45.2 % more than in 2019/2020. Thus, a pattern has been established that the longer the growing season of plants, the higher the yield of winter durum wheat grain.

Thus, it is determined that the yield of winter durum wheat grain is significantly influenced by the duration of interphase and growing seasons and the amount of precipitation. Thus, in the favourable years 2015/2016 and 2018/2019, the duration of the growing season of plants was the greatest – 296 and 288 days, respectively, with the amount of precipitation for the reporting period – 358.5 – 402.0 mm, and in unfavourable – 2017/2018 and 2019/2020, the growing season was 272 and 276 days with the amount of precipitation of 256.9 and 308.9 mm.

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Вплив погодних умов на тривалість міжфазних періодів та урожайність пшениці твердої озимої

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Анотація. Попри високий генетичний потенціал продуктивності нових сортів, урожайність пшениці твердої озимої залишається низькою. Однією із причин цьому є недотримання рекомендованих технологій вирощування, які б враховували генетичні особливості різних сортів, їх пристосування до кліматичних умов регіону. Через недостатні проведені наукові дослідження впливу погодних умов на продуктивність пшениці твердої озимої з врахуванням основної стратегії адаптації сільського господарства до негативних змін клімату на Півдні України, тема досліджень є актуальною. Метою роботи було визначити ступінь впливу змін погодно-кліматичних умов в основні міжфазні періоди на ріст і розвиток та урожайність зерна пшениці твердої озимої залежно від сортового складу. Упродовж шести років (2014/2015—2019/2020) на дослідному полі Навчально-науково-практичного центру Миколаївського національного аграрного університету (ННПЦ МНАУ) проводили польові дослідження з чотирма сортами пшениці твердої озимої. У ході дослідження були використані загальноприйняті методи: системний підхід і системний аналіз, монографічний, аналіз і синтез, польовий та статистичний. Попередник — чорний пар, строк сівби — 1 жовтня. За результатами досліджень визначено, що на формування врожайності зерна пшениці твердої озимої значний вплив мала тривалість міжфазних і вегетаційного періодів та сума опадів. Більш сприятливі для проростання насіння пшениці твердої озимої склалися погодні умови 2014, 2016 та 2019 рр., коли рослини набрали суму ефективних температур 70,0—89,1 °C, тривалість міжфазного періоду «сівба-сходи» при цьому становив лише 11—12 діб. У сприятливих за врожайністю 2016 р. та 2019 р. тривалість вегетаційного періоду рослин була найбільшою — 296 і 288 діб відповідно з сумою опадів за звітний період — 358,5—402,0 мм, а несприятливих 2018 р. та 2020 р. вегетаційний період становив 272 і 276 діб з сумою опадів 256,9 і 308,9 мм. Вищу середню по сортам врожайність зерна пшениці твердої озимої сформовано у 2016 р. — 7,24 т/га, що на 8,3—43,5 % — ніж у інші досліджувані роки

Ключові слова: пшениця тверда, сорти, міжфазний період, сума ефективних температур, сума опадів, урожайність зерна

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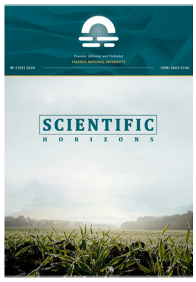

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Influence of Mineral Fertiliser and Foliar Dressing Rates on Buckwheat Yield

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Abstract. A significant problem in the cultivation of buckwheat is its low yield, therefore, it is relevant to improve the elements of the technology for growing this crop. The purpose of the study was to establish optimal norms and terms for applying mineral fertilisers and foliar dressing with chelated microfertilisers in the forest-steppe conditions of Western Ukraine, in a zone of sufficient moisture to obtain stable and high yields of buckwheat grain. For this purpose, a two-factor experiment was conducted on the experimental fields of the Lviv National Agrarian University on dark grey podzolized light loamy soil, which included fertiliser rates: $N_{20}P_{20}K_{20}$, $P_{20}K_{20}+N_{20}$ (foliar dressing), $N_{40}P_{40}K_{40}$, $P_{40}K_{40}+N_{40}$ (foliar dressing), $N_{60}P_{60}K_{60}$, $P_{60}K_{60}+N_{60}$ (foliar dressing) and foliar dressing: control (without foliar dressing), Vuksal Boron 2.0 l/ ha, Intermag Legumes 2.0 l/ha. Research methods: field studies – to determine the interaction of the object of research with weather factors and elements of the fertiliser system; calculation and weight – setting parameters of crop structure indicators and determining buckwheat yield; methods of mathematical statistics – dispersion, correlation, regressive and graphical display of findings. An increase in fertiliser rates from $N_{20}P_{20}K_{20}$ to $N_{60}P_{60}K_{60}$ provided an increase in all indicators of the buckwheat crop structure. Without foliar dressing, they reached the following values: the number of first-order branches – 1.56 pcs./plant, the number of inflorescences and flowers – 10.68 and 1,011 pcs, respectively, the number of full-size and undeveloped grains (pcs./plant) – 41.23 and 11.37, the weight of full-size grains – 1.15 g and the weight of 1,000 grains – 28.00 g. The introduction of nitrogen fertilisers in foliar dressing (at the beginning of flowering) has significant advantages over the introduction of nitrogen for pre-sowing cultivation. One of the proofs of this assumption is the increase in the number of grains, their weight, and the weight of 1,000 grains, respectively, from 35.43 pcs., 0.97 g, and 27.37 g (variant with $N_{40}P_{40}K_{40}$) up to 37.27 pcs., 1.03 g, 27.80 g (variant with $P_{40}K_{40}+N_{40}$). This trend is typical for all experiment designs. A positive effect of foliar dressing with microfertilisers on the elements of the crop structure was observed. The use of Vuksal Boron 2 l/ha was more effective. The maximum weight of full-size grains was in the variant $P_{60}K_{60}+N_{60}$ (foliar dressing) + Vuksal Boron 2 l/ha – 1.21 g, while the use of Intermag Legumes 2 l/ha on a similar background of mineral fertilisers provided this indicator at the level of 1.17 g. Studies have established the positive effect of nitrogen application by foliar dressing during the beginning of flowering on the yield level, and buckwheat yield also increased with an increase in the rate of mineral fertiliser application from $N_{20}P_{20}K_{20}$ to $N_{60}P_{60}K_{60}$ and under the influence of foliar dressing with microfertilisers. The maximum yield indicator on average for three years of research is obtained in variant $P_{60}K_{60}+N_{60}$ (foliar dressing) + Vuksal Boron 2.0 l/ha – 2.64 t/ha

Keywords: buckwheat, nutrition, microfertilisers, structure, productivity

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INTRODUCTION

The first priority of agro-industrial production has always been and will always be to provide food for the world's population (Olifir *et al*., 2021). Buckwheat is an important food crop, the main purpose of growing which is to produce cereals that are characterised by high taste and nutritional qualities and contain an average of 8.9% protein, 71% starch, 1.6% fat, and 0.3 % sugar (Ciesarova *et al*., 2016; Dębski & Horbowicz, 2020). Buckwheat can synthesise rutin, an antioxidant that stimulates the human cardiovascular system (Vojtíšková *et al*., 2012).

The need of any agricultural crop, including buckwheat, for nutrition elements, depends on its chemical composition and the removal of nutrients with the harvest. According to Rubin (1970), buckwheat requires 88 kg of nitrogen, 51 kg of phosphorus, and 151 kg of potassium to produce a yield of 2 t/ha. Before flowering, it consumes up to 60% nitrogen and potassium, 40% phosphorus, and the remaining nutrients – during the flowering-maturation period (Petrychenko & Lykhochvor, 2022). The root system of buckwheat is able to absorb phosphates in a hard-to-dissolve form, which should be taken into account when setting fertiliser application standards.

Analysing the studies by Ukrainian and foreign researchers, there is a significant difference in the recommended standards and methods of application B. Parkhuts (2018) studied the buckwheat fertiliser system in the conditions of the Western forest-steppe of Ukraine on dark grey light loamy soil. The maximum yield was recorded in the variant with $N_{60}P_{45}K_{45}$ – 1.87 t/ha. Application of fertilisers in the amount of $N_{45}P_{60}K_{45}$ and $N_{45}P_{45}K_{60}$ has led to a decrease in the yield to 1.76 and 1.62 t/ha, respectively. Yu.V. Mashchenko (2010) recommends applying fertilisers in the amount of $N_{80}P_{115}K_{120}$ in the conditions of the Kirovohradska oblast on ordinary, light loamy chernozems with low humus content I.D. Tkalich & Y.V. Tkalich (2019) emphasise the importance of observing the economic feasibility of the proposed fertiliser options and consider the amount of $N_{60}P_{30}$ and $N_{60}P_{60}$ to be optimal, because they provide the cheapest grain. O.F. Tymchyshyn & V.V. Lykhochvor (2009) in the conditions of the western forest-steppe, studying the effect of mineral and biological fertilisers on buckwheat productivity, recommend applying mineral fertilisers in the amount of $N_{60}P_{60}K_{60}$ in combination with the use of nitrogen-fixing and phosphorus-mobilising preparations, which contributes to an increase in leaf surface area by 71%, net photosynthetic productivity by 20 %, and an increase in yield by 118% (up to 2.59 t/ha). The retail method of applying nitrogen in the form of foliar dressing is supported by V.F. Kaminsky & R.I. Grishchenko (2011) and V.Ya. Bilonozhko & A.P. Berezovsky (2010). The first dressing of buckwheat is carried out in the budding phase (stage VI of organogenesis) with a rate of up to 25% of the total demand and mainly on wide-row crops, the second – at stage IX of organogenesis during the mass flowering phase at a rate of 15-20 kg/ha, while the yield increase is up to 0.3 t/ha and a larger grain with a high core yield is formed.

The issue of buckwheat fertiliser also attracts the attention of foreign researchers, in particular F. Xiaomei (2018), studying the nitrogen fertiliser system of the Youqiao 2 variety in China, came to the conclusion that the maximum stem thickness, the number and weight of 1,000 grains, the yield of the buckwheat plant is formed with fertilisation rate of N_{30}, increasing it to N_{90} led to a decrease in the yield. Ya. Wang (2018), growing buckwheat variety Ningqiao 01 in Japan, concluded that an increase in nitrogen fertiliser rates does not lead to an increase in yield, but contributes to plant lodging. M.R. Sobhani (2014) recommends nitrogen application rates of 100 kg/ha in the Arak region (Iran), which provides a yield of 2.5 t/ha and protein content of 15.24%. G. Podolska (2011) conducted a study in the fields of the IUNG-PIB experimental station and claims that buckwheat does not require more than 30 kg/ha of nitrogen to form high yields.

The physiological role of trace elements is revealed by B.A. Rubin (1970), V.V. Lykhochvor & V.F. Petrichenko (2021), P.I. Anspok (1990), M.L. Tyrus (2018), V.M. Katelevsky (2017) *et al.* The theory and practice of using microfertilisers has gone through a rather long evolutionary path from the use of metal salts in fertilisers that were introduced into the main fertiliser, seed treatment, to leaf dressing with chelated highly effective microfertiliser suspensions (Dębski & Horbowicz, 2020; Olifir *et al*, 2018; Priadkina, 2020).

The study of buckwheat leaf dressing with trace elements has become widespread in the world agronomic science, so, in particular, Y. Jiang (2015) investigated the effect of selenium on buckwheat growth processes during 2012-2013 in the fields of the Chifeng Academy of Sciences. T. Knapowski & E. Majcherczak (2016) recommend using Vigor fertiliser, which contains 90% S in a tank mixture with Micro Plus fertiliser – (B – 0.3%, Cu – 0.15%, Fe – 2.4%, Mn – 1.0%, Mo – 0.06%, Zn – 0.4%). R. Tobiasz-Salach & B. Krochmal-Marczak (2018) recommend applying Herbagreen at a rate of 2 kg/ha in different phases of vegetation: BBCH 33, BBCH 59, BBCH 67. The use of microfertilisers is an element of the technology of growing agricultural crops, which, with a small investment, provide an additional crop (Veremeenko *et al*., 2020)

The purpose of the study was to clarify the norms and methods of applying mineral fertilisers and the features of foliar dressing of buckwheat in the forest-steppe conditions of Western Ukraine.

MATERIALS AND METHODS

In order to improve the buckwheat fertiliser system in the experimental fields of Lviv National Agrarian University (Pasmove Pobuzhya 49°53'46" N 24°05'33" E) a two-factor experiment was carried out according to generally accepted methods and in compliance with: the principle of unified logical declension, the typicality of the experiment, the ability to reproduce research results in identical conditions, the availability of necessary documentation (field journals), and statistical processing of experiment data. Structural analysis was carried out according to the "Methodology of state variety testing of agricultural crops, 2000". The weight of 1,000 grains was determined according to the state standard 10842-82. Buckwheat yield was recorded in the full ripeness phase by threshing with a Sampo-500 combine and weighing from each accounting area.

The soil of the experimental sites is dark grey podzolic and light loamy. In the soil layer of 0-20 cm, the humus content according to the Tyurin method in the Nikitin modification (DSTU 4289:2004) is 2.2-2.3%, easily hydrolysed nitrogen according to the Kornfield method (DSTU 7863:2015) – 98 mg/kg, phosphorus and potassium according to the Chirikov method (DSTU 4115-2002), respectively, 116-134 mg/kg and 125-135 mg/kg of soil, hydrolytic acidity according to the Kapen method (DSTU 7537:2014) is 5.8-6.0, the content of mobile sulphur is low, and other trace elements are at a sufficient level.

The hydrothermal conditions of the research years were characterised by certain differences both among themselves and in comparison with the long-term average data, mostly favourable and were not a limiting factor for the formation of the buckwheat crop. In 2018, it was warm – an average of 9.1°C per year, which is 1.3°C higher than the long-term data. The annual precipitation also exceeded the norm by 146 mm and amounted to 818 mm in 2020.

In 2020, the annual temperature also exceeded the long-term temperature by 1.0°C. Yields in 2020 decreased due to uneven precipitation distribution. If in April-May the amount of precipitation was 36 mm less, then in June it fell 153 mm, which is 69 mm more than normal. This led to the displacement of air from the soil, created a lack of oxygen for the root system, and a decrease in grain yield.

In 2021, the annual temperature exceeded the long-term one by 0.8°C. Precipitation fell evenly throughout the growing season. Hydrothermal conditions were favourable for buckwheat harvest.

The field experiment was based on the study of the action and interaction of two factors:

- factor A (mineral fertiliser rate);
- factor B (foliar dressing).

Variants were placed by the method of split sites. The accounting area of the elementary plot – 50 m^2, three-fold repetition. Method of sowing buckwheat – row with spacing of 15 cm The seeding rate is 3.5 million tonnes of seeds of the Oranta variety per hectare (originators – NSC Institute of Agriculture of the National Academy of Sciences and TOV NVMP Antaria). The technology of buckwheat cultivation corresponds to the recommended one for this zone, with the exception of agricultural measures, the influence of which was studied in this paper.

In the experimental plots, winter wheat was the precursor during the years of research. After harvesting, BDT-3 + T-150 stubbles were peeled to preserve moisture and provoke the growth of weeds. After the regrowth of weeds, they were destroyed using glyphosate at a rate of 5 l/ha, then phosphorus-potassium fertilisers (potassium chloride and superphosphate) were applied under ploughing (MTZ-82+PN-3-35) with a depth of 20-22 cm according to the experiment scheme.

In the spring, when the soil was physically ripe, harrowing was carried out with heavy harrows BZTS-1.0 across the ploughing direction to preserve moisture. Further tillage included two cultivations with the MTZ-82+ KPS-4 cultivator. Before carrying out the second (pre-sowing) cultivation, nitrogen fertilisers were applied according to the experiment design in the form of ammonium nitrate. Sowing was carried out with a SN 4B seed drill at a given seeding rate.

The foliar dressing was carried out during the budding phase according to the experiment scheme Vuksal Boron – 2 l/ha (produced by Aglukon Spezialdünger GmbH & Co KG) and Intermag Legumes – 2 l/ha (produced by Intermag). Spraying was carried out with a satchel sprayer at the rate of 200 litres of working solution per 1 ha, in the first half of the day in calm weather, to avoid spraying of drugs to neighbouring areas. In variants where foliar dressing was not used, spraying was carried out with water. At the beginning of the flowering phase, nitrogen was fed in the form of ammonium nitrate in the corresponding variants of the experiment.

Sheaf samples were taken the day before harvesting plants from sites with an area of 1 m^2, which were arranged to determine the density of plants. During the analysis of the sheaf material, the following parameters were measured: the number of first-order branches (pcs.); number of inflorescences and flowers (pcs.); number of grains (pcs.), including developed and underdeveloped; the weight of full-size grains from 1 plant (g); the weight of 1,000 grains (g). Harvesting was carried out separately when 70-80% of the grains were disturbed and the plants were previously mowed into swaths. After 4-6 days, with the grain humidity of 16-18%, harvesting was carried out by a combine harvester. After threshing, the grain was cleaned and dried to a humidity of 14-15%.

Mathematical processing of results was performed using Statistica and MS Office Excell software suites.

RESULTS

Methods of achieving an increase in buckwheat yield in the zone of sufficient moisture in the forest-steppe of Western Ukraine by increasing only fertiliser rates are considered ineffective. Therefore, the authors proposed an experiment design where nitrogen fertilisers were applied both for pre-sowing cultivation and during the beginning of flowering. In addition, the effect of mineral fertilisers is studied in combination with foliar dressing, while special attention is paid to the boron trace element.

The results of studies on the influence of mineral fertilisers and foliar dressing standards on the development of the buckwheat crop structure allow establishing the following regularities (Table 1).

***Table 1**. Influence of mineral fertilisers and foliar dressing on the elements of the buckwheat crop structure (on average for 3 years)*

Fertiliser variant	Number of first-order branches, pcs./plant	Quantity pcs./plant		Number of grains, pcs./plant		Weight of full-size grains, g/plant	Weight of 1,000 grains, g
		Inflorescences	Flowers	Full-size	Underdeveloped		
Without foliar dressing							
$N_{20}P_{20}K_{20}$	1.51	9.57	891	27.70	12.30	0.75	26.93
$P_{20}K_{20}$+N_{20} (foliar dressing)	1.44	8.81	833	30.83	13.13	0.83	27.03
$N_{40}P_{40}K_{40}$	1.53	10.41	980	35.43	11.13	0.97	27.37
$P_{40}K_{40}$+N_{40} (foliar dressing)	1.46	8.90	868	37.27	12.63	1.03	27.80
$N_{60}P_{60}K_{60}$	1.56	10.68	1,011	39.23	9.93	1.08	27.67
$P_{60}K_{60}$+N_{60} (foliar dressing)	1.48	9.04	903	41.23	11.37	1.15	28.00
Intermag Legumes 2 l/ha							
$N_{20}P_{20}K_{20}$	1.52	9.58	891	28.37	12.07	0.76	26.93
$P_{20}K_{20}$+N_{20} (foliar dressing)	1.44	8.81	833	31.57	12.87	0.85	27.03
$N_{40}P_{40}K_{40}$	1.53	10.41	981	36.20	10.87	0.99	27.37
$P_{40}K_{40}$+N_{40} (foliar dressing)	1.46	8.92	868	38.17	12.40	1.06	27.80
$N_{60}P_{60}K_{60}$	1.56	10.68	1012	40.17	9.70	1.11	27.67
$P_{60}K_{60}$+N_{60} (foliar dressing)	1.48	9.05	904	42.07	11.10	1.17	28.00
Vuksal Boron 2 l/ha							
$N_{20}P_{20}K_{20}$	1.51	9.59	892	29.53	11.60	0.79	26.93
$P_{20}K_{20}$+N_{20} (foliar dressing)	1.44	8.83	834	32.83	12.37	0.89	27.03
$N_{40}P_{40}K_{40}$	1.52	10.41	980	37.43	10.80	1.03	27.37
$P_{40}K_{40}$+N_{40} (foliar dressing)	1.47	8.91	868	39.43	11.93	1.10	27.80
$N_{60}P_{60}K_{60}$	1.57	10.69	1012	41.40	9.37	1.15	27.67
$P_{60}K_{60}$+N_{60} (foliar dressing)	1.50	9.05	904	43.47	10.63	1.21	28.00

1. The maximum number of first-order branches (pcs./plant), the number (pcs.) of inflorescences and flowers are provided by options with the introduction of nitrogen fertilisers in pre-sowing cultivation $N_{20}P_{20}K_{20}$ – 1.51, 9.57, 891; $N_{40}P_{40}K_{40}$ – 1.53, 10.41, 980; $N_{60}P_{60}K_{60}$ – 1.56, 10.68, 1,011, respectively. The use of nitrogen fertilisers on similar phosphorus-potassium backgrounds in foliar dressing during the phases of the beginning of flowering reduces the indicators mentioned above, and this trend is observed in all variants of the experiment.

2. The use of Vuksal Boron and Intermag Legumes in foliar dressing at the rate of 2 l/ha did not significantly affect the number of first-order branches, inflorescences, and flowers.

3. A positive effect of foliar dressing on the indicators of the buckwheat crop structure was observed, while the use of Vuksal Boron 2 l/ha was more effective compared to the introduction of Intermag Legumes 2 l/ha. Thus, the number of full-size grains (43.47 pcs.), their weight (1.21 g) was the largest when combined with the application of mineral fertilisers $P_{60}K_{60}$+N_{60} (foliar dressing) and foliar dressing with Vuksal Boron 2 l/ha. This is 1.40 pcs., and 0.04 g more compared to the variant $P_{60}K_{60}$+N_{60} (foliar dressing) + Intermag Legumes 2 l/ha and 2.24 pcs., and 0.46 g more compared to the same variant for applying mineral fertilisers, where the foliar dressing was not carried out. Notably, the foliar dressing did not affect the weight index of 1,000 grains;

4. Elements of the buckwheat crop structure increase with an increase in the fertiliser application rate from $N_{20}P_{20}K_{20}$ to $N_{60}P_{60}K_{60}$ and at the same time they vary widely: the weight of 1,000 grains is in the range of 26.93-28.00 g; the weight of full-scale grains – 0.75-1.21 g; the number of full-scale grains – 27.70-43.47 pcs.

The level of buckwheat yield is the result of a complex interaction of the genetic potential of plants with a complex of environmental conditions, which includes hydrothermal conditions and factors that were studied: fertiliser rates and foliar dressing (Table 2).

Table 2. *Yield, t/ha of buckwheat depending on the norms of mineral fertilisers and foliar dressing*

Fertiliser variant	Years			Average for 3 years
	2018	2020	2021	
Without foliar dressing				
$N_{20}P_{20}K_{20}$	1.63	1.29	1.63	1.52
$P_{20}K_{20}$ + N_{20} (foliar dressing)	1.79	1.47	1.79	1.68
$N_{40}P_{40}K_{40}$	2.17	1.72	2.24	2.05
$P_{40}K_{40}$ + N_{40} (foliar dressing)	2.29	1.86	2.36	2.17
$N_{60}P_{60}K_{60}$	2.47	1.98	2.53	2.33
$P_{60}K_{60}$ + N_{60} (foliar dressing)	2.63	2.15	2.68	2.49
Intermag legumes 2 l/ha				
$N_{20}P_{20}K_{20}$	1.68	1.32	1.69	1.57
$P_{20}K_{20}$ + N_{20} (foliar dressing)	1.84	1.50	1.87	1.74
$N_{40}P_{40}K_{40}$	2.24	1.78	2.31	2.11
$P_{40}K_{40}$ + N_{40} (foliar dressing)	2.36	1.94	2.45	2.25
$N_{60}P_{60}K_{60}$	2.53	2.04	2.63	2.40
$P_{60}K_{60}$ + N_{60} (foliar dressing)	2.70	2.21	2.75	2.55
Vuksal boron 2 l/ha				
$N_{20}P_{20}K_{20}$	1.71	1.34	1.81	1.62
$P_{20}K_{20}$ + N_{20} (foliar dressing)	1.87	1.58	1.97	1.81
$N_{40}P_{40}K_{40}$	2.28	1.88	2.44	2.20
$P_{40}K_{40}$ + N_{40} (foliar dressing)	2.40	2.00	2.58	2.33
$N_{60}P_{60}K_{60}$	2.60	2.14	2.74	2.49
$P_{60}K_{60}$ + N_{60} (foliar dressing)	2.77	2.28	2.88	2.64
$LSD_{0.05}$ t/ha A	0.06	0.15	0.07	
$LSD_{0.05}$ t/ha B	0.04	0.11	0.05	
$LSD_{0.05}$ t/ha A+B	0.10	0.23	0.12	

After analysing the obtained research data, it can be argued that:

1. The maximum yield levels were provided by hydrothermal conditions of 2021. The yield varied depending on the variant in the range of 1.63-2.88 t/ha. In 2018 and 2020, the yield indicators ranged from 1.63-2.77 and 1.29-2.28 t/ha, respectively.

2. An increase in the norms of nitrogen and phosphorus-potassium fertilisers leads to an increase in buckwheat yields, which reach maximum values in variants $N_{60}P_{60}K_{60}$ (2.33 t/ha) and $P_{60}K_{60}$ + N_{60} (foliar dressing) (2.49 t / ha);

3. The use of nitrogen fertilisers in the flowering phase ensured an increase in the yield and reached its maximum values on average for three years of research in the following variants: $P_{60}K_{60}$+N_{60} (foliar dressing) – 2.49 t/ha; $P_{60}K_{60}$+N_{60} (foliar dressing) + Intermag Legumes 2 l/ha – 2.55 t/ha; $P_{60}K_{60}$+N_{60} (foliar dressing) + Vuksal Boron 2 l/ha – 2.64 t/ha. The yield increase in variants where nitrogen fertilisers were applied at different rates during the flowering phase is 0.16-0.97 t/ha (without foliar dressing), with the use of microfertilisers, this growth was even more significant (Fig. 1).

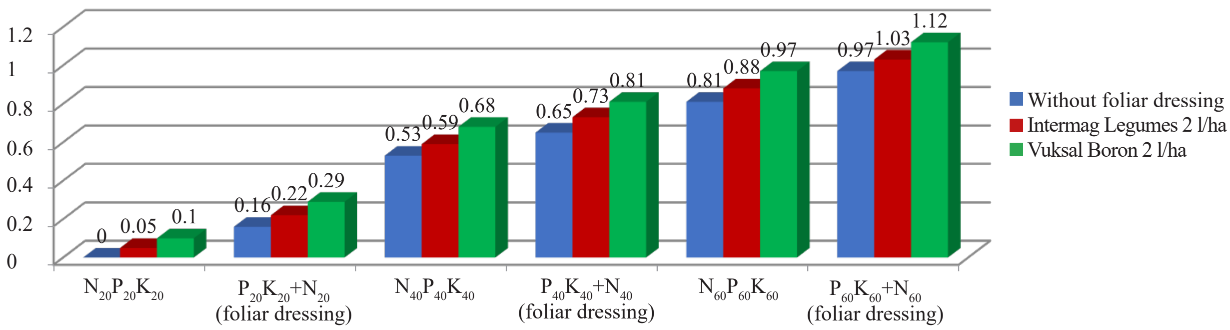

Figure 1. *Increase in buckwheat yield depending on the norms of fertilisers and foliar dressing in comparison with option $N_{20}P_{20}K_{20}$ (without foliar dressing)*

4. A positive effect of using foliar dressing with chelated microfertilisers in the budding phase was noted. Thus, the option of applying mineral fertilisers in the amount $N_{40}P_{40}K_{40}$ on average, during three years of research, provided 2.05 t/ha of buckwheat. The use of mineral fertiliser Intermag Legumes 2 l/ha allowed additionally obtaining 0.06 t/ha, and the yield increase for the use of Vuksal Boron 2 l/ha was 0.15 t/ha, that is, the introduction of Vuksal Boron 2 l/ha is more effective than the introduction of Intermag Legumes 2 l/ha.

The relationship between buckwheat yield and weight of 1,000 grains is described by the regression equation:

$$Y=252496+1,0516X$$

where Y – yield t/ha, X – weight of 1,000 seeds, pcs.

Coefficient of determination R^2=0.9049. Strong correlations between these indicators R=0.9513 were noted. The relationship between buckwheat yield and the number of full grains is described by the regression equation:

$$Y=-0,5461+0,07324X$$

where Y – yield t/ha, X – number of full-size grains, pcs.

Coefficient of determination R^2=0.9966. Strong correlations between these indicators R=0.9983 were noted.

DISCUSSION

The nutritional value of buckwheat and the increase in yield under the influence of fertilisers are noted in many sources. Buckwheat groats (Fagopyrum esculentum Moench) are an excellent source of nutrients, as they contain high levels of essential amino acids, minerals, and B vitamins compared to other cereals (Linh *et al*., 2014). Microorganisms and trace elements effectively affect the yield of buckwheat (Jaroszewska *et al*., 2019).

One of the technological problems in growing buckwheat is its relatively low resistance to lodging. This feature is especially important to consider in conditions of sufficient and excessive moisture in the western forest-steppe. Increased fertilisation rates, especially nitrogen fertilisers, can increase the risk of lodging. Therefore, it is promising to improve the technology of growing buckwheat to find ways to increase the resistance of plants to lodging.

In this study, the yield of buckwheat increased under the influence of fertilisers by more than a tonne (Table 2). Most of all, crop growth was affected by the weight of grain from the plant and the weight of 1,000 grains (Table 1). Under the influence of fertilisers, the weight of 1,000 grains also increased in studies conducted in Iran (Fallah *et al*., 2016) and India (Maruti *et al*., 2018). According to the data (Bunchak, 2018), the application of organic fertilisers in the Elena variety provided an increase in field germination by 4.4-8.1% and plant density by 0.184-0.324 million pcs./ha.

In Turkey, five types of fertilisers were studied for buckwheat varieties Aktash and Gunesh, the highest yield was provided by the introduction of mineral fertiliser urea, enriched with trace elements of copper, iron, and manganese (Çürük *et al*., 2020). According to Indian researchers (Hulihalli & Shantveerayya, 2018), the highest yield of buckwheat grain was formed when mineral fertilisers were applied at the rate of $N_{35}P_{20}K_{20}$.

According to Italian researchers (Mariotti *et al*., 2016), in the Mediterranean, buckwheat is only an alternative crop. Only in very early spring sowing periods can 2 t/ha of seeds be collected. Later sowing dates are unsuitable for growing buckwheat due to the negative impact of high summer temperatures on the setting and germination of seeds. Due to global warming, in some years similar climatic conditions are also typical for Ukraine. Therefore, certain elements of technology, especially the nutrition system, should be used to create conditions for intensive buckwheat development and fruiting before the onset of heat. This is confirmed by studies conducted in Serbia (Kolarić *et al*., 2021), where four fertiliser rates were investigated ($N_0P_0K_0$, $N_{30}P_{30}K_{30}$, $N_{60}P_{60}K_{60}$, $N_{90}P_{90}K_{90}$) when growing the Novosadska variety. The maximum yield of buckwheat grain was obtained by applying $N_{90}P_{90}K_{90}$. Yield significantly positively correlated with such structural indicators as the number of seeds per plant, the weight of seeds per plant, the height of plants, and the number of side branches.

CONCLUSIONS

Increasing the rate of application of mineral fertilisers from $N_{20}P_{20}K_{20}$ to $N_{60}P_{60}K_{60}$ helps to increase the amount and weight of full-scale grains, respectively, from 27.70 to 41.23 pcs., and from 0.75 to 1.15 g, the weight of 1,000 grains – from 26.93 to 28.00 g. When nitrogen fertilisers are applied to dressing (the beginning of the flowering phase), the number of first-order branches, inflorescences, and flowers decreases, but the number and weight of full-size grains and the weight of 1,000 grains increases, which reach their maximum with fertiliser variant of $P_{60}K_{60}+N_{60}$ (foliar dressing) – 41.23 pcs., 1.15 g, and 28.00 g, respectively.

The use of foliar dressing has a positive effect on the development of elements of the buckwheat structure, while this growth is more significant than the introduction of Vuksal Boron at a rate of 2 l/ha. The largest number of full-size grains (43.47 pcs.), their weight (1.21 g), and weight of 1,000 grains (28.00 g) were obtained in variant $P_{60}K_{60}+N_{60}$ (foliar dressing) + Vuksal Boron 2 l/ha.

Increasing the norms of mineral fertilisers, applying nitrogen fertilisers to foliar dressing (the beginning of the flowering phase) and applying foliar dressing (the budding phase) have a positive effect on the buckwheat yield indicator. The maximum yield on average for three years of research was obtained in the variant where nitrogen fertilisers are in the norm of N_{60} was applied to foliar dressing (the phase of the beginning of flowering) on a phosphorus-potassium background of $P_{60}K_{60}$ for the use of Vuksal Boron 2 l/ha – 2.64 t/ha. Such a fertiliser system is recommended for production.

The use of nitrogen fertilisers in foliar dressing during the beginning of flowering (and not for pre-sowing tillage) will be of practical importance, since the vegetative mass and the risk of lodging plants are reduced. In addition, "late nitrogen" will be used to form the regenerative part of the plant, which will ensure a higher grain yield.

Increasing the application rates of phosphorous, potash and, especially, nitrogen mineral fertilisers in the cultivation of buckwheat will be economically impractical. Further study on improving the buckwheat fertiliser system will be aimed at investigating the effectiveness of applying sulphur and magnesium fertilisers.

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Вплив норм мінеральних добрив та листкових підживлень на урожайність гречки

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Анотація. Значною проблемою у вирощуванні гречки є низька врожайність, тому актуальним є удосконалення елементів технології вирощування цієї культури. Метою досліджень було установити оптимальні норми та строки внесення мінеральних добрив та листкових підживлень хелатними мікродобривами в умовах Лісостепу західної України, в зоні достатнього зволоження для отримання стабільних та високих врожаїв зерна гречки. Для цього на дослідних полях Львівського Національного аграрного університету на темно-сірому опідзоленому легкосуглинковому ґрунті був закладений двофакторний дослід, який включав норми добрив: $N_{20}P_{20}K_{20}$, $P_{20}K_{20}+N_{20}$ (підживлення), $N_{40}P_{40}K_{40}$, $P_{40}K_{40}+N_{40}$ (підживлення), $N_{60}P_{60}K_{60}$, $P_{60}K_{60}+N_{60}$ (підживлення) та листкові підживлення: контроль (без листкового підживлення), Вуксал Борон 2,0 л/га, Інтермаг Бобові 2,0 л/га. Методи дослідження: польовий – для визначення взаємодії об'єкта досліджень з погодними факторами та елементами системи удобрення; розрахунково-ваговий – встановлення параметрів показників структури врожаю та визначення врожайності гречки; методи математичної статистики – дисперсійний, кореляційний, регресивний та графічне відображення результатів досліджень. Зростання норм добрив від $N_{20}P_{20}K_{20}$ до $N_{60}P_{60}K_{60}$ забезпечило збільшення усіх показників елементів структури врожаю гречки. Без листкових підживлень вони досягали таких значень: кількість гілок першого порядку – 1,56 шт/рослину, кількість суцвіть та квіток відповідно 10,68 та 1011 шт, кількість повноцінних зерен та рудяку (шт/рослину) відповідно 41,23 та 11,37, маса повноцінних зерен – 1,15 г та маса 1000 зерен – 28,00 г. Варто відмітити, що внесення азотних добрив у підживлення (фаза початку цвітіння) має суттєві переваги порівняно з внесенням азоту під передпосівну культивацію. Одним із доказів цього судження є зростання показників кількості зерен, їх маси та маси 1000 зерен відповідно від 35,43 шт., 0,97 г та 27,37 г (варіант внесення $N_{40}P_{40}K_{40}$) до 37,27 шт., 1,03 г, 27,80 г (варіант внесення $P_{40}K_{40}+N_{40}$). Така тенденція характерна для усіх варіантів досліду. Спостерігався позитивний вплив листкових підживлень мікродобривами на елементи структури врожаю. Більш ефективним виявилось застосування Вуксал Борону 2 л/га. Маса повноцінних зерен максимальною була у варіанті $P_{60}K_{60}+N_{60}$ (підживлення) + Вуксал Борон 2 л/га – 1,21 г, тоді як застосування препарату Інтермаг Бобові 2 л/га на аналогічному фоні мінеральних добрив забезпечило цей показник на рівні 1,17 г. Дослідженнями установлено позитивний вплив внесення азоту методом підживлення за фази початку цвітіння на рівень врожаю, також врожайність гречки зростала зі збільшенням норми внесення мінеральних добрив від $N_{20}P_{20}K_{20}$ до $N_{60}P_{60}K_{60}$ та під впливом листкових підживлень мікродобривами. Максимальний показник урожаю у середньому за три роки досліджень, отриманий у варіанті $P_{60}K_{60}+N_{60}$ (підживлення) + Вуксал Борон 2,0 л/га – 2,64 т/га

Ключові слова: гречка, живлення, мікродобрива, структура, продуктивність

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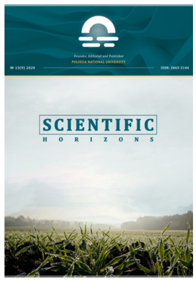

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Energy Aspects of Alfalfa Seed Production in Southern Ukraine

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Abstract. This paper presents the findings of the study on determining the energy efficiency of alfalfa seed production in the first year of life in the south of Ukraine using various technologies, which is relevant for their adequate assessment in conditions of energy conservation of non-renewable resources. The purpose of the study was to determine the most energy-efficient technology for growing alfalfa varieties for seeds. Methods of observation, comparison, and field experiment were used. The study investigated the varieties Nadezhda, Veselka, and Unitro for cultivation using conventional technology (without manual and chemical weeding), which included manual weeding without herbicides and a chemical method to reduce crop contamination. It is established that the production of alfalfa seeds requires a significant expenditure of energy-intensive non-renewable resources for the reliable protection of crops from weeds. It was found that the energy intensity of the technology with chemical weeding of alfalfa crops in the first year of life increased by 32.1-32.4% compared to the control (without weed destruction). Energy consumption reached 13,706 MJ/ha (Nadezhda grade, yield 1.46 centner/ha) against 10374 MJ/ha (yield 0.43 centner/ha) in the control. At the same time, due to the introduction of herbicides, 2.6 times less energy was consumed per 1 centner of seeds (9,388 MJ) compared to the control (24,126 MJ). The energy efficiency coefficient (K_{ee}) for chemical weeding of crops increases from 1.28 to 2.99 (Nadezhda variety) and from 1.35 to 3.13 (Unitro variety). Labour costs are reduced by 2.9 or more times due to chemical weeding of crops. Thus, in the control areas, 25.3 (Nadezhda variety) – 23.3 person-hours were consumed per 1 centner of seeds (Unitro variety), and with the introduction of herbicides, this indicator decreases to 8.8, 8.4 person-hours, respectively. The practical significance of the study lies in the proposal of an energy-saving technology for growing alfalfa for seeds

Keywords: alfalfa for seeds, herbicides, manual weeding of crops, energy efficiency

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INTRODUCTION

Energy analysis in agricultural research is important since it allows substantiating various options for experiments in terms of both profitability and energy-saving, which occupies a special place in terms of economic profit in the market (Zhuchenk *et al*., 1983; Kalashnikova *et al*., 1986). The bioenergy method has become popular in practice as a universal method for assessing anthropogenic energy flows in agroecosystems. It allows expressing all the diversity of both human and mechanic labour in uniform indicators according to the "CI" system in Joules (J). Determining the balance of energy, both consumed for production and produced, allows for quantifying the energy efficiency of growing various crops (Medvedovsky & Ivanenko, 1988; Poisa *et al*., 2016).

Perennial grasses are plants that not only provide farm animals with high-protein feed, but also play a very important role in the biologisation of agriculture, because they have a positive impact on soil fertility and the state of the environment, replenish the soil with organic and biologically environmentally friendly nitrogen, and therefore energy. The activation of biological processes in the soil during the production of perennial grasses should be significant enough to leave a certain reserve to prevent the negative impact of any anthropogenic factor on the environment. Alfalfa is one of the crops that can improve the production of high-quality feed to provide animals with the necessary proteins and at the same time contribute to the biologisation of agriculture (Pachev, 2014; Kvitko *et al*., 2021; Vasileva & Antipova 2021).

An important biological feature of alfalfa is the structure of the root system, which plays a crucial role in the nutrition system. In the process of its ontogenetic development, this plant forms a root system up to 3, and sometimes up to 5 meters deep. At the same time, alfalfa poorly utilises nutrients from such a deep soil profile, because it is poorly supplied with nutrients (Holoborodko & Tyshchenko, 2011).

The most significant factor for choosing a legume perennial grass is drought resistance, since the development of the root system significantly affects this property of the crop and determines the level of its productivity. A.P. Tkachuk study found that alfalfa roots penetrate deeply into the soil and are placed horizontally (Tkachuk, 2021). Alfalfa has a large root neck thickness and many lateral roots. These features contribute to the plasticity, durability, and productivity of its crops.

In the experiments by N.M. Galchenko, energy efficiency coefficient (K_{ee}) for the production of green alfalfa mass was 5.4-6.6, haylage – 4.3-6.1. This figure was highest for growing alfalfa for hay – from 6.2 to 7.6. When using brome grasses, K_{ee} decreased by 30.3-33.3 %, because nitrogen fertilisers were used, which are quite energy-intensive (Halchenk, 2016).

The purpose of the study is to establish regularities of changes in the coefficient of energy efficiency of growing individual varieties of alfalfa for seed purposes based on energy analysis of various technologies of its production in non-irrigated conditions.

LITERATURE REVIEW

A literature review shows that to determine the effectiveness of both individual elements and crop cultivation technologies, it is important to carry out not only energy calculations of total energy consumption for production, but also energy calculations for the energy intake with the crop. Thus, in the experiments of R.A. Vozhehova *et al*. (2019) on the dark chestnut soils of the experimental field of the Institute of irrigated agriculture of the NAAS of Ukraine, when comparing energy indicators, it was found that the energy intensity of white sweet clover of the annual Pivdennyi variety is less than the use of the Donetskyi variety. When sowing the Pivdennyi variety, the energy coefficient value was higher in the variant without mineral fertilisers. This indicator ranged from 1.59-1.77. Fertilisation caused its deterioration.

Application of phosphorus-potassium fertilisers ($P_{120}K_{180}$) to alfalfa under irrigation conditions with a high sensitivity of the crop to phosphorus-potassium nutrition and low energy equivalent contributed to a significant reduction in energy costs for the production of 1 centner of seeds. This figure was 3,276 MJ for alfalfa in the first year of fruiting, 5,266 MJ in the second year, and 7,514 MJ in the third (Holoborodko & Tyshchenko, 2011).

N.M. Halchenko (2016) found that alfalfa cultivation (*Medicago sativa* L.) mixed with medium wheatgrass (*Elytrigia intermedia* Host.) and a boneless bonfire (*Bromus inermis* Leyss) contributed to an increase in the energy efficiency coefficient (K_{ee}) to the level of 4.3-5.9. Since this indicator is significantly higher than 1, this indicates a high efficiency of feed production from perennial grasses in a grass mixture with alfalfa.

A.S. Shpakov *et al*. (2001) proved that perennial grasses provide cheap fodder. The total energy consumption for their cultivation and mowing was 6.8 GJ/ha per mixture of clover and timothy. Kee reached the level of 9.9 in terms of yield of 67.3 GJ/ha of exchange energy. At the same time, it was noted that perennial grasses are an important source of soil replenishment with organic matter and nitrogen. Thus, the legume-cereal mixture provided an average of 94 centners/ha of organic biomass, that is, 21% more than the single-species agrophytocenosis of legumes.

Researchers of the Institute of Feed Research and Agriculture of Podillya of the NAAS have found that the yield of legume seeds strongly depends on the environmental factor (52-75%). Diseases and pests account for 10-15%, and varieties – 15-25%. It is indicated that the "outsized" use of phosphorus and potash fertilisers for three years was more effective than their annual application in a dose of $P_{60}K_{60}$ and provided an increase in yield in the range of 20-28% (Antoniv *et al*., 2018).

Researchers claim that for the surface improvement of meadows and pastures in the conditions of floodplain mountain meadows of the Carpathians, it is mandatory to apply various types of fertilisers and seeds to the sod of mixtures of cereals and legumes that are long-lasting (Kurhak *et al*., 2021). The productivity of grass stands depends on the methods of soil treatment (Karbivska *et al.*, 2020).

I. Nikolova & N. Georgieva (2019) emphasise that alfalfa prevents wind and water erosion, improves agrophysical indicators of soil fertility, and is the best precursor of many agricultural crops due to the fixation of environmentally safe biological nitrogen in the atmosphere.

During studies in the northern part of the forest-steppe of Ukraine, it was found that symbiotic nitrogen accumulates the most in alfalfa plants (1.91-2.66 centner/ha), and the least – in meadow clover plants (Kurhak *et al.*, 2020).

V.H. Didora & M.M. Kluchkevych (2021) determined that in the Polissya region, up to 3.57-4.00 centner/ha of biological nitrogen are fixed from the air by soybean plants, while up to 1.17-1.60 centner/ha remain in the soil profile.

An important factor that significantly reduces the "nitrogen fixation activity of legume-rhizobial symbiotic systems" is insufficient water supply (Kots *et al.*, 2021).

In the experiments by A.V. Tishchenko *et al.* (2020) conducted in the steppe zone (Inguletsky irrigated Massif), irrigated alfalfa of the second year of vegetation (Zoryana variety) formed 3.02 centner/ha of seeds, and the Unitro variety – significantly more (3.91 centner/ha) and accumulated air-dry root mass at the level of 51.40 and 51.00 centner/ha; symbiotic fixation of 2.05 and 2.00 centner/ha, respectively.

At the same time, insufficient research has been conducted on the energy efficiency of alfalfa seed production, which is one of the main forage crops among perennial legumes.

MATERIALS AND METHODS

A study to determine the most energy-efficient technology for growing alfalfa for seed purposes in non-fertile agrophytocenoses of arid conditions was conducted in the southern massif of Ukraine, in a branch of the Mykolaiv National Agrarian University. The sown area was 50 m^2, and accounting area – 30 m^2.

Soils – southern chernozems are residual slightly saline, heavy loamy, containing humus (according to Tyurin, DSTU 7855:2015) in the arable layer of 0-30 cm on average 2.9%. The reaction of the soil solution is close to a neutral value: the pH of the salt extract ranges from 6.8. 100 g of soil is provided on average with: nitrates – 1.2 mg, mobile phosphorus – 8.5 mg, and exchange potassium –18 mg.

The density of 0-60 cm soil layer is 1.25 g/cm^3, wilting humidity – 11.4%. Underground water lies deeper than 20 m and does not affect the process of soil formation. An average of 400 mm of precipitation falls per year, and the hydrothermal coefficient is 0.7-0.8.

The predecessor of alfalfa was winter barley, and after harvesting it, stubble was cleaned. In autumn, the soil was loosened with a KPE-3,8 cultivator to a depth of 12-14 cm.

Alfalfa varieties Nadezhda, Veselka, and Unitro were studied. All these varieties are suitable for growing in non-irrigating conditions. They are included in the State register of plant varieties of Ukraine.

In the spring, mineral fertilisers were applied (nitroammofoska – 1 centner/ha) and pre-sowing cultivation was carried out by harrowing with the KPS-4G cultivator. Varieties without cover were sown in the third decade of March 2018, 2019, and 2020 with row spacing of 70 cm. The depth of seed embedding is 2-3 cm, the seeding rate is 3 kg/ha.

Weeding (chemical) was carried out with the herbicide pivot manually with a satchel sprayer at the rate of 1 l/ha in the phase of the 1st trigeminal leaf in alfalfa on plots according to the experimental design.

After the appearance of full shoots in the experiment, row-to-row tillage with a KRN-4.2 cultivator was carried out on the entire array. Working bodies – razors.

Weeding of crops manually was carried out twice: the first time, when weeds grew en masse, and the second time – 2 weeks after the first only in areas for manual weeding according to the experimental design.

The second row-to-row loosening of the soil in the entire experiment was carried out during the period of mass germination of weeds. Desiccation of crops was carried out by Reglon Super, and the seed yield was accounted for by the Sampo-500 combine. Before desiccation, sheaf samples were taken at all sites of the experiment to determine the crop structure.

Weather conditions varied over the years. 2018 was more favourable for the grass yields. In March, 75.5 mm of precipitation fell, and in April-July, another 179.4 mm was added. The average daily air temperature during April-July ranged from 10.2-23.3°C. 2020 turned out to be the driest. The above indicators are listed at the level of 8.5 mm, 118.0 mm, 10.4-24.2°C. In August 2020, there was no rain at all, which adversely affected the productivity of alfalfa.

The experiments were conducted according to generally accepted methods, considering the publications "Fundamentals of scientific research in agronomy" and "Methodology of field experience" by B.O. Dospekhov (Yeshchenko *et al.*, 2005; Dospekhov, 1985).

The energy efficiency was analysed using technological maps and energy equivalents (Eeq), defined by Medvedovsky A.K., Ivanenko P.I. for machinery, electricity, fuel, fertilisers, pesticides, transportation, processing, and storage of agricultural products, labour costs, etc. (Medvedovsky & Ivanenko, 1988).

To calculate labour productivity, the direct labour costs of tractor drivers, combine harvesters, workers, etc. were taken into account.

Energy efficiency coefficient (K_{ee}) is calculated by equation (1):

$$K_{ee} = OE : \sum E \quad (1)$$

where OE – exchange energy of the crop, MJ; $\sum E$ – amount of total energy spent on growing alfalfa, MJ.

The obtained data were processed by the method of variance analysis, which was carried out using the software and information complex Agrostat (Ushkarenko *et al.*, 2008).

RESULTS AND DISCUSSION

High and stable yields of alfalfa seeds are obtained only when all innovative agronomic measures are applied to the seedlings, developed considering the biological characteristics of this plant. Neglecting at least one of the planned types of work can reduce total energy costs, but at the same time, it can lead to a significant decrease in the productivity of alfalfa for seed purposes.

Main soil treatment methods play an important role in energy saving. In previous years, experiments were conducted to investigate the influence of this factor on alfalfa seed productivity (Antypova, 2008). The experiment scheme is shown in Table 1. Calculations indicate the energy efficiency of shallow (12-14 cm) loosening of the soil with an anti-erosion cultivator (KPE-3.8), that is, without a barrow. The use of this option in the autumn period leads to a decrease in energy consumption in the production of alfalfa seeds. This method should be attributed to energy-saving agrotechnical in comparison with the conventional shelf with a depth of 28-30 cm, which was taken as control. At the same time, the total energy intensity of labour resources decreases from 57.7 to 29.0 MJ/ha, that is, almost twice.

***Table 1**. Energy intensity of basic cultivation methods for alfalfa**

Main soil treatment		Output for 1 person – hour, ha	Energy intensity, MJ/ha			
Methods	Depth, cm		Labour resources	Fuel	Total	± to control
Control – tillage	28-30	1.06	57.7	1,006.5	1,064.2	0
Tillage	22-24	1.08	56.7	901.5	958.2	-106.0
Without tillage	28-30	1.37	44.7	758.4	803.1	-261.1
Tillage	22-24	1.41	43.4	663.0	706.4	-357.8
Tillage	12-14	2.11	29.0	357.8	386.8	-677.5

***Note:** calculated by the author based on technological map and energy equivalents for machinery, fuel, and labour costs*

It was found that during shallow sweep tillage, fuel consumption is 13.6 kg/ha less compared to deep ploughing. The cost of such a non-renewable resource as fuel, which is an energy carrier, is reduced from 1006.5 (control) to 357.8 MJ/ha, that is, by 2.81 times, and the total cost of total energy, which includes labour with fuel, is reduced by 2.75 times (from 1064.2 to 386.8 MJ/ha, respectively).

Considering the fact that there was no significant difference in seed productivity between the considered options, it can be concluded that among the methods of basic tillage, sweep tillage to a depth of 12-14 cm is preferred in terms of energy efficiency. Alfalfa seed production also requires a significant expenditure of energy-intensive non-renewable resources (in particular fuel and herbicides) to reliably protect crops from weeds. The spread of unwanted plants in the agrophytocenosis significantly reduces the productivity of crops, especially in the first year of life of alfalfa seeds, when it grows slowly and cannot compete with weeds.

The highest yield of alfalfa seeds and dry matter was formed in 2018 due to more favourable weather conditions for plant growth and development. On average, 1.24 centner/ha of seeds and 15.9 centner/ha of dry matter were collected in the experiment in 2018. For drier weather conditions in 2020, these indicators are in the range of 1.11 and 12.9 centner/ha, respectively (Table 2).

***Table 2**. Yield of alfalfa for seed purposes depending on the studied factors*

Technology (factor A)	Variety (factor B)	Yield by year, centner/ha			
		2018	2019	2020	Average
Seeds					
Without herbicides and manual weeding	Control – Nadezhda	0.49	0.42	0.38	0.43
	Veselka	0.51	0.44	0.41	0.45
	Unitro	0.50	0.49	0.42	0.47
Manual weeding	Nadezhda	1.61	1.57	1.43	1.54
	Veselka	1.64	1.61	1.49	1.58
	Unitro	1.74	1.67	1.54	1.65
Application of herbicide	Nadezhda	1.50	1.48	1.40	1.46
	Veselka	1.56	1.58	1.42	1.52
	Unitro	1.61	1.59	1.48	1.56
Average in the experiment		1.24	1.21	1.11	1.18

Table 2, Continued

Dry matter					
Without herbicides and manual weeding	Control – Nadezhda	7.1	5.2	4.8	5.7
	Veselka	7.2	5.3	4.9	5.8
	Unitro	7.5	5.7	4.8	6.0
Manual weeding	Nadezhda	19.9	19	16.6	18.5
	Veselka	20.3	19.1	17.3	18.9
	Unitro	21.4	19.7	17.7	19.6
Application of herbicide	Nadezhda	19.2	16.8	16.2	17.4
	Veselka	19.9	16.8	17	17.9
	Unitro	20.5	17.5	16.9	18.3
Average in the experiment		15.9	13.9	12.9	14.2

On average, over three years of study, in areas without herbicides and without manual removal of competing plants, the seed yield ranged from 0.43-0.47 centner/ha. Due to the introduction of herbicides, the contamination of crops decreased, and the yield increased to 1.46-1.56 centner/ha. The best protection of crops from weeds is manual weeding. According to this model of seed production, the highest yield was obtained (1.54-1.65 centner/ha). The Unitro variety had an advantage in this indicator. The Veselka variety has fewer seeds per unit of sown area.

Due to the existing shortage of energy resources and high prices for agrochemicals and modern agricultural machinery, it is necessary to justify the efficiency of crop production technologies not only from the standpoint of economic feasibility but also based on accounting for energy equivalents (Misiuk, 2013).

The energy analysis shows that with the chemical weeding of alfalfa crops in the first year of life, the energy intensity increases by 32.1-32.4% compared to the control, where the crop was not protected from weeds by either herbicide or manual weeding. Energy costs reached 13,706 MJ/ha (Nadezhda variety) – 13,758 MJ/ha (Unitro variety) against 10,374-10,395 MJ/ha, respectively, for varieties on control plantings (Table 3).

Table 3*. Energy costs for the production of alfalfa seeds in the first year of life, depending on the studied factors (on average for 2018-2020)*

Technology (factor A)	Variety (factor B)	Yield, centner/ha		Energy costs, MJ	
		Seeds	Dry matter	Per 1 hectare	Per 1 centner seeds
Without herbicides and manual weeding	Control – Nadezhda	0.43	5.7	10,374	24,126
	Veselka	0.45	5.8	10,384	23,076
	Unitro	0.47	6.0	10,395	22,117
Manual weeding	Nadezhda	1.54	18.5	15,341	9,962
	Veselka	1.58	18.9	15,362	9,723
	Unitro	1.65	19.6	15,447	9,362
Application of herbicide	Nadezhda	1.46	17.4	13,706	9,388
	Veselka	1.52	17.9	13,737	9,038
	Unitro	1.56	18.3	13,758	8,819
LSD_{05}, centner/ha for factor A		0.03	0.54	–	–
LSD_{05}, centner ha for factor B		0.03	0.54	–	–
LSD_{05}, centner/ha for AB interaction		0.05	0.94	–	–

It was found that energy costs for seed production significantly decreased due to the introduction of the herbicide (in the range of 2.5-2.6 times) and amounted to 8,819 MJ/centner (for the Unitro variety) – 9,388 MJ/centner (for the Nadezhda variety) compared to the control plots (herbicide-free technology), where fluctuations in this indicator were recorded in the range of 22,117 and 24,126 MJ, respectively, for the above-mentioned varieties. Due to the higher productivity of alfalfa sowing for seed purposes using herbicides, that is, by reducing the number of weeds, the content of energy accumulated by plants in the studied crop increases 3.1 times compared to the control and averages 42,060 MJ/ha for factor A. This indicator was slightly higher (3.3 times) when manually weeding crops – 44,689 MJ/ha (Table 4).

***Table 4**. Energy accumulation of alfalfa seeds in the first year of life, depending on the factors studied (on average for 2018-2020)*

Technology (A)	Variety (B)	Energy content in the crop from 1 ha, MJ				
		Seeds	Dry matter	Total	Average for factor A	Average for factor B
Without herbicides and manual weeding	Nadezhda – control	869	12,443	13,312	13,643	32,581
	Veselka	909	12,661	13,570		33,389
	Unitro	949	13,098	14,047		34,422
Manual weeding	Nadezhda	3,111	40,386	43,497	44,689	
	Veselka	3192	41,259	44,451		
	Unitro	3,333	42,787	46,120		
Application of herbicides	Nadezhda	2,949	37,984	40,933	42,060	
	Veselka	3,070	39,076	42,146		
	Unitro	3,151	39,949	43,100		

Most of the energy was generated by Unitro plants during manual weeding of crops (46,120 MJ/ha). On average, for factor B in the production of seeds of this variety, 34,422 MJ/ha of energy was accumulated in the yield, which is 5.7% more than the control variety Nadezhda (standard).

According to S.P. Holoborodko & A.V. Tyshchenko, (2011), the production of alfalfa seeds in the South of Ukraine in the average dry (within 75%) and dry (within 95%) years without irrigation during the growing season led to significant expenditures of total energy for growing 1 centner of seeds, which caused the unprofitability of seed production. Energy consumption for seed production (Khersonskaya 7 variety) under natural conditions of moisture in the first year of fruiting (second year of life) was 11,144 MJ/ha and 20,262 MJ/centner of seeds, and Nadezhda variety – 11,144 MJ/ha and 16,151 MJ/centner of seeds, respectively. The implementation of vegetation irrigation once in the period from the beginning of regrowth to the beginning of budding increases energy consumption by 2,255 MJ/ha. At the same time, the energy intensity of 1 centner of seeds decreases by 4,768 and 3,774 MJ, respectively, for the above-mentioned varieties. These figures are considerably better when watered twice during the growing season. Notably, the energy efficiency coefficient (Kee) for chemical weeding of crops increases from 1.28 to 2.99 (for the Nadezhda variety) and from 1.35 to 3.13 (Unitro variety). Consequently, the energy costs of applying herbicides contribute to the conservation and more efficient use of total energy (Fig. 1).

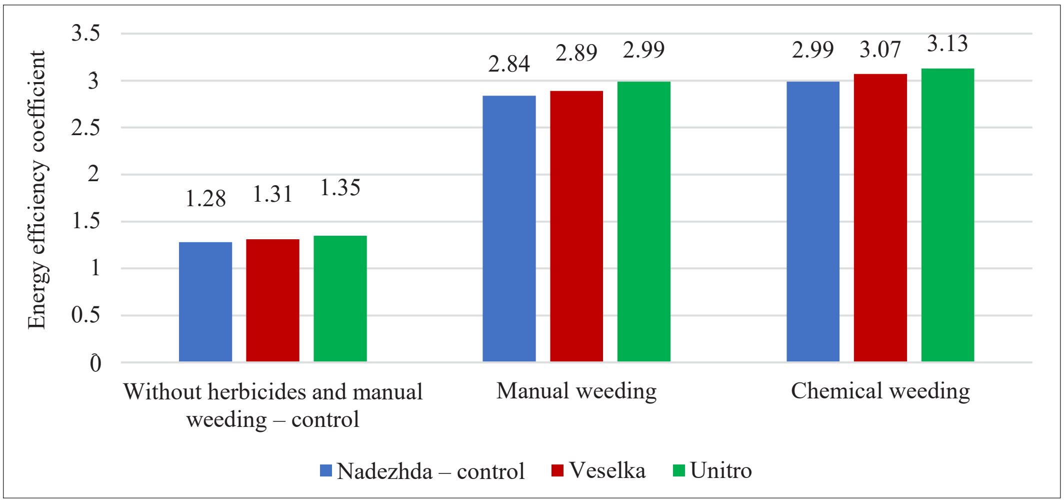

***Figure 1.** Coefficients of energy efficiency (Kee) of alfalfa seed production in the first year of life, depending on the studied factors (on average for 2018-2020)*

When manually weeding the agrophytocenosis, the coefficient of energy efficiency of seed production of the studied alfalfa varieties of the first year of life was slightly lower compared to chemical weed control. For plants of the Nadezhda variety, it fluctuated on average over three years of research at the level of 2.84, and for the production of Unitro seeds, it increased by 0.15 units, or by 5.3%. As for the Veselka variety, it had minor advantages over the Nadezhda variety, but they were not reliably confirmed.

It is appropriate to calculate labour productivity, that is, the ability of a particular type of work when growing alfalfa to form a certain amount of products (seeds) in one working hour. This indicator may increase if alfalfa seed production increases by one working hour, or if labour costs per unit of the generated crop are reduced. Labour costs were expressed in person-hours. During the production of agricultural products, in this case, alfalfa seeds, direct labour costs of tractor drivers, combine harvesters, workers, etc. are determined.

According to the technology with the use of herbicides, the highest level of labour productivity was observed: 11.89 (Unitro variety), 11.66 (Veselka variety), 11.30 (Nadezhda variety) kg of seeds/person-hour were obtained compared to the control: 3.96, 4.13, 4.30 kg of seeds/person-hour, respectively (Fig. 2).

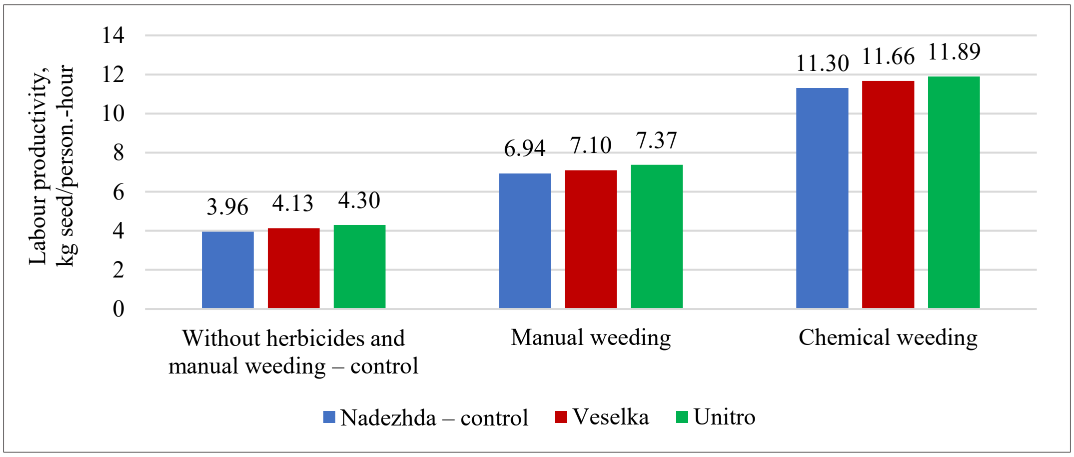

Figure 2. *Labour productivity for the production of alfalfa seeds of the first year depending on the studied factors (on average for 2018-2020), kg of seeds/person-hour*

The technology, which includes manual weeding, is 1.6 times inferior to the chemical weeding model in terms of the above indicator, but labour productivity was 1.7 times higher compared to the control: 6.94-7.37 kg of seeds were obtained per 1 person-hour.

The analysis of the data in Figure 3 indicates that labour costs are reduced by 2.9 or more times due to chemical weeding of crops. Thus, in the control areas, 25.3 (Nadezhda variety) — 23.3 (Unitro Variety) person-hours were consumed per 1 centner of seeds. With the introduction of herbicides, this indicator decreases to 8.8 (Nadezhda variety), 8.6 (Veselka variety), 8.4 (Unitro variety) person-hours.

When using the technology with manual weeding of crops, the energy intensity increases by 11.9% (up to the level of 15,341 MJ/ha), labour intensity of the percentage of seeds for growing Nadezhda variety increases from 8.8 to 14.4 person-hours and in the Unitro variety – from 8.4 to 13.6 person-hours compared to the technology that is based on the use of chemical weed control. The growth of Kee shows the advantages of chemical weeding technology, especially in the Unitro variety, over other seed production technologies studied.

It should be noted that biological nitrogen enters the soil during the cultivation of alfalfa, which causes a replenishment of the meter layer with total energy.

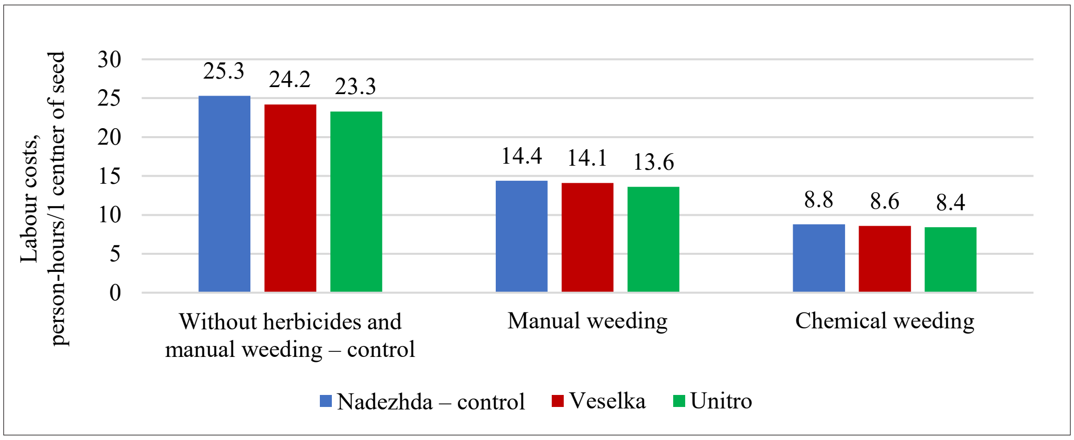

Figure 3. *Labour costs for the production of alfalfa seeds in the first year of life, depending on the factors studied (on average for 2018-2020), person-hour/ centner of seeds*

As evidenced by the results of research by Bulgarian researchers I. Nikolova and N. Georgieva 2019, alfalfa most of all fixes nitrogen against the control (untreated) crop with combined treatment with biological preparations Agricol with Nagro and Litovit, which were used for spraying crops against aphids. The increase in nitrogen fixation was 2.77 and 2.95 kg/kg of dry matter.

N.V. Tsurkan (2014) determined the coefficient of conversion of alfalfa hay crop to nitrogen (K_N), which gets into the soil. This indicator in the conditions of the Southern Steppe for recalculation is 0.025. Considering the above-mentioned coefficient for the transfer of the formed alfalfa hay yield to the nitrogen recorded and trapped in the soil, the intake of this element, and therefore energy, into the soil profile of the root layer, was determined.

The study calculated that as a result of nitrogen fixation, the soil was most replenished with environmentally friendly nitrogen (51.48 kg a.s./ha) using a technology based on manual weeding of alfalfa crops in the first year (Table 5).

***Table 5**. Energy supply to the soil depending on the studied factors (average for 2018-2020)*

Technology (factor A)	Variety (factor B)	Entered the soil per 1 ha					
		Nitrogen, kg of active substance			Total energy, MJ		
		Total	Average for factor A	Average for factor B	Total	Average for factor A	Average for factor B
Without herbicide and manual weeding	Control – Nadezhda	15.33	15.71	37.53	1,330	1,363	3,257
	Veselka	15.63		38.45	1,356		3,338
	Unitro	16.18		39.65	1,404		3,442
Manual weeding	Nadezhda	50.10	51.48		4,348	4,468	
	Veselka	51.20			4,444		
	Unitro	53.13			4,611		
Application of herbicides	Nadezhda	47.15	48.45		4,093	4,206	
	Veselka	48.55			4,214		
	Unitro	49.65			4,310		

***Note**: the energy equivalent (Kee) of 1 kg of active substance of nitrogen fertilisers is 86.8 MJ (Medvedovsky & Ivanenko, 1988)*

For chemical weeding of crops, this indicator was slightly lower – 48.45, and in crops that were not protected from weeds, nitrogen fixation was even lower (15.71 kg of active substance of nitrogen per 1 ha).

There is a tendency for greater nitrogen fixation by plants of the Unitro variety – 39.65 kg a.s./ha, which is 2.12 kg a.s./ha more compared to the control Nadezhda variety.

An identical pattern was established in the flow of total energy into the soil conditioned by nitrogen fixation. This property of alfalfa plants should be considered when calculating both the energy and economic efficiency of its production.

The results of the analysis of the energy structure show that when growing alfalfa for seeds without weeding and herbicides (control), the share of fuel (in conditions of acute energy shortage) reaches 41.5%, and mechanisms – 27.7% (Fig. 4).

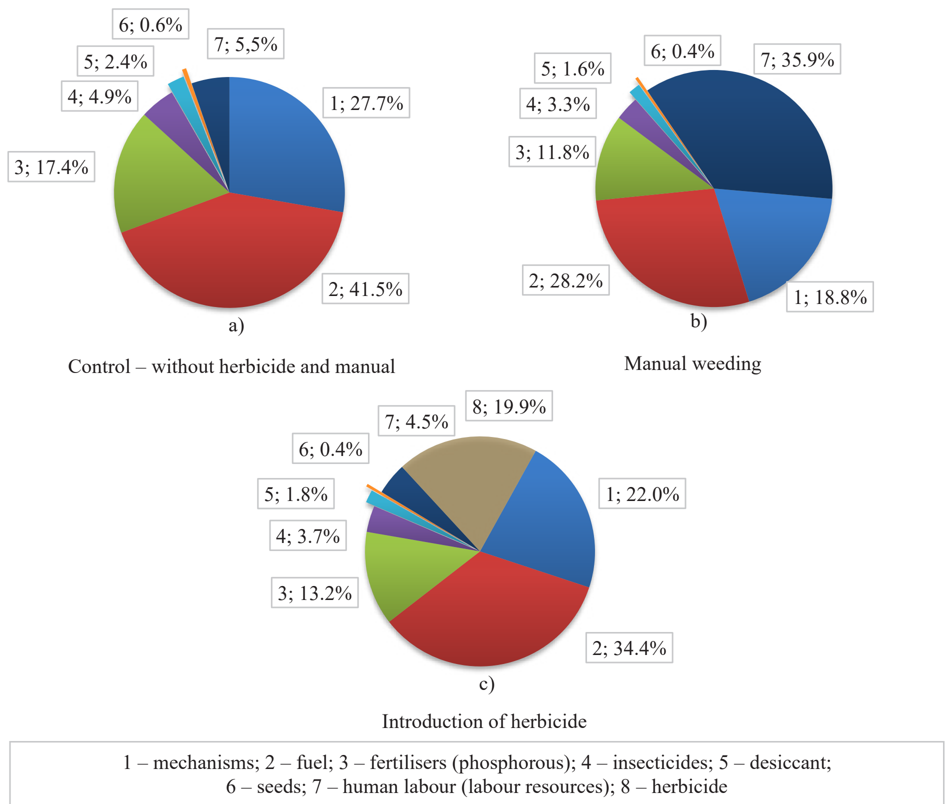

***Figure 4**. Specific weight of energy consumption by alfalfa seed cultivation technology in the first year of growth*

A smaller part is spent on mineral fertilisers (17.4%), insecticides (4.9%), and desiccants (2.4%).

Although the share of human labour using this technology is reduced to 5.5%, the development of the crop, as noted above, was the worst compared to the areas that were cleared of weeds.

The share of fuel and equipment in the structure of energy consumption during manual weeding with wide-row sowing decreases to 28.2 and 18.8%, respectively. At the same time, the main energy consumption falls on labour resources (35.9%), which does not justify a slight increase in seed productivity of the crop compared to chemical weeding.

CONCLUSIONS

The level of energy consumption per unit of production depends primarily on the year of growth, technologies that are implemented, and the equipment used in growing and harvesting alfalfa for seeds.

With sweep tillage to a depth of 12-14 cm, 13.6 kg/ha less fuel is consumed, the total energy costs of human labour are reduced by almost 50%, and the total energy costs (labour resources + fuel) are 2.75 times less compared to deep ploughing by 28-30 cm for sowing alfalfa for seeds.

The formation of crop productivity significantly depends on weather conditions during the growth and development of alfalfa.

When using herbicides, the productivity of alfalfa for seed purposes increases from 0.43 (control without herbicides and manual weeding) to 1.46 entner/ha of seeds, especially with the Unitro variety (from 0.47 to 1.56 centner/ha). Due to the release of crops from the weed component by chemical method, the collection of dry matter also underwent changes and amounted to 5.7, 17.4, 6.0, and 18.3 centner/ha, respectively.

Since manual weeding of the agrophytocenosis accounts for the main share of energy costs in labour resources (35.9%), this technology should not be offered to production. Energy consumption for the production of 1 centner of seeds during chemical weeding is reduced by 2.5-2.6 times compared to the control (without herbicides and weeding), and Kee is 2.99-3.13 against the control level of 1.28-1.35.

The change in the energy efficiency coefficient from 1.28 (for the technology without weeding of the Nadezhda variety, which is taken as a control) to 3.13 (for the technology of growing alfalfa for seed purposes of the Unitro variety with the introduction of herbicides) indicates the advantages of the latter model based on energy analysis of various technologies for the production of seed material in non-irrigated conditions.

During the production of alfalfa seeds of the Unitro variety in the first year, protected from weeds by chemical weeding of crops, 49.65 kg of active substance of nitrogen/ha accumulates in the soil, which is 3.2 times more compared to the control. The property of alfalfa plants to accumulate nitrogen in the soil should be taken into account when calculating both the energy and economic efficiency of its products.

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Енергетичні аспекти виробництва насіння люцерни на півдні України

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Анотація. У цій роботі представлені результати досліджень щодо визначення енергетичної ефективності виробництва насіння люцерни першого року життя на півдні України за різними технологіями, що є актуальним для адекватної їх оцінки за умов енергозбереження непоновлюваних ресурсів. Метою досліджень було визначення найбільш енергоефективної технології вирощування сортів люцерни на насіння. Використовували методи спостереження, порівняння та польового експерименту. Досліджували сорти Надєжда, Веселка, Унітро за вирощування з використанням традиційної технології (без ручного і хімічного прополювання), яка включала ручне прополювання без внесення гербіцидів і технології з застосуванням хімічного методу зменшення забур'яненості посівів. Встановлено, що виробництво насіння люцерни потребує значних витрат енергоємних невідновлюваних ресурсів для надійного захисту посівів від бур'янів. З'ясовано, що енергоємність технології з хімічним прополюванням посівів люцерни першого року життя зросла на 32,1–32,4 % порівняно з контролем (без знищення бур'янів). Витрати енергії досягли 13706 МДж/га (сорт Надєжда, урожайність 1,46 ц/га) проти 10374 МДж/га (урожайність 0,43 ц/га) на контролі. Водночас завдяки внесенню гербіцидів на 1 ц насіння було витрачено енергії у 2,6 рази менше (9388 МДж) порівняно з контролем (24126 МДж). Коефіцієнт енергетичної ефективності (КЕЕ) за хімічного прополювання посівів збільшується з 1,28 до 2,99 (сорт Надєжда) та з 1,35 до 3,13 (сорт Унітро). За рахунок хімічної прополки посівів витрати праці зменшуються у 2,9 і більше разів. Так, на контрольних ділянках на 1 ц насіння витрачалося 25,3 (сорт Надежда) – 23,3 люд/год. (сорт Унітро), а з внесенням гербіцидів цей показник зменшується до 8,8, 8,4 люд./год. відповідно. Практична цінність дослідження полягає в пропозиції енергозберігаючої технології вирощування люцерни на насіння

Ключові слова: люцерна на насіння, гербіциди, ручна прополка посівів, енергоефективність

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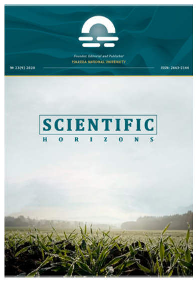

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Ecological Mechanisms of *Sus Scrofa* Population Regulation in Modern Conditions

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Abstract. Wild boar population (*Sus scrofa*) has been growing rapidly in most countries of the world over the past decades. The invasive species has high reproduction rates and well-developed adaptive responses, which allows it to successfully expand the boundaries of its habitat, create significant economic losses to agriculture and horticulture, urban ecosystems, and threatens the loss of biological diversity and the spread of zoonotic infections. The purpose of the paper was to analyse the factors that contribute to the expansion of the *Sus scrofa* species in the world, to determine the ecological mechanisms of population regulation against the background of rapid anthropogenic transformation of the habitat and global climatic anomalies; to assess changes in the dynamics of population size in hunting farms of Ukraine for the period from 2010 to 2020 in the Chernihivska oblast, in particular. Conventional methods of retrospective analysis, synthesis, environmental, general biological, and epizootic research were used. The paper analyses the world experience and identifies the main factors of low effectiveness of strategies for controlling the rapidly growing population of wild boar in agroecosystems, mixed forest and urban ecosystems. Due to the unique features of forming a life strategy, the *Sus scrofa* species demonstrate successful development, expansion of the range of available food resources, effective use of daily diversification of ecological niches in the conditions of transformed ecosystems, etc. It is established that the reason for the inefficiency of ecological mechanisms of pressure on the population of the species in the "predator-prey" system is the absence of large predators in the forest ecosystems of Chernihivska oblast. At the same time, the absence of deterrent mechanisms in the predator-prey system ensured the manifestation of next-level mechanisms, namely, the appearance of foci of African swine fever along the forest cycle in the natural biocenoses of the region. Response – the response of populations was manifested by a rapid short-term decrease in the population of *Sus scrofa*, as a temporary deterrent effect with a subsequent recovery trend. The results obtained can be used in the development of practical recommendations for biological monitoring, environmental control, and the development of effective forest management measures to prevent biological safety associated with the uncontrolled distribution of *Sus scrofa* and African swine fever based on universal ecological mechanisms of population regulation

Keywords: invasive species, habitat, African swine fever, epizootics, biotic regulatory mechanisms

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INTRODUCTION

The transformation of natural landscapes, anthropogenic pressure, and climate anomalies have serious implications for the conservation of biological diversity. The response of species to global climate change and anthropogenic pressure has a wide range of manifestations: from rapid population growth, habitat expansion, and establishment of new types of interspecific ties, to a decrease in its number and extinction. Some populations respond positively to changing environmental conditions. They fill free ecological niches, move to new territories, and effectively use the available trophic resource, which contributes to the rapid reproduction of the species and the formation of dominant cells. At the same time, displacement or loss of less adaptable native species can deal damage to agriculture, forestry and the national economy, and cause uncontrolled outbreaks of infectious diseases in a rapidly growing population (Vetter *et al.*, 2020).

Factors of influence are divided into external (availability of available resources, population size of predators and parasitic organisms) and internal, associated with density-dependent regulatory mechanisms (changes in gene- and phenotypic composition, biochemical and behavioural reactions). A population responds to external influences with positive and negative feedback, and to internal influences with ecological mechanisms for regulating its own abundance by forming an oscillatory mode of population waves. Adaptive endogenous mechanisms in populations create additional stability in their structural and functional organisation. At the population level, the cyclicity of different species and the ecological features of their spectra as an element of the overall adaptive structure are of prognostic significance and require additional research (Froehly *et al.*, 2020).

The leader among the growth rates of the mammalian population of the European continent is the wild boar or wild pig (*Sus scrofa* L., 1758). The species is characterised by adaptability, flexible eating habits, great reproductive potential, high survival rates among young animals under favourable climatic conditions, and in unfavourable conditions — physiological adaptations to low temperatures with the development of alternative thermogenesis, unique survival among females and their fertility. Only one female *Sus scrofa* gives birth to up to 14 piglets in one litter (Ruf *et al.*, 2021).

The wild pig is a eurytopic species that poses economic threats and leads to the transformation of ecological systems, and its geographical range has gone far beyond the primary (Southeast Asia, the Far East, and Asia Minor). Nowadays, the species is distributed on all continents except Antarctica. At the same time, over the past century, the wild boar has significantly expanded its range to areas with high winter temperatures (up to −30°C) and has been seen near the Arctic Circle (Ruf *et al.*, 2021).

On the territory of European countries, a constant increase in the population of Wild Boars has been recorded since the 1960s and 1970s. In the period from 1980 to 2010, the number of wild boar increased 6-fold in Germany and Slovenia, 5-fold — in Austria and France, 4-fold — in the Czech Republic and Italy, 2.5-fold — in Belgium (Tack, 2018). As of 2017, the number of wild boars in Poland reaches 228 thousand with a constant upward trend. The expansion of the hunting license in the period from 1975 to 2015 and about 3 thousand animal units lost from African swine fever (ASF) did not significantly affect the situation (Pejsak *et al.*, 2018). In general, today in Europe the population of wild boars exceeds the figure of 10 million units (ENETWILD, n.d.). In Canada, signs of exponential growth in the wild boar population within 9% per year were recorded mainly in agricultural regions, and in the state of Florida (USA) near freshwater bodies, which is associated with the degradation of 19% of wetlands (Wong, 2021).

The purpose of the study was to analyse scientific developments on the ecological mechanisms of population regulation of an invasive species of *Sus scrofa* and to establish its effectiveness in retrospect in the conditions of Ukraine and Chernihivska oblast, in particular.

To achieve this goal, the following tasks were defined:

- to analyse the current state of investigation of the issue of ecological features of an invasive species of *Sus scrofa* under conditions of anthropogenic pressure on natural biocenoses and the role of biotic mechanisms of population regulation in the global expansion of the species;
- to assess the reasons for changes in the dynamics of the wild boar population in hunting farms of Ukraine for the period from 2015 to 2020, and Chernihivska oblast for the period from 2010 to 2020;
- to evaluate the effectiveness of population regulation mechanisms of *Sus scrofa* on the example of Chernihivska oblast.

The results obtained are aimed at practical solutions to the issue of biological monitoring, environmental control, and the development of effective measures to prevent the biological hazard associated with the spread of African swine fever based on universal environmental mechanisms for population control.

LITERATURE REVIEW

A sharp increase in the population size and expansion of the habitat of wild boar in most countries of the world is associated with high rates of biotic potential and reproduction among ungulates (2.0), as well as adaptation to various habitats (Croft *et al.*, 2020). According to D. Liu *et al.* (2022), the reasons for the expansion of the species lie in indirect factors, in particular, the nutritional value of the available food ration, ecological relationships between habitat types, interspecific co-actions, genetic diversity, population structure, etc. Thus, over the past 30 years, American researchers have noticed a rapid increase in mixed populations of wild pigs. The vast majority of the studied livestock had a genotype of oligonucleotide polymorphism of mixed origin, with dominant genetic associations with Western breeds of domestic pigs and European wild populations (Niedziałkowska *et al*., 2021; Smyser *et al*., 2021).

One of the hypotheses regarding the promotion of the species to new territories is associated with the liberation of ecological niches by other species of wild animals and adaptation to a wide range of climates. The researchers suggest that wild boar infestation on all continents does not show signs of an evolutionary niche, and the innovative potential of the species is associated with reproductive, trophic and morphological characteristics combined with behavioural thermoregulation (Sales *et al*., 2017).

At the same time, the development of an adaptive complex was recorded, which manifested itself as the response of the species to an increase in average annual temperatures, precipitation, relative humidity, availability and caloric content of food (Brivio *et al*., 2017). As a result of a decrease in the body's need for energy expenditure, a tendency to reduce body weight in adult animals and a smaller number of newborns in Central European wild boar populations were observed (Vetter *et al*., 2020; Ruf *et al*., 2021).

Spatial strategy of *Sus scrofa*, the size and shape of the habitat depend on the landscape characteristics, the size of the area, meteorological conditions, and access to water and food. Cases of migration of the species to megacities and suburban areas in the autumn-winter period are associated with attractive warm locations and the search for easily accessible food resources (human food residues) (Amendolia *et al*., 2019), and moving to nature reserves is associated with feeding of wild animals (Brogi *et al*., 2020). Increasing population density in certain areas (along water bodies, in nature reserves, in urban areas) is important for monitoring species and predicting foci of zoonotic infections (Amendolia *et al*., 2019; Clontz *et al*., 2021).

Due to its high adaptive property, the species easily switch to nocturnal activity under increased anthropogenic pressure, while increasing the size of their population. In addition, phenotypic plasticity allows the species to quickly adapt to local conditions, which indicates behavioural adaptation of *Sus scrofa* to the circadian rhythm. There is a temporary diurnal diversification of ecological niches between humans and wild boar in the absence of other mechanisms of interaction. This fact poses new challenges to find effective methods to counteract species and protect them from entering undesirable territories (Brivio *et al*., 2017; Johann *et al*., 2020).

Mechanisms of artificial containment of epizootics, in particular, species-specific African swine fever (ASF), today in 80% of cases are focused on depopulation of wild boars (Vetter *et al*., 2020). Thus, the study of the "Reserve effect" by J. Colomer *et al.* (2021) showed the effectiveness of wild boar population control, mitigation of conflict caused by the species, and localisation of ASF foci in areas with hunting bans. The results obtained by E. Jori *et al.* (2020), confirm the effectiveness of the buffer and transition zones in the elimination of ASF foci with subsequent culling of animals. According to A. Yang (2021), there is an effective culling zone within a radius of 2 kilometres around the epizootic focus, while high culling pressure threatens to intensify interpopulation contacts and spread the disease to large areas. Studies by Jo & Gortázar (2021) confirmed an increase in the risk of spreading the disease when moving people and vehicles in the area of ASF focus, in particularm natural biogeocenoses (Jo & Gortázar, 2021; Gortázar, 2019).

Conventional methods of controlling the number of wild boars are shooting, trapping, and the use of toxicants. At the same time, hunting is declining in most countries, and in some regions, there is a direct ban on hunting and trapping animals. The use of toxic substances to control the species contradicts animal welfare regulations and threatens the environment. This is the situation, against the background of a rapid increase in the population size of *Sus scrofa*, it is necessary to review effective means of reducing them quickly. In this regard, individual researchers focus their efforts on developing mathematical models for population reduction using fertility controls in combination with culling. According to the researchers, this would allow achieving the target reduction in the number of animals by half. The use of birth control alone has a threat of the "placeholder effect" when infertile animals occupy areas inaccessible to fertile ones (Croft *et al*., 2020).

A whole complex of adaptive advantages and opportunities for uncontrolled growth of the species population invariably triggers regulatory mechanisms based on the principle of reverse feedback. These mechanisms are poorly understood, especially in the context of the transformation of the climate system and anthropogenic pressure on natural biocenoses, which opens up wide opportunities for researchers for analytical, fundamental, and applied research.

Thus, the analysis of available sources indicates the urgency of the problem of controlling a rapidly growing population of *Sus scrofa* in many countries of the world and the search for ways of effective management based on the study of the ecology of the species and favourable environmental factors of abiotic, biotic, and anthropogenic origin.

MATERIALS AND METHODS

A systematic approach was used to determine the ecological prerequisites and mechanisms for regulating the population size *Sus scrofa,* including manifestations of emerging infections in the population on the territory of Ukraine and Chernihivska oblast, in particular. Conventional methods of retrospective analysis, synthesis, environmental, general biological, and epizootic research were used.

The analysis of the dynamics of the wild boar population in hunting farms in Ukraine covered the period from 2010 to 2020. Registration of outbreaks of African swine fever in Ukraine covers the period from 2012 to 2022.

As basic materials for analytical generalisations about the population of *Sus scrofa* in Ukraine, the study used the reporting data of the Environmental passport of the regions of Ukraine for the period 2016-2020 and the Environmental passport of the Chernihivska oblast for 2012-2020 (Ministry of Environmental Protection and Natural Resources of Ukraine, 2021), data of the Chernihiv Regional Department of Forestry and Hunting (Chernihiv Regional Department of Forestry and Hunting, 2016), the report on the state of the natural environment in the Chernihivska oblast for 2020 (Chernihiv Regional State Administration, 2020) and open data from the website "African swine fever" of the State Service of Ukraine for Food Safety and Consumer Protection (The official website of the African swine fever, 2021).

A bibliographic review of classical and modern literature on the adaptive mechanisms of wild boar, their behavioural reactions, containment mechanisms, and methods of artificial population control adopted in international practice was conducted.

RESULTS AND DISCUSSION

Nowadays, human activity has become the driving force that affects the transformation of landscapes and, consequently, changes in the structural and functional organisation of biocenoses and biological diversity. Key factors contributing to the population growth of *Sus scrofa* include: forest restoration, increasing the availability of food resources for the species in the form of crops, feeding in winter in forestry, and mitigating climatic conditions (Croft *et al*., 2020).

Uncontrolled growth of the wild boar population is accompanied by the transformation of natural ecosystems and the impact on biological diversity, economic damage to agriculture and farms, colonisation of settlements and urban neighbourhoods, damage to public parks, sports grounds, cemeteries, collisions with vehicles on roads, the spread of zoonotic infectious diseases among companion species.

Manifestation of species-specific adaptive reactions inherent in *Sus scrofa,* in combination with favourable climatic conditions and wide access to food, has led to the low effectiveness of measures aimed at controlling the wild boar population. In some regions, farmers independently struggle with attacks by wild boars on livestock and raids on fields with agricultural crops.

Researchers study and use a variety of strategies to control the rapidly growing wild boar population to develop effective management mechanisms that would slow down this process and prevent potential environmental threats and conflicts conditioned by the penetration of animals into urban ecosystems and agrocenoses (Vetter *et al*., 2020).

Today, the following options for managing the wild boar population are used:

1) recreational hunting, with a transition to targeting certain age groups (1-2 years), longer or year-round hunting periods;

2) culling and use of traps;

3) measures in the long term, namely reducing the capacity of the habitat, that is, restricting access to a food resource (stopping feeding animals and fencing fields, using electric fencing and other means to restrict access to crops) (Tack, 2018; Gortázar, 2019).

At the same time, the issue of artificial species control is quite controversial. On the one hand, some researchers suggest that for the structural and functional organisation of biocenoses, significant reduction or removal of *Sus scrofa* is harmful. This is conditioned by a violation of the balance in the predator-prey system, since the wild boar is an important element of the trophic chain, an ecosystem engineer, and is able to influence soil properties, soil processes, and the cycle of nutrients in the forest floor through digging activities. In addition, the species plays a sanitary role, especially valuable in reforestation. On the other hand, according to D.R. Risch *et al.* (2021) and Johann *et al.* (2020) the large distribution and high population density of wild boar poses a threat to rare species of flora and fauna. Thus, studies conducted in 54 countries revealed a threat to 672 taxa of vulnerable populations caused by the transformation of the wild boar habitat, including 345 plant species (out of 59 families), 123 representatives of herpetofauna (out of 25 families), 96 birds (out of 38 families), 84 invertebrates (out of 22 families), and 24 mammals (out of 11 families), including their natural habitats (Risch *et al*., 2021).

In natural conditions, the regulation of the number of species is provided by multiple types of regulating interspecific and intraspecific relationships. Biotic mechanisms of population regulation include functional and numerical responses (predator-prey regulation), outbreaks of infectious and parasitic diseases, and intraspecific competition.

In the case of the *Sus scrofa* population, environmental regulatory mechanisms are not of decisive importance and are temporary. This is associated with a whole range of factors, namely, the complete absence or an insignificant number of natural predators. In particular, in the predator-prey system, the main regulator of the wild boar population is the wolf *(Canis lupus)* (Tack, 2018).

C. Nores *et al.* (2008) proved that the wolf predator provides a key ecosystem service in forest ecosystems by influencing populations of *Sus scrofa*, and one wolf can kill about 50-80 wild boars a year. Studies conducted in Spain during 2000-2014 show a significant role of wolves in regulating the number of wild boars. In areas where wolves live, the population density increased from 1.65 to 2.55 individuals per km^2, while without them – from 1.2 to 3.6.

According to Resolution 6 of the Bern Convention on the Conservation of European Wildlife and Natural Habitats, the wolf is under strict protection. In the European habitat, the diet of wolves consists mainly of wild ungulates (wild boar, deer, roe deer) and agricultural animal species (goats and sheep). In some European regions (Italy, Spain), wild boar is the dominant prey of wolves and accounts for 3 to 31% of their diet, mainly piglets (up to 75%) (Nores *et al*., 2008). According to experts, wolf predation affects 4.5% of the wild boar population and reaches 12% in terms of causes of death (Nores *et al*., 2008; Petridou *et al*., 2019). Studies conducted in 2018-2021 in Belgium found that wild ungulates make up about 69 %, and wild boar — almost 23% of the wolf's diet (Van Der Veken *et al*., 2021). The restoration of the wolf population in Greece in 1980-1990 has led to an increase in their population and an expansion of their habitat. At the same time, easy access to livestock for grazing in agricultural landscapes and low population density of wild ungulates in natural biocenoses led to a substitution of up to 25% in the wolf's diet for domestic animals (Petridou *et al*., 2019).

Some researchers suggest that predation does not depend on the population density of wild boars, but is inversely related to the availability of alternative prey species and has a non-significant impact on the population of wild ungulates compared to factors such as low winter temperatures, availability of food resources, and hunting (Nores *et al*., 2008).

In a sense, in ecosystems with a low density of the species *Canis lupus,* the hunters took over the role of the predator. At the same time, interest in hunting in many countries decreases every year and often hunting licenses remain unused. For example, as of 2017 in Poland, the number of wild boars reached 228 thousand units with a constant growth trend. The expansion of the hunting license in the period from 1975 to 2015 and about 3 thousand animal units lost from ASF did not significantly affect the situation (Pejsak *et al*., 2018).

The ineffectiveness of the predator-prey system and hunting led to the start of epizootics as the next stage of the population regulation mechanism. As a rule, infectious diseases in wild animal populations occur when the victim population reaches such a high number that it goes beyond the influence of predators. In the case of *Sus scrofa*, a highly contagious viral disease, African swine fever (ASF), has manifested itself in European countries (Croft *et al*., 2020).

The body of wild boar is a source and carrier of a large number of pathogens of infectious and parasitic diseases (zoonotic, species-specific, and with a wide range of hosts). Among them: tuberculosis, trichinosis, African swine fever, and others that lead to significant economic losses.

African swine fever (ASF) or Montgomery's disease is a viral emergent infection of wild and domestic pigs included in List A of the World Organization for Animal Health (WOAH). Due to its rapid cross-border spread and high mortality rates among patients (mortality in 98-100% of cases), there is a real threat to human health, animal welfare, and food security (Agricultural Research Service, 2021). At the same time, despite proactive measures to control the population size of *Sus scrofa* in agroecosystems and ecosystems of mixed forests and the ASF epidemic, in some countries, the wild boar population does not stop increasing (Khwarahm *et al*., 2022).

ASF is a difficult process to control in the wild boar population. The measures used for mass depopulation, removal of wild boar carcasses, poisoning, and construction of fences turned out to be ineffective and unethical. The creation and development of predictive models of the spread of ASF showed that the determining prognostic risk factor in the models is the population size and the availability of a suitable environment for its habitat. At the same time, the population density in the transmission and spread of the disease is contradictory. The experience of the Czech Republic and Belgium in countering ASF shows the positive impact and reality of integrated efforts to eliminate ASF using individual approaches (Sauter-Louis *et al*., 2021).

Today, in the epidemiology of ASF, there are 4 models of the virus transmission mechanism: "wild boar-wild boar", "wild boar-environment", "corpse-wild boar", and "wild boar-argass ticks of genus Ornithodoros", which are independent, although inter-cyclical transmission of the disease periodically occurs. The prevalence of ASF in the population remains at the same level <5% with characteristic local persistence. In the Baltic states, the virus was recorded in about 85% of corpses, while in captured animals the proportion of detected cases of damage was low (up to 3%) (Chenais *et al*., 2018).

Penetration of any new type of pathogen or its strain into the biocenosis can affect not only the population itself, but also the trophic network, various types of coactions, and overall stability of the biocenosis, while compensating for mortality from the absence of predation (Voloshyn *et al*., 2022).

In Ukraine, studies of the dynamics of changes in the wild boar population are fragmentary. Data on the population size of wild animals are presented in the environmental passports of regions, which is an analytical collection on the state of the natural environment and its components, including the animal world, in particular, the retrospective dynamics of the number of the main species of hunting animals and their extraction (Voloshyn *et al*., 2022; Pavlenko, 2018).

The analysis of the dynamics of the number of wild boars in the hunting grounds of Ukraine and the volume of their withdrawal under the license for 2015-2020 is shown in Figure 1 (Ministry of Environmental Protection and Natural Resources of Ukraine, 2021).

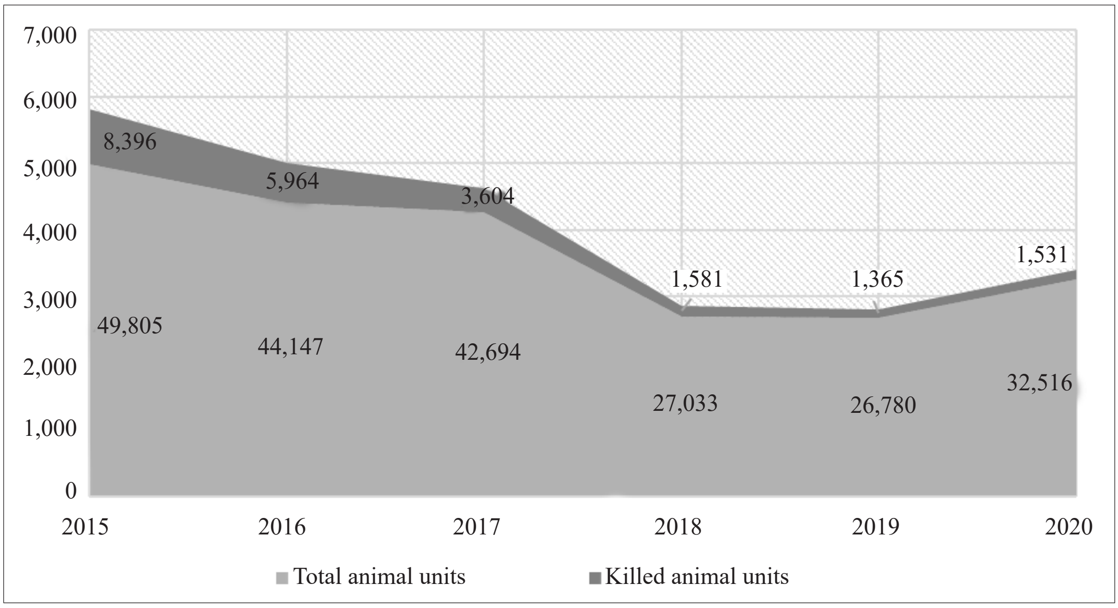


***Figure 1.** Dynamics of the number of wild boars in hunting grounds of Ukraine and the volume of withdrawal under the license for 2015-2020*

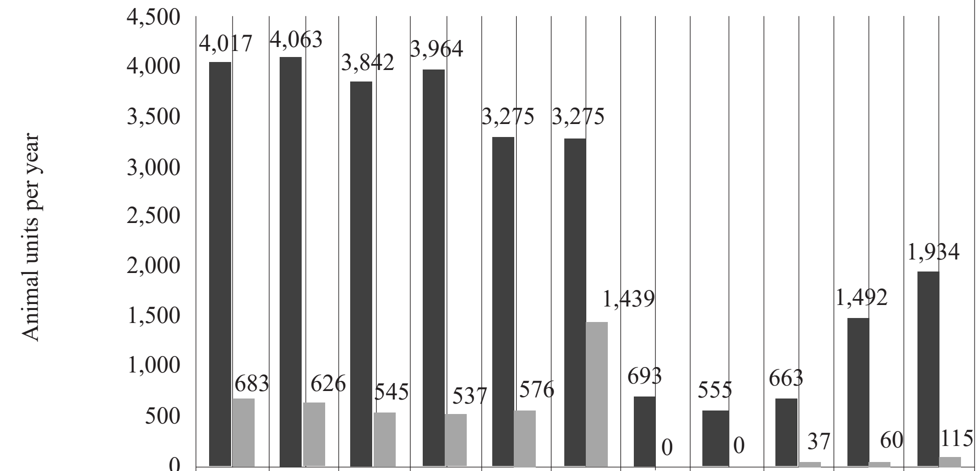
The decline in the population size by more than six times in the period from 2015 to 2019 is associated with the epizootic ASF in Ukraine (the first cases began to be registered in 2012).

The analysis of changes in the dynamics of the wild boar population on the example of Chernihivska oblast of Ukraine is presentable from the standpoint of optimal conditions for the existence of the population, since the forest fund of the region reaches 31,903.0 km^2, with a forest cover index of 20.9%. The area of forest plots is 708,063.7 hectares, of which almost 15% are under environmental protection. Chernihivska oblast accounts for 8.75% of the state's territory in terms of the total volume of nature reserves (7.86) and the number of territories and objects of the nature reserve fund (667). 2,733,224 hectares (more than 85%) are allocated for hunting and economic activities, where the main ungulates for hunting are deer, roe deer, and wild boar (Ministry of Environmental Protection and..., 2021).

According to A.V. Pavlenko (2018), trends in the population density of wild boar in Chernihivska oblast were +4.4%, with the volume of withdrawal in the range of 10-12%, which indicates the well-being of the population. The loss of livestock in the range of 46% occurred in 2014-2015 is conditioned by the occurrence of an epizootic of African swine fever in the region. At the same time, during the study period, 0.6-1.3% of the forest area of Chernihivska oblast was lost due to deforestation and forest fires, which led to a decrease in the forest cover indicator by 24.7% from the original value and had no negative consequences for the number and density of the wild boar population. The abrupt decline in the number of wild boar in hunting farms of Chernihivska oblast almost by five times in the period 2015-2017 coincides with the outbreak of ASF in the region, and trends toward population recovery in 2019 and 2020 are associated with the high biotic potential of the species (Pavlenko, 2018).

A favourable factor for population recovery of *Sus scrofa* in Chernihivska oblast is a large number of objects of the nature reserve fund and objects of the Emerald Network, of which there are 16 in the region. The presence of populations within these territories provides them with access to food and protection due to the European Environment Agency (n.d.).

At the same time, the dynamics of the wild boar population and the volume of withdrawal under the license in Chernihivska oblast (according to the Environmental passport of Chernihivska oblast for 2012-2020) (Fig. 2) show an abrupt decrease in the wild boar population almost five times in the period 2015-2017, which coincides with the outbreak of ASF in the region. 2019 and 2020 are marked by the same rapid trend toward population recovery, which is explained by the high biotic potential of the species (Chernihiv Regional State Administration, 2020).



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Total animal units	4017	4063	3842	3964	3275	3275	693	555	663	1492	1934
Killed animal units	683	626	545	537	576	1439	0	0	37	60	115

Figure 2. *Dynamics of the wild boar population in hunting farms of Chernihivska oblast*

According to A.V. Pavlenko, interspecific competition and predator-prey interactions in the faunal complex of Chernihivska oblast do not function, but there are unrelated changes in the population density of large mammals in the ecosystem. According to the findings, conservation activities to preserve in-situ biodiversity are environmentally effective for the wild boar population and allow it to recover quickly. In addition, a positive effect is manifested from ploughing land for corn (R_{emp}=0.824), oilseeds (R_{emp}=0.682) and sunflower (R_{emp}=0.760), which is a food resource for the species, and unfavourable – from ploughing agricultural land for cereals (R_{emp}=–0.664), fodder grasses (R_{emp}=–0.841) (Pavlenko, 2018).

The main factors influencing the static distribution and dynamics of wild boar population density in Chernihivska oblast are: demographic indicators (density and volume of withdrawal) and dominant external influences (concern factor due to deforestation and forest fires, agricultural activities) (Pavlenko, 2018).

In the absence of natural predators in the area, it is logical to manifest the mechanism of epizootic development in fast-growing animal populations. Thus, since 2012, the first isolated cases of the disease have been registered in Ukraine, and in 2014, out of 16 recorded cases, 12 were found in wild pigs (The official website of the African swine fever, 2021).

In total, 553 cases of ASF were registered in Ukraine from 2012 to 2022, 120 of them were wild pigs. Analysis of the dynamics of ASF epizootology development in Ukraine confirmed the existence of a direct link between ASF cases in different sectors of the economy. The presence of a correlation between the number of cases in private farms of the population and in the wild (R=0.8, P-value=0.045, R^2=0.6, n=7) indicates the synchronicity of a single infectious process and a decrease in cases of the disease in constant proportions on farms, private farms, and the population of wild pigs in the period 2017-2018 (Fig. 3) (The official website of the African swine fever, 2021).

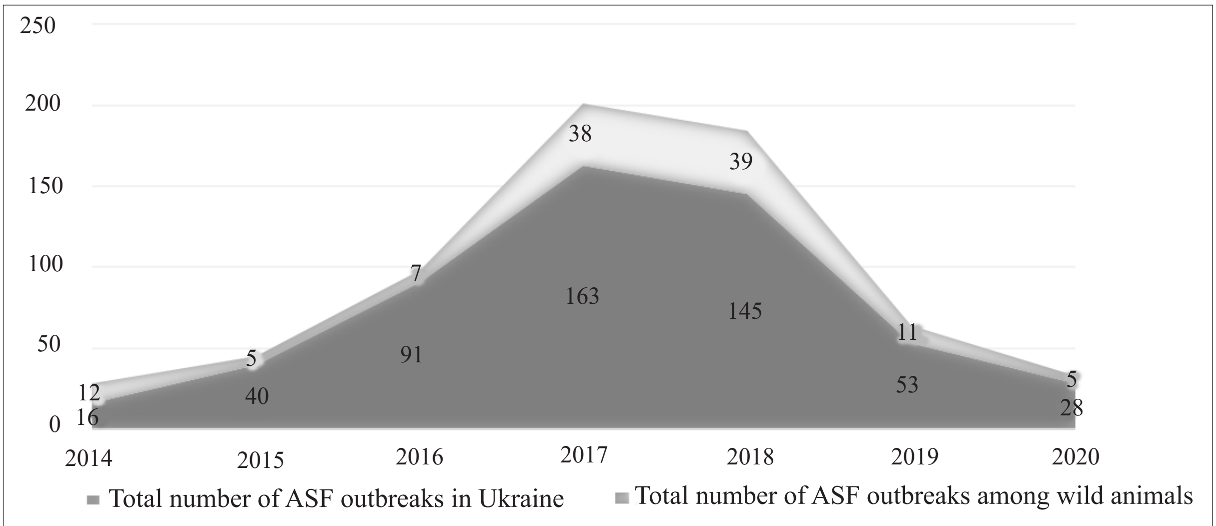


Figure 3. *Total number of ASF outbreaks in Ukraine and number of cases among wild animals in 2014-2020*

Cases of ASF outbreaks among wild boars were recorded mainly in regions with high forest cover and border areas (Fig. 4). 34 outbreaks of ASF were detected in Chernihivska oblast for the period from 2012-2021, 11 of them in wild animals (32%), the pathogen attack rate was 0.0015 among wild boars and 0.0028 in the region in general. Most ASF outbreaks were recorded in areas bordering Belarus (Fig. 5) (The official website of the African swine fever, 2021).

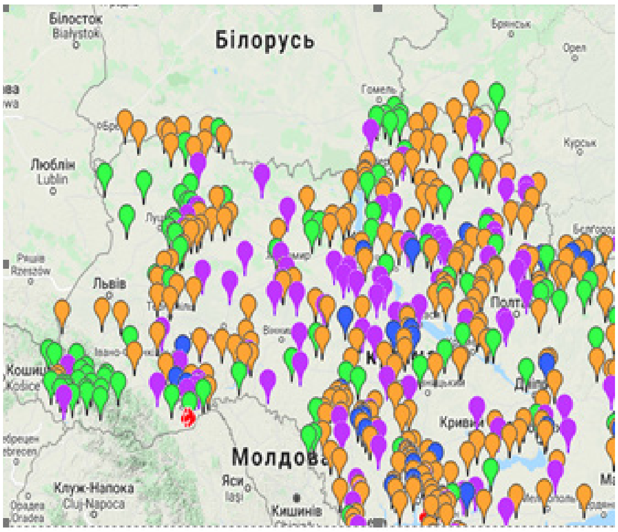


Figure 4*. Map of ASF outbreaks in Ukraine for the period from 2012-2021*

Note*: green – detected sick wild pigs; orange – in the private sector, lilac – at the enterprise*

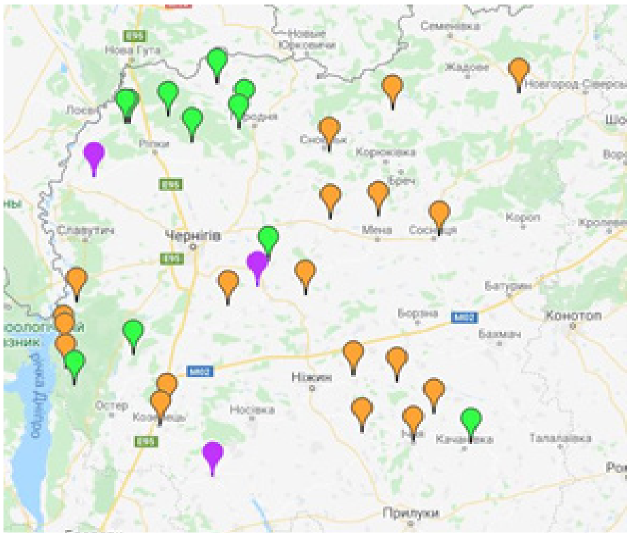


Figure 5*. Map of ASF outbreaks in Chernihivska oblast for the period from 2012-2021*

Note*: green – detected sick wild pigs; orange – in the private sector, lilac – at the enterprise*

In officially registered epizootic units of various types in the time spectrum in the period from 2014 to 2020, most cases of ASF were registered in 2017 (163 cases) and 2018 (145 cases). The risk assessment model with geographical visualisation of attack rates for wild pigs has an indicator of 83 %, with a high probability of the highest risk of ASF outbreaks in remote areas with low rural population densities. The areas marked on the map (Fig. 6) in red are areas with the maximum risk of ASF spread, which allows timely measures to be taken in hunting farms, namely: to raise awareness of hunters about biosafety when hunting, conduct diagnostic studies, and ensure an appropriate level of passive monitoring of the wild boar population.

OBLAST	Wild pigs
Zakarpatska	0.0114
Luhanska	0.0034
Rivnenska	0.0033
Odeska	0.0027
Kharkivska	0.0027
Volynska	0.0026
Ivano-Frankivska	0.0018
Mykolaivska	0.0018
Chernivetska	0.0015
Khersonska	0.0013
Sumska	0.0011
Khmelnytska	0.0011
Chernihivska	0.0011
Kyivska	0.0009
Vinnytska	0.0009
Zaporizka	0.0007
Cherkaska	0.0006
Dnipropetrovska	0.0005
Zhytomyrska	0.0004
AR Krym	0.0004
Kirovohradska	0.0004
Lvivska	0.0003
Poltavska	0.0001
Ternopilska	-0.0004
Donetska	-0.0004

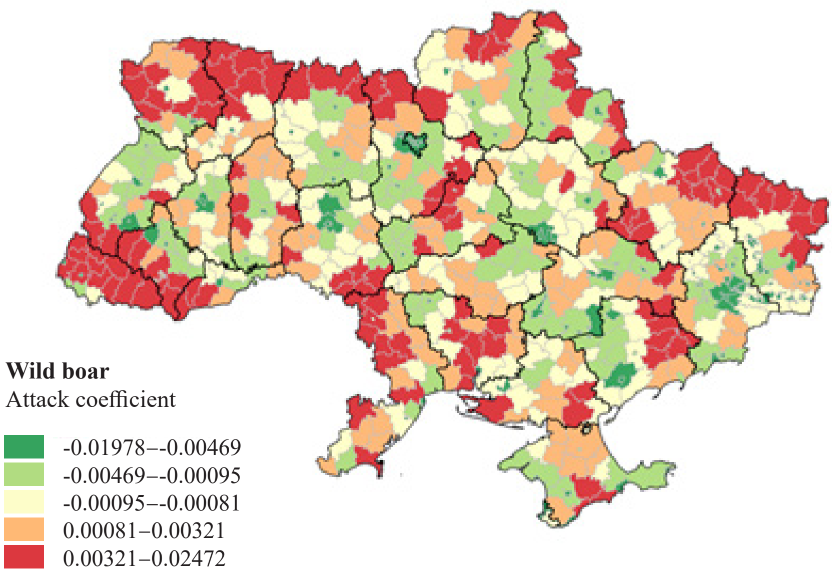


Figure 6*. Model for assessing the risk of ASF introduction in wild pig populations with an average annual attack rate (AR*100=% of localities where ASF can be detected per year)*

Note*: red – in the wild; orange – in the private sector, green – at the enterprise, blue – average*

Analysing the collected statistical data, it can be noted that the biotic mechanisms of regulation of the wild boar population on the example of Chernihivska oblast indicate a temporary effect of the ASF pathogen on the population of the species with a tendency to its rapid recovery. The manifestation of the effect of "unexpected increase in pathogenicity", complication of immune mechanisms, and synchronisation of behavioural programmes stimulate the development of adaptive processes in partners in the "parasite-host" system and reflect the acceleration of the rate of evolution in parasitic systems characteristic of transformed ecosystems, which is confirmed by the resumption of growth in the wild boar population in the conditions of Ukraine.

The lack of regulatory environmental mechanisms will lead to a transition to the next level in the future and will manifest itself in acute competition for available resources and the development of stressful manifestations in the population (aggressive behaviour, endocrine response of mammals, etc.).

The outbreak of hostilities throughout Ukraine since February 2022 has become an uncontrolled factor affecting ecosystems and populations of wild animals in particular. The experience gained on the dynamics of wild animal populations in the period 2014-2022 in the temporarily occupied territories of Ukraine in Donetska and Luhanska oblasts, in particular, in the National Nature Park "Sviati Hory", shows an increase in the number of wild boars and foxes, despite aerial shelling and explosions, flights of air transport. Mass migration of the species was not recorded. This was facilitated, according to the researchers, by the reduction of anthropogenic impact after the end of the intensive phase of hostilities, the restriction of hunting and forestry activities (Ukrainian Helsinki Human Rights Union, 2017).

As of 04/01/2022, due to military operations, 1/3 of the nature reserve fund of Ukraine is in danger, which includes 900 territories and almost 200 territories of objects of the Emerald Network (Ministry of Environmental Protection and Natural Resources of Ukraine, 2020). Chernihivska oblast was at the epicentre of active military operations. In particular, in forest ecosystems, through forest fires and active hostilities, irreparable damage to valuable natural objects and natural monuments is already registered, including the destruction of natural dwellings, rare and endangered plant and animal species, a decrease in biological diversity, loss of biological stability of forests, an increase in damage to stands by stem pests. In the forests of the region, wild animals were "in the line of fire", and a large number of detonated missiles and unexploded ordnance pose a potential threat to people and animals (Ministry of Environmental Protection…, 2022).

Part of the wild boar population is likely to be destroyed, while the other is forced to temporarily migrate to safer territories due to the alarm factor from explosions, artillery attacks and bombardments, forest fires, loss of habitat, formation of belligerent landscapes, expansion of areas unsuitable for the habitation of the species. Restoring ecosystems, returning populations, and keeping records of wild animals in such areas will be difficult over a long period of time.

An effective tool for restoring unique natural objects and biodiversity in the natural ecosystems of the state is the creation of a unified state environmental monitoring system for monitoring at 4 levels – from national to object. The Draft Law of Ukraine "On Amendments to Certain Legislative Acts of Ukraine Concerning the State Environmental Monitoring System" was approved on 04/28/2022 (2022).

CONCLUSIONS

The rapid increase in the wild boar population in many countries is of concern for several reasons: first, damage to livestock and crop production and urbanised landscapes; second, the spread of African swine fever and other zoonotic diseases. Retrospective analysis of population dynamics of *Sus scrofa* in Ukraine, in particular, in Chernihivska oblast, allows the study to establish classical mechanisms of biotic regulation of the population size of the species and the influence of concomitant factors associated with anthropogenic activities. The rapid decrease in the population size in Chernihivska oblast in the period from 2015-2017 is associated with a temporary manifestation of the effect due to the mechanism of population regulation in the absence of predators on the considered territory and the manifestation of species-specific zoonotic infection – African swine fever. At the same time, the influence of regulatory mechanisms tends to coadaptation in the "parasite-host" system and move on to the next stage – aggravation of intraspecific competition, which is confirmed by this study and the recovery of the wild boar population is noted.

Investigation of natural mechanisms for controlling the dynamics of the wild boar population and the causal relationships of the epizootic process in the natural and climatic conditions of Ukraine requires a thorough scientific search based on a systematic approach to preserve the structure and function of natural biocenoses and biological diversity in the future.

During the preparation of the material, the war on the territory of Ukraine and active hostilities in the Chernihivska oblast began. The consequences of military operations for wild animals in the coming years will be unpredictable, which encourages the author to investigate the above issue in unpredictable conditions.

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Екологічні механізми регуляції чисельності популяції *Sus scrofa* в сучасних умовах

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Анотація. Популяція дикого кабана виду (*Sus scrofa*) збільшується стрімкими темпами в більшості країн світу упродовж останніх десятиліть. Інвазивний вид володіє високими показниками відтворення та добре розвиненими адаптивними реакціями, що дозволяє йому успішно розширювати межі свого ареалу, створювати значні економічні збитки сільському і садовому господарствам, урбоекосистемам, загрожує втраті біологічного різноманіття та поширенню зоонозних інфекцій. Метою статті було проаналізувати чинники, які сприяють експансії виду *Sus scrofa* у світі, визначити екологічні механізми регуляції чисельності популяції на фоні стрімкої антропогенної трансформації середовища існування та глобальних кліматичних аномалій; оцінити зміни динаміки чисельності популяції в мисливських господарствах України за період з 2010 по 2020 роки і Чернігівської області, зокрема. Застосовували традиційні методи ретроспективного аналізу, синтезу, екологічних, загально-біологічних, епізоотичних методів дослідження. Проаналізовано світовий досвід та визначено основні чинники низької ефективності стратегій контролю за швидко зростаючою популяцією кабана дикого в агроекосистемах, екосистемах мішаних лісів та урбоекосистемах. За рахунок унікальних особливостей формування життєвої стратегії вид *Sus scrofa* демонструє успішний розвиток, розширення ареалу та спектру доступних харчових ресурсів, ефективне використання добової диверсифікації екологічних ніш в умовах трансформованих екосистем тощо. Встановлено, що причиною неефективності екологічних механізмів тиску на популяцію виду в системі «хижак-жертва» є відсутність великих хижаків в лісових екосистемах Чернігівської області. Водночас, відсутність стримуючих механізмів в системі «хижак-жертва» забезпечило маніфестацію механізмів наступного рівня, а саме формування осередків африканської чуми свиней за лісовим циклом в природних біоценозах регіону. Реакція-відповідь популяцій проявилася стрімким короткочасним зниженням чисельності популяції *Sus scrofa*, як тимчасовий стримуючий ефект з наступною тенденцією до відновлення.Отримані результати можуть бути використані у розробці практичних рекомендацій щодо біологічного моніторингу, екологічного контролю та розробки ефективних заходів менеджменту лісового господарства щодо запобігання біологічній безпеці, пов'язаній з неконтрольованим поширенням виду *Sus scrofa* та африканської чуми свиней на основі універсальних екологічних механізмів регуляції чисельності популяції

Ключові слова: інвазивний вид, ареал, африканська чума свиней, епізоотія, біотичні механізми регуляції

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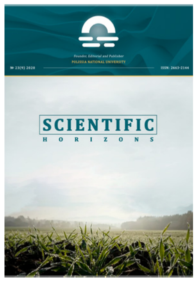

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Operationalizing the Sustainable Fertilizer Management Global Initiative at National Level: A Conceptual Framework

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Abstract. Humanity is tasked with finding a balance between the need to increase the amount of food and the negative socio-environmental and economic consequences of the irrational use of fertilisers. At the global level, a number of initiatives have been launched to consolidate countries' efforts to address this problem. However, existing national fertiliser management systems and policies are characterised by insufficient consistency and low efficiency. This study aims to formulate a conceptual framework for developing a national sustainable fertiliser management system that meets the principles set out in existing global initiatives. Through the generalisation of the content of existing intergovernmental initiatives on sustainable fertiliser management, the subject composition was formulated, and estimates of the relationship between fertiliser application and public health (through the number of cancer diseases) through the use of regression analysis methods, assessment of economic damage from irrational fertilisation served as a substantiation (illustration of the importance of highlighting) of components covering: awareness, knowledge, tools. The national sustainable fertiliser management system is considered three-dimensional integrity containing the following interrelated components: government, fertiliser production and supply industries, and users. The functioning of this system is seen as a continuous process of raising awareness, generating and transferring knowledge, selecting and applying appropriate tools, and improving fertiliser application practices in accordance with the principles of sustainable development, with the leading role of government. The process of raising awareness of all actors of the system about the problem of irrational fertilisation is proposed to be considered in a broader context – through the demonstration of negative consequences not only for the environment (soil condition), but also from the standpoint of the impact on public health and related consequences – through the assessment of economic damage caused by pollution and consumption of food containing harmful substances. The main principles of interaction of subjects in this system should be the following: professionalism, transparency, information support, etc. Special attention should be paid to the formulation of a set of strategic goals that would lay the foundation for the development of control and evaluation procedures, a system for monitoring and reviewing mechanisms for economic incentives for fertiliser use, considering the social and environmental aspects of fertiliser use

Keywords: sustainable fertiliser management, national fertiliser policy, awareness, knowledge transfer, safe fertiliser, food security

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INTRODUCTION

Food security — provision of the physical and economic availability of food for present and future generations — is the biggest challenge of modern development. Due to the need to increase food production, the intensification of agriculture seems to be the only way to achieve food security goals, with the use of fertilisers as an integral part. According to some estimates, the expected population growth in the coming decades will increase the burden on agricultural production by 50-80%, which will lead to an increase in the sector's dependence on fertiliser use (Yang *et al*., 2017). Intensive agricultural practices, which allow increasing or reducing the cost of food production, simultaneously threaten the balance of agroecological systems (Pandey & Diwan, 2018) and lead to increased pollution of agricultural resources, a decrease in the quality of agricultural products and food. Thus, soil health and sustainable fertiliser management should be an important part of the investigation of environmental aspects of food security (Kolesnyk *et al*., 2018; Ramankutty *et al*., 2018). The most difficult part is finding a compromise between producing enough food at affordable prices through fertiliser application and the associated negative impact of agriculture on the environment, ecosystems, and public health. The global fertiliser management initiative, launched in recent years, is a way to address this problem.

The purpose of the study is to define the main conceptual components and principles of forming a comprehensive system for ensuring sustainable fertiliser management at the national level.

LITERATURE REVIEW

Despite the fact that the problems of soil fertility as a component of achieving food security, the problems of the impact of anthropogenic activities (agricultural production) on the components of the environment and the state of soils are not new, these issues have recently remained behind the scenes of global actions towards achieving the goals of sustainable human development. A number of global initiatives have been launched only since 2016, aimed at drawing public attention to the problems of soil health, nutrients, and fertilisers. Thus, in September 2016, at the 25th session of the Committee on Agriculture (COAG), a call was made to the Food and Agriculture Organisation of the United Nations (FAO) regarding the need for more intensive action toward ensuring food safety, in particular, in terms of the safe use of fertilisers and pesticides (FAO, 2016). Within the framework of the Global Soil Partnership (GSP) initiative, voluntary Guidelines for Sustainable Soil Management were presented together with the FAO, aimed at addressing the problems of nutrient imbalances and soil pollution caused, among other things, by unstable fertilisation (excessive, insufficient, or polluting). (FAO, 2017). The result of a long multilateral process of discussion and agreement, the search for compromise solutions on the issues raised in these documents was the release of an International Code of Conduct for the Sustainable Use and Management of Fertilisers (FAO, 2019), containing a set of voluntary standards for government, industry, researchers, users, and other stakeholders in the use and management of fertilisers, the implementation of which should ensure sustainable agricultural production and food security in terms of nutrient management (FAO, 2019). Ultimately, under the auspices of the United Nations in 2019, Sri Lanka approved the Colombo Declaration, which sets the task for the signatories to develop a Roadmap for Action on Sustainable Nitrogen Management 2020-2022, considering it as one of the mechanisms of interconnection and coordination for better and more sustainable nitrogen management (Colombo Declaration on Sustainable Nitrogen Management, 2019). The focus on nitrogen emissions, to a certain extent, is a consequence of active global actions in the context of climate change, but similar initiatives are also being developed for sustainable management of phosphorus (Brownlie *et al*., 2021; Garske & Ekardt, 2021) and other nutrients. In the summary of the contents of the UN Declaration and Initiative on International Nitrogen Management System (INMS), the task set is to halve nitrogen emissions (Sutton *et al*., 2019; UNEP, 2019) — is, first of all, critical from the standpoint of countering climate change, ensuring food security, and ecosystem health (Pandey & Diwan, 2017; Yin *et al*., 2020). And secondly, it can only be solved within the framework of a comprehensive system of actions for sustainable management of nutrients and fertilisers in general, because the efficiency of using one element is inseparable from managing a complex of nutrients.

Thus, a certain conceptual framework has now been formed at the global level and a global discussion and joint actions have been initiated to address the problems associated with soil pollution, and one of the reasons for this is the use of fertilisers. At the same time, mechanisms for operationalising these global decisions at the national (and, accordingly, regional and local) levels need to be developed.

Commenting on the content of the Code (FAO, 2019) and Declarations (Colombo Declaration on Sustainable Nitrogen Management, 2019) the Code establishes the complexity and multi-level system of sustainable fertiliser management, the need to involve various groups of stakeholders in this process, among which government structures play a decisive role. A comprehensive system of sustainable fertiliser management should contain various functional components: assessment, analysis, justification, knowledge, information, timely monitoring and control, support for implementation, etc. (FAO, 2019). Proper management and use of fertilisers should cover operations at all levels of the value chain: responsible production, storage, transportation, use to improve plant growth or other parameters while maintaining or improving the health of fertilisers and minimising negative environmental impact (FAO, 2019). The code of conduct covers the following areas: soil fertility and plant nutrition; fertiliser use and management; nutrient reuse and recycling; composition, restriction, and testing; access, distribution and labelling; information, consultation, and dissemination of information on sustainable fertiliser management; implementation of the code (all governments, supported by FAO and other organisations, are expected to be involved in this process to the fullest extent possible, although this code is also voluntary). And in all areas, the role of the government component is the most significant, consisting mainly in the development of policies that promote sustainable fertiliser management (FAO, 2019).

According to the approved Declaration (Colombo Declaration on Sustainable Nitrogen Management, 2019), governments are called upon, as far as possible: to develop and implement appropriate policies for sustainable nitrogen management; to develop roadmaps in accordance with these policies to halve nitrogen emissions by 2030; to assess the quantitative and qualitative apsects of nitrogen management policies and conditions; to encourage innovation for nitrogen reuse in accordance with the principles of the circular economy; to encourage populations and best practices for better nitrogen management; to develop partnerships and report on progress in this area (Colombo Declaration on Sustainable Nitrogen Management, 2019).

Many technological solutions have already been developed to improve fertiliser management practices and enhance fertiliser efficiency (Srinivasarao, 2021), which cover, in particular: the use of organic substances and biofertilisers, the combination of chemical fertilisers with organic ones, crop rotation, waste management, various ploughing practices (tillage) (Naher *et al.*, 2019; Young *et al.*, 2021) and even digital technology support solutions (Golicz *et al.*, 2021; Hou *et al.*, 2020). At the same time, the level of implementation of these technologies is insufficient (Melnyk *et al.*, 2021) and it does not solve the problem of soil health errors, which is global in nature. The reason for this is the difficulty of finding solutions that would ensure a balance of individual economic interests of commodity producers with the interests of society and illustrate the need and advantages of such a balance.

Noting the growing global focus on sustainable nutrient and fertiliser management as its component (Baritz *et al.*, 2018; Brownlie *et al.*, 2021), researchers point out, at the same time, the problem of transforming global solutions and attracting attention at the level of national politicians, and therefore users (Baritz *et al.*, 2018), lack of nationally adapted solutions, unsystematic and, as a result, low effectiveness of national policies in this area, even in developed countries, in particular, in the EU (Garske *et al.*, 2020; Helming *et al.*, 2018), Canada (Kröbel *et al.*, 2021), etc. An explanation for this may be the lack of information on the effects of fertiliser use in terms of human health and economic losses, in particular, relevant national estimates. Thus, many results of assessments of the negative effects of fertiliser use are currently available. For example, it is known and documented that nitrogen fertilisers cause the formation of "dead zones" in the Midwest of the United States, bring about EUR 70-320 billion annually in economic losses in Europe, cause environmental problems in China and India (Pandey & Diwan, 2017), and is one of the reasons of cancer diseases (Yin *et al.*, 2020). Researchers assess the state of agricultural production and environmental consequences and try to form an integrated framework for assessing the risk of food hazard and agroecological risk use indicators: the state of the food system (crops grown), losses due to natural hazards; the ratio of supply/demand mismatch and the associated risk of food hazard, the index of environmental load on water resources and the associated agroecological risk (Qi *et al.*, 2018). And if the results of assessments of the impact of fertiliser use on soils are regularly published and make society talk more and more about soil health, then the study on the impact of fertilisers on public health began in the mid-1930s and peaked in the 1970s and 1980s (Senesil *et al.*, 1999). The main subject of attention was the connection between the practices of fertiliser use and the spread of cancer (Senesil *et al.*, 1999), but now the impact of agriculture on public health is being considered in relation to the use of pesticides (Bonner & Alavanja, 2017; Budzinski & Couderchet, 2018; Iriti & Vitalini, 2020), although, the existing strict rules allow mitigating the relevant risks (Iriti & Vitalini, 2020). Since the 1990s, research on the health effects of fertilisers has been declining, mainly due to a shift in research funding priorities towards climate change (Senesil *et al.*, 1999). It is equally important that negative environmental consequences should be transformed into clear economic indicators, but today such studies are not enough. For example, Yang *et al.* (Yang *et al.*, 2017) found that in China, health care costs caused by fertilisation account for about 0.5% of agricultural output, and interregional fluctuations in the deterioration of health caused by fertilisation also affect the assessment of economic losses (Yang *et al.*, 2017).

China's experience in implementing a strategy to maximise the yield of agricultural products while reducing the use of fertilisers is quite successful. The corresponding policy was established in 2004 through a number of political innovations, which, among other things, contributed to the implementation of innovative technologies in production. The components of China's success in this area are: legislative regulation of the need for soil testing and the development of recommendations for fertilisation based on the results of analysis within the framework of the soil testing and fertiliser recommendations STFR initiative and Zero Increase Action Plan (This facilitates a 50% reduction in nitrogen and phosphorus use and 100% nutrient efficiency, without reducing yields (Jiao *et al.*, 2018) and already in 2019, all provinces reported on the achieved zero level of increase in the amount of fertilisers (Yu *et al.*, 2020); development and implementation of a package of flexible economic tools (depending on the socio-economic conditions of the region) that encourage producers to analyse soils, introduce recommendations for fertilisers, use organic substances to increase soil fertility; ensure the coordinated work of all components of the fertiliser management chain; support for scientific developments and their distribution (Jiao *et al.*, 2018).

In particular, to solve the problem of knowledge transfer, a network of advisory structures Science and Technology Backyards (STB) was created in 2009 in different ecological zones, which "brought together" science and practitioners, and the result of its work was an increase in technology implementation by 80%, an increase in yields by 20%, and a reduction in environmental costs by 20% (Jiao *et al.*, 2018). At the same time, the problem of raising awareness and transferring knowledge in the field of sustainable fertiliser management still remains one of the most urgent and not fully solved (Jiao *et al.*, 2018; Yu *et al.*, 2020).

Existing studies on the construction and development of national incentive systems for sustainable fertiliser management focuses mainly on a separate component (tools) of such a system, in particular: impact assessments (Helming *et al.*, 2018) as a means of raising awareness and meeting the goals of society; assessing the state of soils and developing appropriate indicators that can serve as a basis for informing (Hou *et al.*, 2020; Tingyu *et al.*, 2020) and decision making (Kik *et al.*, 2021); identifying participants and developing targeted strategies (Kanter *et al.*, 2020); consulting and knowledge dissemination practices (Baritz *et al.*, 2018; Hou *et al.*, 2020) economic instruments (quotas and trade in emissions of substances – Cap-and-trade schemes; subsidies; taxation of the content of pollutants in fertilisers) (Garske & Ekardt, 2021; Scholz & Geissler, 2018); regulation of the size of animal husbandry (Garske & Ekardt, 2021) development of methodology and rationing (limiting) the amount of fertilisers applied for each zone, taking into account natural and climatic factors (Jiang *et al.*, 2020; Lemaire *et al.*, 2021; Wang *et al.*, 2019); development and use of programmes to support solutions in the field of fertiliser use (Villalobos *et al.*, 2020). Special attention is paid to the mechanisms of knowledge dissemination, consulting (Mills e al., 2020; Pan & Zhang, 2018), and investigation of factors that influence individual decisions on the use and management of fertilisers (Andan *et al.*, 2019; Hu *et al.*, 2019; Rahman & Zhang, 2018).

The available findings reveal certain aspects of building a comprehensive system for stimulating sustainable fertiliser management practices at the national (and sub-national) level, but there is still an urgent need to develop more systematic integrated government concepts that would eliminate the transition of the problem from one area to another and provide optimal solutions at the system-wide level (Garske & Ekardt, 2021; Garske *et al.*, 2020), based on a clear understanding of the problem, and above all, through an understanding of the consequences of irrational use of fertilisers.

MATERIALS AND METHODS

Highlighting the main participants in the national system of sustainable fertiliser management and the investigation of the content of relationships between them was carried out through the analysis and generalisation of the provisions of international and intergovernmental initiatives in the field of sustainable fertiliser management. To substantiate the component components of the fertiliser management system and their content, the relationship between fertiliser application levels and public health (cancer incidence) was evaluated using regression analysis methods. The study was carried out using the built-in functions of the MS Office Excel software suite. The data from the state statistics service of Ukraine (collections "Health care institutions and morbidity of the population of Ukraine" and "Application of mineral and organic fertilisers for crops") for 2010-2020 was used to build a regression model based on average data for Ukraine.

In the model used, the number of oncological diseases registered in medical institutions at the end of the year per 100 thousand population cases is selected as a dependent variable (y); as a regressor (X) – the amount of mineral fertilisers in nutrients in kg per 1 ha of sown area, kg/ha.

To investigate the spatial variations in fertiliser exposure and cancer incidence, administrative districts are grouped by natural and geographical zones. Thus, the Polissya zone includes Volynska, Zhytomyrska, Rivnenska, Chernihivska oblasts; forest-steppe – Kyivska, Vinnytska, Poltavska, Sumska, Ternopilska, Khmelnytska, Kharkivska, Cherkaska oblasts; steppe – Dnipropetrovska, Zaporizka, Kirovohradska, Mykolaivska, Odeska, and Khersonska oblasts; the Carpathian Mountain zone includes Zakarpatska, Ivano-Frankivska, Lvivska, and Chernivetska oblasts. Donetska and Luhanska oblasts were not analysed due to incomplete information caused by the military conflict.

To illustrate the economic impact of fertilisation practices, economic health losses from consumption of contaminated food for 2020 for different natural and geographical zones were estimated, according to regional estimates of average annual environmental damage from pollution (air, water resources) for 2001-2009 (Sotnyk & Kulyk, 2014; Sotnyk & Kyrychok, 2012) and data on the structure of environmental damage (Karintseva, 2018; Rsarenko *et al.*,2002).

RESULTS AND DISCUSSION

Summarising the provisions of the Code of conduct in the field of sustainable fertiliser management (FAO, 2019), and the results of a previous study, the national system for ensuring sustainable fertiliser management can be presented as integrity formed by three basic components: the government; the industry for developing, manufacturing, testing, and bringing fertilisers to the end-user (including research organisations, institutes, and universities); fertiliser users. At the same time, providing sustainable use and management of fertilisers is also the result: awareness of the existing problem, generation and accumulation of knowledge about possible ways to solve it, and development and implementation of specific tools at each level of decision-making (within each system and structural component) (Fig. 1).

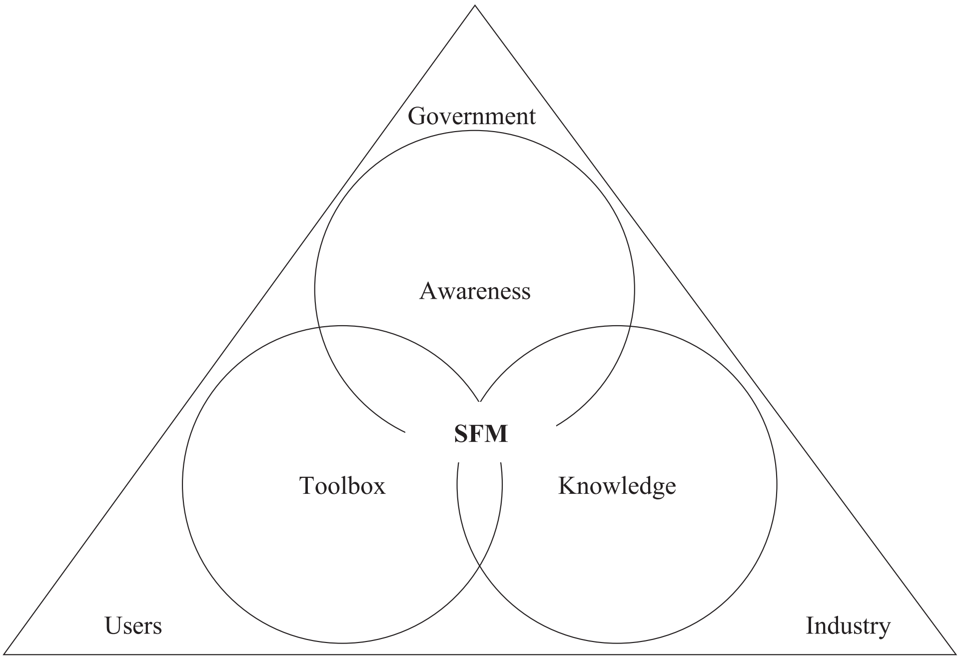

***Figure 1**. National sustainable fertiliser management (SFM) system view: actors & component dimension*

Representatives of the industry, including individual economic agents – producers of agricultural products – act (make decisions) in accordance with their own economic interests, based on existing socio-economic and production conditions, resource opportunities and restrictions, and considering their own psychological attitudes. These are the main factors influencing decision-making (Pandey & Diwan, 2021), which are the embodiment of the components of the problem, respectively: knowledge, tools, and awareness. Consequently, the role of the government is crucial and consists in coordinating the economic interests of producers (the fertiliser industry and food producers) and society, forming a link between these interests and providing feedback (Helming *et al*., 2018). And the main component here should be ensuring awareness of the problem.

The problem that leads to the need to review fertiliser practices is that fertiliser application is perceived as a means of improving the productivity of agricultural enterprises in all conditions, and the negative consequences are largely overshadowed by fluctuating weather conditions and the associated risks to agricultural production (Pandey & Diwan, 2018).

Fertilisation, for the most part, appears as a means of obtaining short-term economic results against the background of limited resources, and the lack of direct manifestation of negative social and environmental consequences in the short term leads to neglect of them. An illustration of this, for example, is the results of study (Zand *et al*., 2020), which established that the impact of fertilisation on the sustainable development of rural areas is considered in the context of mainly economic and managerial components (protection of grain, income, reduction of production risk), and social criteria, such as protection and support of normal health of the population, were only on the 11th position out of 12 (Zand *et al*., 2020). Therefore, an urgent problem for the government is the transformation of long-term, socio-ecological and economic consequences of various practices of fertiliser use and management into understandable and acceptable categories for producers and industry, which are already important today – in the short term. Such a demonstration of backward impact, in addition to assessing the effects of anthropogenic activities on environmental components, may be more useful in terms of increasing public awareness of the problem of unsustainable fertiliser use. Actually, this approach is the basis of the concept of promoting the importance of Biodiversity Mainstreaming, where against the background of assessments of the impact of anthropogenic activities on the state of biodiversity and ecosystems, the consequences of the impact of disturbed ecosystems on the economic and social aspects of business development, industries, local population and society as a whole are also subject to study, control, and documentation (OECD, 2018).

Illustrating the dangers of irrational fertilisation through assessing the relationship between fertiliser application and cancer morbidity can best serve the purpose of raising awareness of the problem for other stakeholders, as shown by previous studies (Senesil *et al*., 1999).

Using statistical data in Ukraine for 2000-2019, a linear regression model of the relationship between the level of cancer incidence per 100 thousand population and the amount of mineral fertilisers in nutrients per 1 ha of sown area in Ukraine was constructed. Figure 2 shows a graphical representation of the results of correlation and regression analysis.

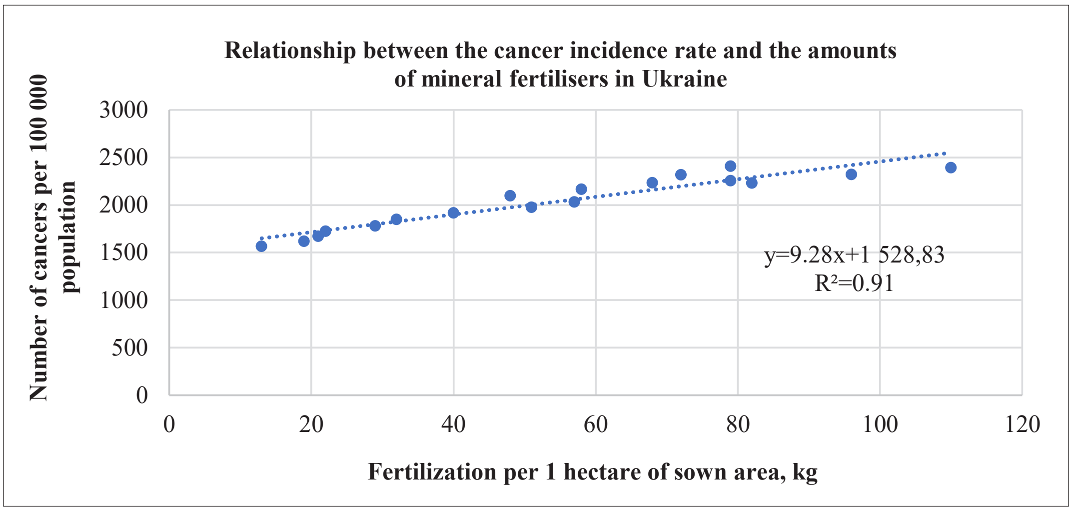

***Figure 2**. Relationship between cancer incidence rate and the amount of mineral fertilisers in Ukraine*
***Source**: compiled based on Ukrainian Statistics Service (n.d.)*

A linear regression model of the dependence of the analysed variables has the form (1):

$$y=9{,}2829x+1528{,}8 \tag{1}$$

The presented dependence indicates that with an increase in the volume of mineral fertiliser application by 1 kg, the number of cancer patients will increase by 9.29 people. Conversely, if the volume of mineral fertiliser application is reduced by 1 kg, the number of cancer patients will decrease by 9.28 people.

It is worth noting that the amount of mineral fertilisers depends on the type of soil, which determines fertility, humidity levels, humus and other nutrients, soil compaction levels, and many others. Different natural and geographical zones have their own soil types. Thus, the least fertile soils are located in the natural and geographical zones of Polissya. To assess environmental and economic losses from increased morbidity due to the chemicalisation of agriculture in the regional context, the relationship between the level of cancer incidence and the amount of mineral fertilisers by natural and climatic zones was analysed (Table 1).

***Table 1**. Generalised results of the analysis for the natural and climatic zones of Ukraine for the period 2010-2019*

Indicators	Polissya	Forest-steppe	Steppe	Carpathian Mountain zone
Average volume of mineral fertiliser application, kg/ha	107.25	99.61	57.94	111.88
Average cancer incidence per 100 thousand people	2,084.21	2,496.26	2,567.17	1,913.53
Regression coefficient	6.0825	11.962	9.1718	11.047
Determination coefficient	0.8383	0.9079	0.7111	0.8689

***Source**: compiled based on Ukrainian Statistics Service (n.d.)*

Such information, distributed among society, provides a broader understanding of the content and scale of the problem associated with irrational fertilisation practices. Analysis of the relationship between the amount of fertilisers applied and population health indicators, in addition to assessments of the state of soils, ecosystems, and biodiversity, forms not only a basis for informing society, but also a "knowledge" of the state of the problem, which can serve as a basis for developing regulatory tools.

The results of a quantitative assessment of the dependence of the level of cancer incidence on the amount of mineral fertilisers applied in the context of natural and climatic zones of Ukraine are of methodological and practical importance, since they form an information and analytical database for determining natural indicators of ecological and economic losses and/or the effects of increasing/decreasing population morbidity for further use in mechanisms to promote and support sustainable fertiliser management at the regional level.

Another aspect that requires more attention is the assessment of the specific economic consequences of irrational practices in the use and application of fertilisers within a particular territory (at the national, regional, and local levels). It is worth noting that now there are only approximate estimates of the economic damage to public health from the consumption of contaminated food, and there are few such studies. In studies of the late 20th – early 21st century (Shcherban, 2004; Tsarenko, 1998), economic losses from the consumption of contaminated food products in Ukraine were estimated in the range of USD 2,100-13,700 million. Considering the previous findings, based on the data of the average annual comprehensive assessment of environmental damage caused by environmental pollution (air, water resources) in the context of regions for 2001-2009 (Sotnyk & Kerychok, 2012) and data on the typical structure of environmental losses (Karintseva, 2018; Starenko *et al*., 2002), this study provides an approximate assessment of the harm to public health from the consumption of contaminated food in natural and geographical areas (Table 2), which is largely associated with the irrational use of fertilisers.

Table 2. *Environmental and economic damage caused by environmental and food pollution, 2020**

Oblast/zone	Pollution damage	
	Environment	**Food products**
	Polissya	
Volynska	501.2	410.1
Zhytomyrska	918.9	751.8
Rivnenska	808.8	661.8
Chernihivska	829.2	678.5
	Forest-steppe	
Kyivska	1,250.2	1,023.0
Kyiv city	764.5	625.5
Vinnytska	673.2	550.8
Poltavska	649.0	531.0
Sumska	629.4	515.0
Kharkivska	901.3	737.4
Ternopilska	195.7	160.1
Khmelnytska	440.2	360.2
Cherkaska	475.0	388.6
	Steppe	
Dnipropetrovska	3,620.4	2,962.2
Donetska	4,936.5	4,039.0
Luhanska	1,700.7	1,391.5
Zaporizka	1,331.7	1,089.6
Kirovohradska	333.3	272.7
Mykolayivska	296.5	242.6
Odeska	808.7	661.7
Khersonska	414.8	339.4
	Carpathian Mountain zone	
Lvivska	1,004.9	822.2
Ivano-Frankivska	934.9	765.0
Chernivetska	376.7	308.2
Zakarpatska	514.7	421.1
Total	25,337.4	20,709.0

Note: ** – in terms of the USD at the average annual exchange rate as of 2020*
Source: *calculated by the author based on Karintseva (2018), Sotnuk & Kulyk (2014), Sotnyk & Kyrychok (2012), Tsarenko (1998)*

The methodology for assessing the total environmental and economic harm to public health (environmental and economic risk) has not yet been fully developed. Therefore, this determines a high level of approximation of such estimates. However, such assessments allow measuring the extent of environmental, economic, and social risks in a regional context and in accordance with natural and geographical zones, and thus make adequate and optimal management decisions for sustainable fertiliser management.

The results of the assessment of economic losses conditioned by irrational fertilisation are quite impressive. In fact, in the context of the country, they make up about 16.3% (if GDP is about USD 155.6 billion (for ecology) and 13.3% (for food) of Ukraine'S GDP) (Ministry of Finance of Ukraine, 2020). Thus, such data demonstrate the threat of irrational fertilisation at the national and regional levels. Therefore, one way to raise public awareness about poor fertilisation practice is to conduct regular studies on the impact of fertilisation and management practices on public health; assess the economic damage caused by pollution of food consumption and disseminate the findings to the general public. As noted above, such data, on the other hand, form a "knowledge component" for the government, providing information about the state of development of the problem to choose tools for solving it.

The success of the national system for ensuring sustainable fertiliser management depends entirely on the relations and interaction between its subjects. Partnership, cooperation, and joint decision-making are the main components of effective and effective government-industry-user relations in this area (Colombo Declaration on Sustainable Nitrogen Management, 2019; FAO, 2019). The basic principles that should form the basis of the system of interaction of agents in ensuring sustainable fertiliser management can be formulated as follows:

– *professionalism* — decisions and tools used to ensure sustainable fertiliser management at the national level should be scientifically substantiated, based on the results of expert discussion, and reliable and relevant data. Notably, the efficiency of the agricultural sector of the economy is conditioned by investment in machinery and equipment only by third, and all the latter depends on the human factor, the intellectual potential used, the qualification level and abilities of managers and specialists;

– *transparency* — it is necessary to ensure a clear definition of the relationship "problem — solution — consequences" and equal conditions for all participants in the system. Transparency allows understanding where the most bottlenecks are in the system of sustainable use and management of fertilisers. In the future, this would allow saving resources, time, and obtaining socio-ecological and economic effects (income). Transparency provides greater "manageability" and not excessive controllability, as well as speed and optimality of decision-making (in particular, transparency helps to manage environmental and economic risks). At the same time, it is necessary to address the availability of information that comprehensively reflects the socio-ecological and economic aspects of fertiliser application practices;

– *scientific and innovative approach* — adequate support should be provided for research and development in the field aimed at both technological solutions and research of the socio-cultural and institutional environment. Innovation in the development of sustainable use and management of fertilisers should see not only an economic orientation, but also a special type of attitudes (in particular, ecological-economic, socio-ecological), value attitudes (public health and food and environmental safety), and motivations (for example, the use of the institute of socio-environmental responsibility). Innovation should determine the trajectory of convergence of economic, environmental and social parameters (guidelines) of fertiliser application practices, which will also be reflected in the socio-cultural and institutional environment;

– *knowledge* — it is necessary to ensure constant monitoring of the state of development of the problem (assessment of the diverse socio-ecological and economic impact of fertiliser use practices), monitoring and tracking, accumulation of innovative technological solutions to solve existing problems. It should be about knowledge management as a component of sustainable fertiliser management. Knowledge management covers the processes of identification, accumulation, use, and transfer of information and knowledge, which are used in determining and evaluating the "problem — solution — effect" relationship at all stages of fertiliser production and use. It is necessary to constantly deepen awareness (knowledge) about the socio-ecological and economic aspects of fertiliser use. Therefore, it is important to develop and accumulate knowledge about the relationship between health care and human capital (in particular, which is considered as a factor of economic growth and can be the subject of a separate study);

– *information support and solution support at all levels* — it becomes possible today due to the increasing spread of information technologies and consists in creating a single information system that would combine data on the volume of production, use, utilisation of fertilisers, data on the characteristics of fertilisers, the results of assessments and tests of soil condition and nutrient needs, data on volumes and beneficiaries of state support in the industry. Information support should cover regulatory reference, accounting and analytical, operational and technical, and forecast information. At the same time, it is important that the processes of formation and development of a sustainable fertiliser management system do not lag behind Information and analytical support and vice versa. It is important that there is no asymmetry in the information support of management processes. Thus, information support should ensure timely implementation of direct and reverse links in the management decision-making system regarding the use of mineral fertilisers;

– *trust* — it is necessary to ensure an appropriate level of trust between all agents of the system, which is the result of professionalism, transparency, and proper information support. A high level of trust is a necessary condition for the sustainable development of the fertiliser use and management system, since distrust indicates certain conflicts, conflict situations, and crisis phenomena. Trust is also a specific mechanism for making managerial decisions in conditions of time constraints, incompleteness or asymmetry of information. It helps to reduce transaction costs, increase balanced productivity, and efficiency of agricultural management, and reduce eco-destructiveness in the practice of applying fertilisers. In a crisis economy it is also important to build ecologically-oriented institutional trust;

– *system constancy* — provision of conditions for the further automatic operation of the system, which can be achieved through proper information support, the development of an appropriate level of trust between participants. This principle also determines the need to assess the effectiveness of the application of information support, quantitative measurement of trust, and the effectiveness of the functioning of the whole system.

The development of a national system of sustainable fertiliser management also requires defining the main strategic performance and targets of production, economic, environmental, and social orientation for the agents of this system. Such main performance targets can be presented as follows:

1. Production and economic:

1.1. Activation of innovation and investment activities for greening reproductive processes in the system of sustainable fertiliser use;

1.2. Growth in the production of environmentally friendly agricultural and food products;

1.3. Activation of marketing activities for the production of environmentally friendly agricultural products;

1.4. Development of "green" logistics;

1.5. Prevention of economic damage caused by the eco-destructive state of agricultural land and water objects due to irrational use of fertilisers;

1.6. Reduction of the cost of environmental protection measures;

1.7. Obtaining a rental effect due to an increase in the monetary valuation of eco-balanced, eco-safe agricultural land and water objects;

1.8. Increase in tax revenues from business entities through the system of environmental taxes and payments;

1.9. Improvement of the level of eco-oriented integration of agriculture, water, fish, and forestry in the organisation of sustainable land use (in particular, based on agroforestry management of agricultural landscapes);

1.10. Gradual introduction of environmental management elements;

1.11. Development of geoinformation systems and IT technologies, monitoring systems of socio-ecological and economic areas for information support;

1.12. Improvement of the "green" image and corporate environmental culture in agent relations;

1.13. Increase in the cost of human capital.

2. Environmental:

2.1. Reduction of environmentally related morbidity in the population;

2.2. Preservation and improvement of physical, chemical, and reproductive properties of soils, and fertility of agricultural lands;

2.3. Reduction of the level of anthropogenic load on land and aquatic ecosystems;

2.4. Reduction of the environmental risk of reducing the productivity of agriculture, water, and forestry management;

2.5. Improvement of the overall and field-protective forest cover at various hierarchical levels of simple development, and, as a result, improving the ecological quality of the agro-natural environment;

2.6. Conservation and improvement of biodiversity and genetic potential in agroforestry landscapes.

3. Social:

3.1. Improvement of the quality of life, improving the level of social and environmental safety, and comfort of life;

3.2. Creation of "green" jobs (for example, for the implementation of agroforestry measures);

3.3. Development of social and environmental responsibility mechanisms;

3.4. Development of social entrepreneurship;

3.5. Development of social infrastructure;

3.6. Improvement of the public consciousness, culture, and spirituality of territorial communities.

Embodying the content of global initiatives for sustainable fertiliser management and the expected results of their implementation, outlined in this way and reflected in the action plans at the national, regional, and local levels, these guidelines can lay the foundation for the development of economic mechanisms to encourage the implementation of best practices, the development of a monitoring and control system for fertiliser management.

The national system for ensuring sustainable fertiliser management can be represented as a complex of interactions between the government, the industry for developing, producing, and transferring fertilisers to users, including agricultural producers – fertiliser users, whose functioning is a continuous process of raising awareness of problems caused by irrational practices of fertilisation, generating, accumulating, and spreading knowledge about the possibilities of solving them and developing and applying appropriate tools.

Sharing an opinion of Helming *et al.* (2018) regarding the role of government as a link between the goals of society and the individual goals of fertiliser users, it is necessary to point out its leading role in raising awareness among all agents of the system about the problems caused by irrational fertiliser use. Notably, the low level of awareness of the society in this area is one of the main obstacles to the successful implementation of global initiatives in this area (Sutton *et al.*, 2019). On the other hand, the role of government should also be reviewed due to the inefficiency of command and control mechanisms in the field of regulating the use and management of fertilisers: it is almost impossible to control all operations with fertilisers; through regulation in one area, there may be effects of shifting externalities to other industries and spheres, countries; the benefits obtained may be accompanied by side effects; it is impossible to reflect the complexity of individual phenomena (for example, biodiversity) through a command and control approach (Garske *et al.*, 2020).

The leading role of the government in the national system of ensuring sustainable fertiliser management should be to transform the existing institutional environment to be filled with more information and knowledge (Golicz *et al.*, 2021). Raising public awareness of the problem is a trigger for generating knowledge for all participants in the system (Adnan, 2018). The basis for attracting public attention to the problem and forming public awareness is considered the impact assessment, which should serve as the basis for developing/transforming policies in accordance with the goals set by society, overcoming suboptimality and ensuring the consistency of policies (Helming *et al.*, 2018). Such estimates are usually based on negative impact on environmental components and soil health (Hou *et al.*, 2020), ecosystems, and resource efficiency (Helming *et al.*, 2018). Expanding the range of aspects studied, considering the impact of fertilisation on public health and the reverse impact of contaminated components on the economic performance of industries, regions, countries, is appropriate and especially significant for developing countries, illustrating the socio-economic side of the problem of fertilisation and the corresponding social costs (Mishenin *et al*., 2015; Mishenin *et al*., 2021).

Methodological and practical tools for assessing environmental and economic damage caused by the consumption of contaminated food products have not yet been developed (Karintseva, 2018; Kubatko, 2017; Yang *et al*., 2017). Thus, the expansion of the information and analytical base of such consolidated damage estimates, in particular, by natural and geographical zones, opens up opportunities for informing and regulating sustainable fertiliser management at the national and regional levels.

Considering the issues of generating and transferring knowledge on sustainable fertiliser management (Adnan *et al*., 2018) researchers note the prospects of cooperation between different agents to achieve better results. For example, joint research with farmers is seen as a source of innovation and successful solutions (Kröbel, *et al*., 2021), and field support of farmers ensures that they acquire the best knowledge on the use of fertilisers (Yu *et al*., 2020). Therefore, the interaction of agents of the national system for ensuring sustainable fertiliser management should be at the centre of attention.

CONCLUSIONS

The findings show that the national system for ensuring sustainable fertiliser management should be considered as a set of interacting entities (government, industry representatives, and fertiliser users) involved in the process of continuous improvement of fertilisation practices through raising awareness of the problem – generation and transfer of knowledge to solve it – selection and implementation of appropriate tools. Such a system should be based on the principles of professionalism, transparency, scientific and innovative nature, knowledge, information support, trust, and constant functioning of the system in the long term. In the context of improving fertiliser management practices, it is necessary to point out the need to formulate strategic performance targets for all parties involved (developers, producers, users of fertilisers), which should prioritise not only production and economic targets, but also environmental and social ones. Such guidelines can be further used as the basis for monitoring and evaluation mechanisms, and economic incentives for sustainable fertiliser management practices. The results obtained can serve as a basis for further shaping policies and strategies for sustainable fertiliser management and use at national and lower hierarchical levels.

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Реалізація глобальної ініціативи з управління добривами на національному рівні: концептуальні засади

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Анотація. Нині перед людством стоїть завдання пошуку балансу між необхідністю збільшення кількості продовольства та негативними соціально-екологічними та економічними наслідками нераціонального використання добрив. На глобальному рівні було започатковано ряд ініціатив для консолідації зусиль країн у вирішенні цієї проблеми. Втім, існуючі національні системи та політики з управління добривами характеризуються недостатньою системністю та низькою ефективністю. Дане дослідження націлене на формулювання концептуальних засад для розбудови національної системи сталого управління добривами, що відповідала би принципам, викладеним в існуючих глобальних ініціативах. Через узагальнення змісту існуючих міжурядових ініціатив щодо сталого управління добривами було сформульовано суб'єктний склад, а оцінки взаємозв'язку між внесенням добрив та здоров'ям населення (через кількість онкозахворювань) за допомогою використання методів регресійного аналізу, оцінки економічного збитку від нераціонального добрення слугували обгрунтуванням (ілюстрацією важливості виділення) компонентних складових, що охоплюють: обізнаність, знання, інструменти. Національна система сталого управління добривами розглядається як тривимірна цілісність, що містить такі взаємопов'язані складові: уряд, галузі з виробництва та постачання добрив та користувачі. Функціонування цієї системи розглядається як безперервний процес підвищення обізнаності, генерування та передачі знань, вибору та застосування відповідного інструментарію та вдосконалення практик застосування добрив відповідно до принципів сталого розвитку за провідної ролі уряду. Процес підвищення обізнаності всіх суб'єктів системи щодо проблеми нераціонального внесення добрив пропонується розглядати в ширшому контексті – через демонстрацію негативних наслідків не лише для навколишнього середовища (стану ґрунтів), а й з точки зору впливу на здоров'я населення та відповідних наслідків – через оцінку економічних збитків, спричинених забрудненням та споживанням продовольства з вмістом шкідливих речовин. Головними принципами взаємодії суб'єктів у цій системі мають стати такі: професіоналізму, прозорості, інформаційної підтримки та ін. Особлива увага має бути приділена формулюванню комплексу стратегічних цілей, що мають закласти основу для розробки процедур контролю та оцінки, системи моніторингу та перегляду механізмів економічного стимулювання використання добрив з урахуванням соціальних та екологічних аспектів застосування добрив

Ключові слова: стале управління добривами, національна політика щодо добрив, обізнаність, трансфер знань, безпечне добрення, продовольча безпека

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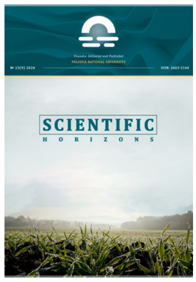

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Energy and ICT Tax Effects on Foreign Direct Investment in a Low-Income Economy

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Abstract. The importance of excellent tax policies in increasing foreign direct investment inflows should be stressed in all growing economies. Foreign direct investment (FDI) is critical to increasing productivity, particularly in developing nations. Taxes emanating from energy related business have also triggered this inquiry due to fumes being contended within the environment and the effect on human existence. Prior researchers have investigated a variety of issues including trade liberalisation, property taxes, market shares, corporate taxation, and rising prices. Fewer researchers have examined the tax implications of energy and information and communication technology (ICT) development as a predictor of FDI in low-income countries. Following the introduction of taxes on energy and ICT activities in Nigeria, foreign investments' responses have not been tried out in studies and yet the dwindling level has been an issue of policy concern. As a result, this study seeks to fill the gaps by evaluating the effects of energy and ICT taxes on FDI from 2010 to 2020. The data applied for this analysis are obtained from World Bank, Federal Inland Revenue Service (FIRS) and Central Bank of Nigeria. Considering the outcome of this investigation, the paper concludes that the ICT development tax is detrimental to FDI inflows using the econometric approach of regression analysis. The correlational analysis also provides evidence that ICT taxation has a strong negative association with FDI. Other factors, such as trade openness and energy taxes, neither have a substantial relationship nor impact on FDI. The study indicates that improving policies to minimise ICT taxation will benefit the expanding economy by recruiting new foreign investors and retaining those who are currently present in the country

Keywords: overseas business, optimal taxation, ICT development, oil extraction, market liberalisation

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INTRODUCTION

Foreign direct investment growth in an economy is heavily influenced by the extent to which overseas investors are taxed in that country. Energy and ICT (Information and Communication Technology) tariffs are crucial to foreign direct investment inflow in emerging countries. Internet and networking innovations encompass all the technology that supports individuals to capture and transfer data while also linking the entire globe (Omodero, 2021; Oreku, 2021). The different ICT channels are universally regarded as accelerating catalysts, enhancing production and efficiency via the use of greater data communication (Chyzhevska *et al.*, 2021; Yu *et al.*, 2022). The energy tax stems from crude oil and gas exploration operations, which are more closely related with foreign investment in most oil-rich nations. Foreign investors benefit from advanced technology that allows for commercial drilling of petroleum, while host governments benefit from exploration taxes, royalties, drilling permits, and other associated energy taxes. When it comes to information and communication technology, foreign direct investment is also affected by the taxes involved in the development stage as well as continuous operating levies. Thus, the degree of taxation in each country decides FDI growth.

FDI is an important source of generating money for emerging economies since it allows them to obtain funds from advanced economies (Kolodkin, 2017; Yang & Shafiq, 2020). The Organisation for Economic Co-operation (OECD) describes FDI as a cross-border venture in which a foreign corporation develops a long-term stake in and/or a significant degree of control over a firm in some other nation. Furthermore, FDI supplies numerous benefits to the local community, including long-term funding needed for the host country's economic growth, the formation of new places of employment, the diffusion of innovations, increased access to international markets, the introduction of new leadership abilities, garnering industries from advanced areas (Kolodkin, 2017). The introduction of green technologies that can boost climatic conditions, raising work opportunities and wage levels, and having a positive effect on commerce.

FDI also contributes to the state's financial role in enhancing intellectual resources, increasing technological advance and performance, and resulting in total economic prosperity (Grossman & Helpman, 1991). The progression of FDI is prompted by three factors: acquisition elements centred on property and equipment; intra-organisational components arising from real worth influence in many places and regions; and site factors culminating from regional resources and capabilities, economic factors, and regulatory frameworks such as funding and fiscal legislation, intellectual property rights, and workforce legislation (Baccini & Urpelainen, 2014). Foreign investment in a developing nation has several advantages that cannot be emphasised. Foreign capital inflows help the economic status of a low-income country by supplying both technology and great human capital development. There is a lot of emphasis on globalisation, which leads to trade liberalisation, which improves the flow of technology and the productivity levels of less developed nations.

Policymakers in emerging economies meet a significant difficulty in attracting foreign investors. Furthermore, a difficult decision must be made on how taxing influences FDI. The government may levy three sorts of taxes on FDI: property tax, value-added tax, and income tax. The FDI properties attract the property tax, while the products that are sold include the worth addition tax and the corporate tax is levied on the overall income of the business. As a result, the significance of taxation in the mobility of money becomes more pronounced, as they lower financial profits to any investments. The influence of tax in deciding FDI inflows may be divided into two categories: economic considerations and organisational characteristics (Nasution, 2020). While taxes affect the inflows of foreign investments through its incidence as an economic indicator, it influences FDI inflows as an organisational element through its administrative responsibilities. Both characteristics have an influence on FDI inflows via efficiency and cost effectiveness, as this is the most crucial factor for capitalists to examine before investing (Krugman *et al.*, 2012).

Fostering productivity expansion is an important measure in emerging economies for reaching different goals, such as lowering poverty and unemployment rates and improving the quality of life. There are several techniques available to reach this goal, one of which is soliciting foreign direct investment (FDI), which is regarded as a key centre of foreign funding. Thus, implementing tax breaks to encourage FDI is a typical tactic used by several emerging regions to attract FDI. According to E. Ferede & B. Dahlby (2012), tax cuts can lower investment costs and increase funds to work. Letting foreign financiers, a tax incentive may result in a significant rise in FDI inflows from exclusion nations but not from provisional economies (Singh, 2016). Tax vacations or tax cuts are commonly used in emerging and lesser undeveloped markets (McKeehan & Zodrow, 2017). In summary, allowing tax breaks for FDI motivates many MNEs to transfer their operations to take advantage of these tax breaks.

The purpose of this study is to investigate the impact of energy and information and communication technology tariffs on foreign company attractiveness in the developing nation under consideration. The study is organised into five sections: the introduction, the literature review, the research methodology, the results and discussion, and finally the concluding remarks.

LITERATURE REVIEW

Using tax receipts barriers, compliant tax representatives, intrinsic tax obligations, and businesses with diverse before-tax earnings, the results proved that tax breaks, when offered to the unfitting enterprises, were not just ineffectual in boosting FDI, but also contributed to a type of tax transferring that might decrease FDI. To circumvent host nation taxes, various global corporations are routing international investment via transit countries with an attractive incentive agreement arrangement. In the light of this claim, F. Weyzig (2013) examined spatial trends and socioeconomic conditions of FDI migration using microcosm statistics from Dutch Special Purpose Corporations. The analysis showed that taxation accords were set up as a crucial driver of FDI channelled via the Netherlands.

J. Voget (2015) confirmed that a one-point reduction in the mandatory company tax rate raised the volume of transnational companies hosted by around 2.5 %, with a 95% credible band spanning from 0.6 % to 4.4 %. S. Hong (2018) investigated the connection between FDI and the design of tax-avoidance pathways. Evidence-based findings showed that the presence of a tax-cutting efficient link was absolutely and considerably correlated with FDI.

R.A. Nasution (2020) assessed the effects of tax cuts on international investment in Southeast Asian nations utilising longitudinal data from 1997 to 2016. The data revealed that, while corporate tax cuts had a detrimental impact on FDI in Southeast Asian nations, they were not the primary factor attracting investors. The major factors that influenced investors to take part in the regions were trade liberalisation and productivity growth. V. Mercer-Blackman & S. Camingue-Romance (2020) discovered, using panel data at the nation and sector levels, that the consequences of US tax policy on sector-specific FDI to Asia differed significantly among industries. After adjusting for size of the market, pricing, accessibility, and the business climate, the corporation tax incidence disparity was often not significant statistically, especially for worldwide price-chain-related FDI to emerging Asia.

J. Pavel *et al.* (2021) found the factors of tax structures – in both the investors and beneficiary state – that impact FDI placement in post-socialist EU nations as well as cross-border movements of certain forms of remittances. For constitutional and functional taxation rates, the study showed that the predicted responsiveness of FDI to the rate of taxation is approximately 1.1 and 1.9 accordingly. The findings revealed that entrepreneurs from the EU looked to capitalise on both corporation tax differential and complex tax optimisation tactics. According to statistical estimations, the shareholder's domestic taxation system was critical if it allowed the non-taxation of investment earnings, the applicability of discounted cost to licenses, and the creation of distinctive drive corporations. Furthermore, the quantity of fees for investment advice and royalty, which were often employed for belligerent tax scheduling, was significantly connected to the extent of FDI.

R.B. Davies *et al.* (2021) supplemented by investigating organisation merge FDI into Europe from a diverse set of homelands between 2007 and 2015 at both funding frontiers. The analysis revealed, similarly to earlier single-country analyses that taxation functioned on the broad margin. Based on those findings, the researchers dug further and discovered substantial variance between enterprises, with lesser financiers from high-tax native region being acutely susceptible to hosts taxes.

A.T. Adejare & O.S. Olatunji (2021) evaluated the influence of non-oil taxes on foreign direct investment and economic activities in Nigeria from 1994 to 2019. The researchers found that taxes had a negative substantial influence on international investment while favourably promoting financial operations in Nigeria. S. Silajdzic & E. Mehic (2022) evaluated the influence of business tax on FDI among less sophisticated emerging markets, examining if the taxing incidence was dependent on size and growth. The analysis found that, while taxation was a considerable FDI predictor, its impacts were reliant on technological advancement. Considering such outcomes, the researchers showed that lowering business taxes might be a significant tool for boosting FDI, which is especially important for less evolved emerging markets.

MATERIALS AND METHODS

This research analyses the effects of energy and ICT taxes on foreign direct investment in Nigeria from 2010 to 2020. The multiple regression model and other pertinent analytical tools which include diagnostic tests and descriptive statistics are used in this work. The diagnostic tests were used to confirm the stability of the study model, normality of datasets and absence of multicorrelation and autocorrelation. The use of descriptive statistics helped to show the nature and suitability of the dataset to the research. The unit root testing was done with the joint tools of PP-Fisher, ADF-Fisher, and lm, Pesaran, and Shin W-stat to set up dataset stationarity. The World Bank Development Indicator is the source of FDI data. While data on energy and information technology taxes were obtained from the Federal Inland Revenue Service (FIRS). The figures on trade liberalisation were obtained from the Statistical Bulletin of the Central Bank of Nigeria (CBN). The functional relationship is below (1):

$$Y=f(X) \quad (1)$$

where Y is the foreign direct investment (dependent variable), X is the energy and ICT taxes (independent variables).

Equation 1 can be explicitly explained as (2):

$$FDI=f(Taxation) \quad (2)$$

To further break down equation 2, the following model configuration (3) is selected for this study:

$$lnFDIit=\beta_0+\beta_1 lnICTit+\beta_2 lnNRGit+\beta_3 lnTPNit+\varepsilon it \quad (3)$$

β_0 is the intercept of the regression; β_1 is the coefficient of Information Communication Technology (ICT) development tax; β_2 is the coefficient of Energy taxes (NRG); β_3 is the coefficient of trade openness (TPN); it is the time coefficient; ε is the error term, β_0 is the regression intercept.

The description of the variables used in this study can be obtained in Table 1. It explains the data sources, their unit in both foreign and local currency, as well as other parameters used in collecting the data.

Table 1. Selected variables

Variable	Abbreviation	Data Source	Unit
Foreign direct investment	lnFDIit	World Bank	USD ($)
Information communication technology taxes	lnICTit	FIRS	NAIRA (N)
Energy taxes	lnNRGit	FIRS	NAIRA (N)
Trade openness	lnTPNit	CBN	[(X-I)/GDP] (N)

Source: *study model explanation, 2022*

RESULTS AND DISCUSSION

Trend analysis of variables

Figure 1 depicts the flow of foreign investment in Nigeria, information and communication technology, energy taxation, and trade openness. FDI was reported to be at its zenith in 2011, coinciding with the amount of trade liberalisation in that year. Looking at trade openness and FDI, the Nigerian administration promoted foreign investment in 2011, resulting in an elevated level of capital influx that year. Energy taxes were at their peak in 2011 and 2012, but ICT taxes were still rising. However, in 2020, although energy taxes have been drastically reduced, ICT taxes have gained speed and hit a record high, while FDI has declined dramatically. These are indications that when FDI inflows increase, so do energy taxes; nevertheless, as oil prices fall, so do energy taxes. Conversely, ICT taxes are rising as more technology-based businesses set up shop in the nation. There is still a need to persuade more international investors, particularly in the energy and ICT industries, to transfer their operations to Nigeria for increased productivity and wealth development. Following the many advantages of technology, the government should strengthen tax laws and create a more accommodating business climate to attract more FDIs.

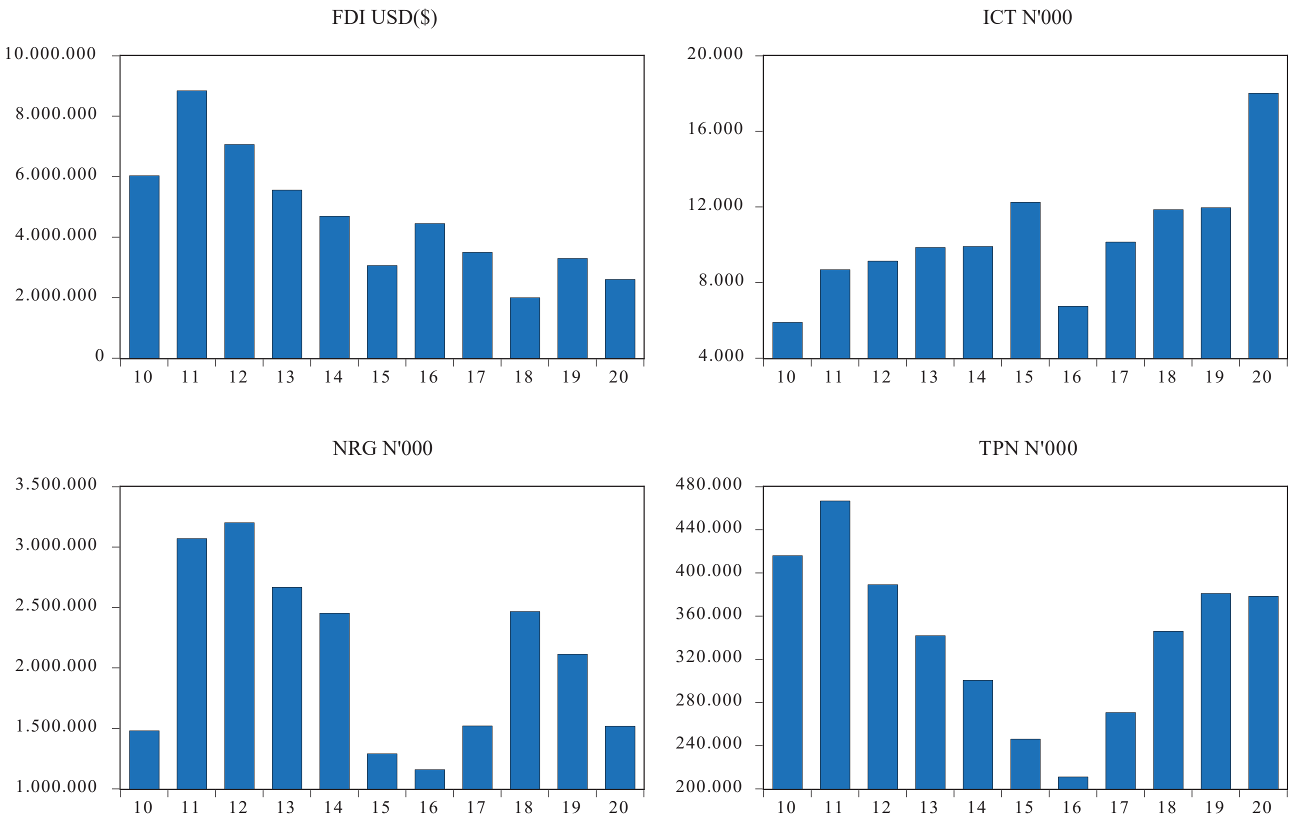

Figure 1. *Trend of data*

Source: *World Bank, FIRS & CBN*

The study examined all datasets for their unit roots, and the results show that Levin, Lin, and Chu t stationarity at level is consistent with the results of PP-Fisher, ADF-Fisher, and lm, Pesaran, and Shin W-stat at stationarity. These joint tools are useful when datasets are stationary at order zero and require impact analysis. The results in Table 2 demonstrate that the datasets collective are stable at the level as confirmed by the p-values which are less than 0.05 level of relevance. As a result, the usage of the multiple regression approach or the lease squares method is suitable. The results for confirmation are presented in Table 2.

***Table 2**. Group unit root test: Summary*

Series: LNFDI, LNICT, LNNRG, LNTPN				
Sample: 2010 2020			Cross-sections	Obs
Method	Statistic	Prob.**		
Null: Unit root (assumes common unit root process)				
Levin, Lin & Chu t*	-3.89221	0.0000	4	35
Null: Unit root (assumes individual unit root process)				
Im, Pesaran and Shin W-stat	-2.96267	0.0015	4	35
ADF – Fisher Chi-square	24.3979	0.0020	4	35
PP – Fisher Chi-square	35.1575	0.0000	4	36

***Note:** probabilities for Fisher tests are computed using an asymptotic Chi-square distribution. All other tests assume asymptotic normality*

***Source:** author's calculation, 2022*

Table 3 shows the results of further analytical testing. According to Table 3, the study does not have any multi-collinearity concerns. This is supported by the Variance Inflation Factor (VIF) value of 1 for ICT and 1.69 for NRG and TPN. As a result, the values are less than 4 (Garson, 2012) and 10 (Gujarati & Porter, 2009). Concisely, all autonomous elements are assessed separately for their impact on foreign investment attractiveness in Nigeria. There is no interrelationship between them. Furthermore, based on the result displayed in Table 3, there is no serial correlation found in the model while the stability test also confirms that the model is firm. The results of the other tests corroborate the model's applicability.

***Table 3**. Analytical checks*

Type diagnostic tests	F-statistics	P-value
Ramsey RESET test for stability	4.60	0.08
Breusch-Godfrey serial correlation LM test	0.17	0.84
Heteroskedasticity test: Breusch-Pagan-Godfrey	0.29	0.83
Multi-collinearity test:	Coefficient variance	VIF
lnICT	0.11	1.00
lnNRG	0.13	1.69
lnTPN	0.29	1.69

***Source:** author's calculation, 2022*

The descriptive statistics in Table 4 show that the variables have approximately the same mean, median, and maximum values, which are approximately: 15, 9, 14, and 13, respectively. Most crucially, the kurtosis is within statistically acceptable bounds, and the Jarque-Bera of all variables has a p-value greater than 0.05. This result confirms that all datasets for the study have been evenly distributed. The standard deviation, on the other hand, shows that the datasets have a lower dispersion around the mean locations.

***Table 4**. Descriptive Statistics*

	FDI	ICT	NRG	TPN
Mean	15.26093	9.208039	14.49233	12.71354
Median	15.30841	9.201098	14.56422	12.75396
Maximum	15.99480	9.798905	14.97907	13.05353
Minimum	14.50866	8.680332	13.96204	12.25951
Std. Dev.	0.449557	0.302150	0.361537	0.240425
Skewness	-0.010265	0.060298	-0.061795	-0.534637
Kurtosis	2.082515	2.995849	1.515140	2.295935
Jarque-Bera	0.386008	0.006674	1.017538	0.751233
Probability	0.824479	0.996669	0.601235	0.686866
Sum	167.8702	101.2884	159.4156	139.8489
Sum Sq. Dev.	2.021019	0.912949	1.307093	0.578044
Observations	11	11	11	11

***Source:** author's calculation, 2022*

The correlational analysis in Table 5 describes the type of link that exists between the dependable variable and the independent components used in this investigation. There is a considerable inverse association between ICT and FDI, as well as trade liberalisation and energy tariffs. Energy taxation and FDI have a moderate link, but trade openness and FDI have a poor relationship. The correlation between ICT and energy tax is quite weak, as well as the interaction between trade openness and ICT.

***Table 5**. Correlation analysis*

Sample: 2010 to 2020 Included observations: 11				
Correlation				
t-Statistic				
Probability	LNFDI	LNICT	LNNRG	LNTPN
LNFDI	1.000000			
LNICT	-0.655379	1.000000		
	-2.603120	-----		
	0.0286	-----		
LNNRG	0.418906	0.050393	1.000000	
	1.384005	0.151373	-----	
	0.1997	0.8830	-----	
LNTPN	0.365311	0.056808	0.640426	1.000000
	1.177303	0.170699	2.501598	-----
	0.2693	0.8682	0.0338	-----

***Source:** author's calculation, 2022*

Table 6 shows the regression result, which proves the extent of effects the predictor variables have on the reliant parameter. FDI is the response variable in this analysis, reacting to the dynamics of energy and ICT development taxing. It is crucial to notice, however, that the F-statistic p-value is less than 0.05, implying that the model is suitable and statistically significant. The standard error of regression also shows that the model prediction is correct, and the Durbin-Watson confirms the absence of autocorrelation. Further evidence using R-squared of 65.6% shows that the predictor factors account for up to 65.6% of the variance in FDI inflows in Nigeria. That is, outside ICT development levies and energy taxes, other macroeconomic factors not included in the model have only 34.4% influence on FDI changes. Figure 2 confirms the regression model's stability by displaying the blue line in the centre of the yellow dotted lines without crossing their borders.

***Table 6**. Regression analysis*

Dependent variable: LNFDI				
Method: Least squares				
Sample: 2010 to 2020				
Included observations: 11				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
LNICT	-1.016143	0.330318	-3.076260	0.0179
LNNRG	0.410065	0.358862	1.142682	0.2907
LNTPN	0.360713	0.539821	0.668208	0.5254
C	14.08888	5.987586	2.353016	0.0509
R-squared	0.656213	Mean dependent var		15.26093
Adjusted R-squared	0.508876	S.D. dependent var		0.449557
S.E. of regression	0.315051	Akaike info criterion		0.803122
Sum squared resid	0.694799	Schwarz criterion		0.947811
Log likelihood	-0.417172	Hannan-Quinn criter.		0.711916
F-statistic	4.453823	Durbin-Watson stat		1.598071
Prob(F-statistic)	0.047436			

***Source**: author's calculation, 2022*

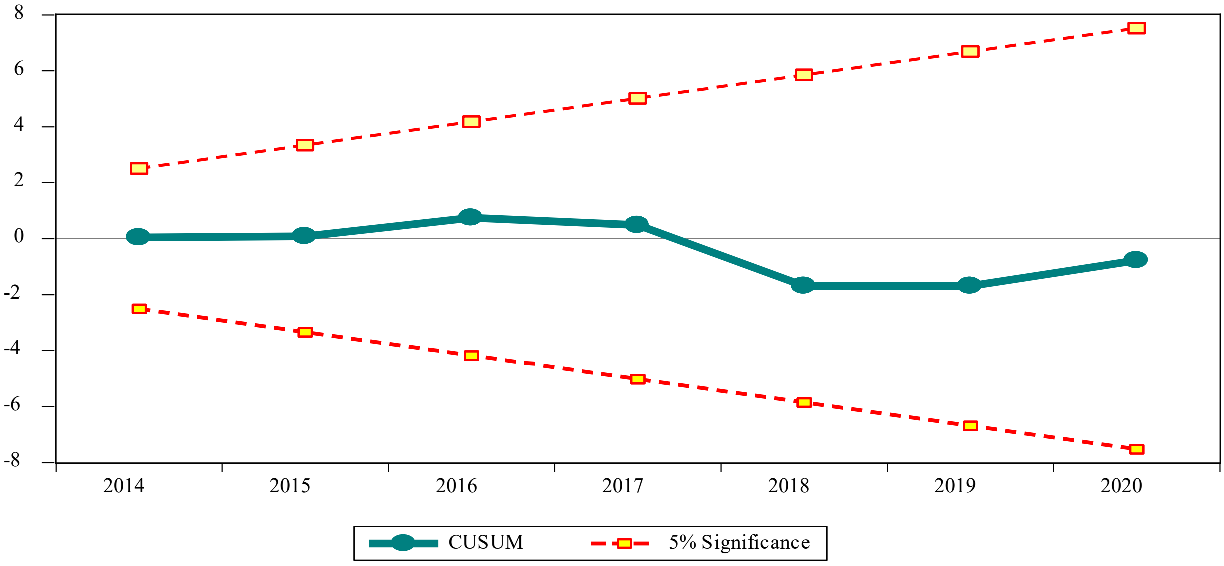

***Figure 2**. Robustness check*

On the specific influence of the independent factors, the results show that ICT tax has a significant negative effect on FDI. This result presents a case which confirms that FDI strong considerable decline in 2020, as seen in Figure 1, is a result of information and communication technology levies. There is need for policy review in favour of foreign investors in this respect. The findings also show that energy tariffs and trade liberalisation have no substantial influence on FDI. The policy implication is that the global drop in oil prices has harmed enterprises engaged in oil exploration. Second, the domestic market may not have been ideal for foreign trade. As a result, the government must expand local markets to promote foreign trade and exchange of products and services.

CONCLUSIONS

The outcome of this study has shown that emerging nations can only reap the full advantages of the foreign investments through improvement on taxation policies. Apart from corporate taxation, which even domestic firms also pay, Nigeria has other levies that primarily affect foreign investors. The principal two taxes affecting foreign operations in the nation have been analysed in this study. The data suggest that energy taxes and market liberalisation have no discernible impact on FDI. Instead, the impact of the information and communication technology development tax is significantly detrimental to international investment. This is quite precise, and it advocates for reforms to ensure that more FDIs are attracted to help the economy.

Tax breaks and exemptions, as stated by various research covered in this paper, will be extremely beneficial to foreign investors. Most international investors favour countries with tax havens for business. Although a tax haven may not be fully beneficial to a rising economy, there are also alternative cost-effective ways of providing overseas investors with tax breaks to promote their activities. Specifically, ICT taxes may be decreased to attract more potential investors and retain existing ones.

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Вплив енергетики та ІКТ-податків на прямі іноземні інвестиції в економіку з низьким рівнем доходу

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Анотація. Необхідність правильно вибудованої податкової політики для збільшення притоку прямих іноземних інвестицій актуальна в усіх країнах, що розвиваються. Прямі іноземні інвестиції (ПІІ) мають вирішальне значення для підвищення продуктивності, особливо в країнах, що розвиваються. Не менш важливі податки, що надходять від бізнесу, пов'язаного з енергетикою через викиди від галузі до навколишнього середовища та вплив на існування людини. Попередні дослідники вивчали різноманітні питання, включаючи лібералізацію торгівлі, податки на нерухомість, частку ринку, корпоративне оподаткування та зростання цін. Менше дослідників вивчали податкові наслідки розвитку енергетики та інформаційно-комунікаційних технологій (ІКТ) як провісників ПІІ в країнах з низьким рівнем доходу. Після введення податків на енергетику та діяльності ІКТ в Нігерії, реакція на іноземні інвестиції не була висвітлена в дослідженнях; водночас зниження рівня інвестицій викликало занепокоєння. Це дослідження намагається заповнити прогалини шляхом оцінки впливу податків на енергетику та ІКТ на ПІІ з 2010 по 2020 рік. Дані, використані для цього аналізу, отримані від Світового банку, Федеральної служби внутрішніх доходів (FIRS) і Центрального банку Нігерії. З огляду на результати цього дослідження, у статті робиться висновок, що податок на розвиток ІКТ завдає шкоди притоку ПІІ за допомогою економетричного підходу регресійного аналізу. Кореляційний аналіз також надає докази того, що оподаткування ІКТ має сильний негативний зв'язок із ПІІ. Інші чинники, такі як відкритість торгівлі та податки на енергію, не мають істотного зв'язку та не впливають на ПІІ. Дослідження показує, що вдосконалення політики мінімізації оподаткування ІКТ піде на користь економіці, що розвивається, залучаючи нових іноземних інвесторів та утримуючи тих, хто зараз є в країні

Ключові слова: закордонний бізнес, оптимальне оподаткування, розвиток ІКТ, видобуток нафти, лібералізація ринку

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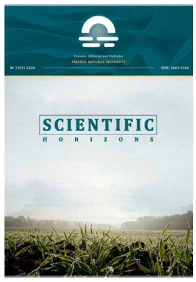

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The Supply Shock in Organic Fertilizers for Agriculture Caused by the Effect of Russia-Ukraine War

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Abstract. Ukraine and Russia are among the leading global agricultural producers, accounting for millions of tons of global foodstuff and the production and exportation of organic fertilizers. With this in mind, the Russia-Ukraine war has caused an immense disruption and great supply shock in organic fertilizer and agricultural production, and food prices across the globe. The authors aimed to analyze the impact of the Russia-Ukraine war on agriculture, in particular organic fertilizers and agricultural production. The research employed a systematic research method to collect data on the extent of the impact of the war on organic fertilizers and food production. The research results indicate that the war has disrupted the supply of organic fertilizers, reducing agricultural products and subsequent rise in the price of agricultural produce. The research indicates that the rising cost of fertilizers directly influences food production and supply. The war has disrupted a viable environment for agricultural and organic production and exportation from these countries, causing the rise in food prices and a threat to food security across the globe. There is a need to ensure that international trade becomes more flexible and open in fertilizers and food production and exports. There is also a need to promote policy dialogues and market scrutiny, and transparency, especially with the uncertain global food market due to the disruptions influenced by the Russia-Ukraine war. The results of the study can be used by scientists, economists and public figures to build further forecasts of the state of agriculture, as well as to build strategies to improve the economy of some countries, including Ukraine

Keywords: supply chain shock, agricultural production, food prices, raw material, fertilizers export

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INTRODUCTION

The wake of the Russia-Ukraine War has intensified the supply shock of organic fertilizers for agricultural growth and food production. The war comes amid COVID-19, which has already ravaged the global economies of Ukraine and Russia included, thus causing a massive threat to global food security (Outlaw *et al*., 2021). With Ukraine being the leading energy producer, the war has massively increased the gap in the supply chain of fertilizers and subsequent plants such as wheat and other grains that depend on fertilizers for growth. According to International Food Agency (IFA) (2022), the intensity and breadth of this supply shock of organic fertilizers due to the war are likely to have detrimental effects by increasing the inflationary pressures, thus leading to spikes in fertilizer and food prices. The supply shock of organic fertilizers, increment in agricultural production, and subsequent rise in food prices do not come as an intense shocker given the close relationship these elements have (Mbah and Wasum, 2022). According to Ibendahi (2022), food and fertilizer production require high energy content in terms of transport, industrialization, process and mechanization, and competition with other industries for raw materials.

Russia is a key producer of nitrogen fertilizer raw material, natural gas, which is mostly exported to the European Union members and India. The Russia-Ukraine war and, most especially, the sanctions imposed on Russia have led to the latter being cut off from the global market, thus limiting the production and exportation of these essential organic fertilizers. The Russia-Ukraine war exposes the global market to greater food risks due to inadequate raw materials and subsequent unmet import and export demand. The war has already caused an immense supply shock in the production and supply of this important commodity. This means that, as the cost of organic fertilizers continues to rise, the farmers are beginning to skip the use of nutrients resulting in low yields. Consequently, this will decrease the scarcity of food products, with the prices of foods projected to continue skyrocketing.

Ukraine and Russia export huge amounts of fertilizers and foodstuff. These countries largely control the food and fertilizer in the global market (Ali *et al.,* 2022). A number of studies of the economic and political consequences of the Russian-Ukrainian war were conducted. Thus, A. Ali et al. (2022) focused on the effects of war on the African economy, exploring the possibility of resource scarcity, rising energy and food prices for different countries. While considering theoretical scenarios of Russia's invasion of Ukraine, V. Astrov et al. (2022) analyzed their possible consequences, paying special attention to the issue of energy trade. I. Liadze et al. (2022) developed a global econometric model and used it to study changes in world GDP due to the conflict in Ukraine, in particular, created forecasts for European countries. They claim that since the war began, important raw materials for fertilizers such as ammonia, phosphates, nitrates and phosphates, sulfates, and potash prices have gone up by 30% (Liadze *et al.,* 2022). The spike in these raw materials has hit a record high since the food and energy crisis experience during the 2007-2008 global financial crisis (Prices, 2022). Russia, which accounts for more than 12% of the global fertilizer production and export, has temporarily suspended its production and exportation, affecting the global agricultural food production and market as the effects can already be felt, especially with the hike in food prices across the globe (Outlaw *et al*., 2021).

The scientific novelty of the article is that the authors consider the impact of the war on prices for organic fertilizers and agricultural production, given the events of the first months of the Russian-Ukrainian war. Research focuses on how the war affected organic fertilizers and further restrictions on crop production.

The purpose of this research is to analyze the impact of the Russia-Ukraine war on organic fertilizers and agricultural production and growth and the relationship between rising organic fertilizer production costs and agricultural production.

MATERIALS AND METHODS

The research utilized a systematic method for data collection, in which published data relevant to the study were extracted for analysis. Databases such as Google scholar and Agricultural and Food Policy Center (AFPC) were used. The inclusion criteria determined the use of published and original data below five years. Commentaries and abstracts were further excluded from the study. The search terms used included "Russia-Ukraine war", "organic fertilizers", "agriculture produce", and "supply shock".

During the systematic research, AFPC and Google Scholar databases were used. Data collected was analyzed using the Farm Economics and Solvency Projector (Farm ESP), developed by Dr. Henry Bryant (Outlaw *et al.*, 2021). The model is used to analyze the changes in farm produce concerning the change in the fertilizer prices. The inflation rates of fertilizers were recorded and evaluated for the 64 crop farms in Texas. The Farm ESP model of analysis assumed that all the fertilizers used in the farms were purchased in 2022 (Outlaw *et al.,* 2021). The inflation rates were analyzed based on the policies and prices of the Food and Agricultural Policy Research Institute (FAPRI). The model analyzed the changes in seed prices of organic fertilizers compared to the agricultural produce in Texas.

The study analyzed the prices of agricultural produce in Texas, including corn, sorghum, soybeans, oats, and wheat, from 2019 to 2022.

RESULTS AND DISCUSSION

The results indicate a sporadic increase in the prices of these products, as indicated in Table 1. The results also indicate a rising scale in the input prices for organic fertilizers such as Nitrogen, potash, and phosphate from

2020 to 2022, as indicated in Table 2. The inflation of organic fertilizers has increased sporadically. According to the FAPRI baseline, the nitrogen baseline has increased from 9.94% and to a higher fertilizer scenario of 55.43% and 13.61% to 50.84% for potash and phosphate, as shown in Table 3.

***Table 1**. Updated crop prices*

Crop prices	2019	2020	2021	2022
Corn ($/bu)	3.56	4.40	4.43	5.67
Sorghum ($/bu)	3.34	4.87	4.88	5.90
Soybeans ($/bu)	8.34	5.87	10.34	12.90
Oats ($/bu)	2.67	2.89	3.01	3.99
Wheat ($/bu)	4.58	4.59	5.37	6.91

***Source**: Outlaw et al., 2021*

***Table 2**. Change in organic fertilizer prices*

Organic fertilizer input price	2020	2021	2022
Nitrogen (%)	-3.22	7.29	9.94
Potash (%)	-0.79	5.87	13.61
Phosphate (%)	-6.05	4.78	7.67

***Source**: Outlaw et al., 2021*

***Table 3**. Change in organic fertilizer*

Nutrient	FAPRI baseline 2021	Higher fertilizer scenario 2022
Nitrogen (%)	9.94	55.43
Potash and phosphate(%)	13.61	50.84

***Source**: Outlaw et al., 2021*

From the results, the Russia-Ukraine war has developed a supply shock in fertilizer production and exportation throughout the global market. From the results, the war has led to increased organic fertilizers input prices. Nitrogen input price was – 3.22 and 7.29 in 2020 and 2021, but sporadically increased to 9.94 in 2022. Potash input price in 2020 and 2021 was at – 0.79 and 5.87, but rapidly increased in 2022 to 13.61. Moreover, phosphate fertilizer has followed the same trend from – 6.05 in 2020 to 7.67 in 2022. The FAPRI baseline shows that Nitrogen increased from 9.94% by six times the percentage to 55.43%, with the same trend visible in the potash and phosphate organic fertilizers. The increase in the organic fertilizer prices due to its inadequacy and supply shock due to the war has led to increasing food prices. As the leading exporters of maize and wheat and tons of these exports were sabotaged because of the war, crop prices have shot up sporadically. For example, from the results, corn, whose price was 3.56 $/lb in 2019, has risen 5.67 in 2022. Wheat, whose selling price was 4.58 $/bu, is now 6.91$/bu.

The war has already caused an immense supply shock in the production and supply of this important commodity. This means that as the cost of organic fertilizers continues to rise, the farmers are beginning to skip the use of nutrients resulting in low yields. Consequently, this will decrease the scarcity of food products, with the prices of foods projected to continue skyrocketing. The results further suggest a threat in the global supply of food products influenced by the supply and disruption of the supply chain in shipments of food products and organic fertilizers from Russia and Ukraine, given the ongoing war. The prices of food are projected to continue skyrocketing because farmers also have to make a profit despite the harsh production environment. According to A. Ali et al. (2022), the inadequate supplies for products, especially affordable food products, like barley and wheat, raise the potential risk of food shortages, especially in Africa, some Asian countries, and the Middle East.

To minimize the supply shock of organic fertilizers due to the ongoing war, international bodies, such as Food and Agricultural Organization, should ensure that the supply chain remains operational in all channels, including logistical systems, livestock protection, standing crops, and food processing infrastructure (Bakst *et al.*, 2022). For global countries to remain resilient to the already felt supply shock in organic fertilizers and subsequent agricultural production, countries, especially those that heavily depend on exportations from Ukraine and Russia, should begin diversifying food production alternatives and sources. With the vulnerable groups and developing countries being hit the most due to the war, there is a need to develop social protection interventions and close monitoring of alternative food sources and farm inputs (Husseini, 2022).

Economies around the globe are already dealing with the detrimental effects of COVID-19 which has severely affected the livelihood of people across the globe (Hosseini, 2022). With many economies at their feet and almost on the verge of collapse, the Russia-Ukraine war is not only another slap in the face but also increased a prolonged period of economic risks and survival. Given the market's vulnerability for oilseeds and grains, the world is staring at one of the most severe times of food price inflation in the contemporary world, given the importance of Russia and Ukraine's position in the market (Kalotay, 2022). Among the regions bound to be affected by the rising prices of organic fertilizers for agricultural plants and production in Latin America and India. According to Hussein (2022), Latin America is highly exposed to the risk of underproduction and complete sabotage of agricultural produce due to the spiking prices of potash and phosphates, which are critical in the production process (Bakeltis, 2022). To be more specific, Latin America is specialized in soybean production, which requires high levels and continuous availability of potash and phosphates (Deng *et al.,* 2022). Russia temporarily stopped production and exportation of these fertilizers, sanctions are imposed on Belarus, Ukraine is at its lowest level of economic, political, and social stability due to the war. It all led to the soybean production facing uncertain times and possible compromise. It is also important to note that Belarus, Ukraine, and Russia make up to 45% of potash production and export, hence controlling the market for these essential organic fertilizers (Yousaf *et al.,* 2022).

Farmer relies on the application of essential organic fertilizers such as Nitrogen (K), potash (K), and phosphate (P) for increased growth and production (Kirilenko and Dronin, 2022). All these organic fertilizers can be accessed globally, with the main producers being Russia, Ukraine, and Belarus. Russia is a particularly major producer of Nitrogen and Potash, as shown in Figure 1. In addition, Russia is also a key producer of nitrogen fertilizer raw material, natural gas, which is mostly exported to the European Union members and India (Nevzorova, 2022). The Russia-Ukraine war and, most especially, the sanctions imposed on Russia have led to the latter being cut off from the global market, thus limiting the production and exportation of these essential organic fertilizers (Korovkin and Makarin, 2021). This phenomenon has increasingly created a supply shock and subsequent imbalance in the global supply and demand chain, thus limiting the production and exportation of Nitrogen and potash as this is being experienced and is much visible to the current market.

Nexus production and exports		Ammonia	Urea	Ammonia Sulfate	Ammonia Nitrate	Calcium Ammonium Nitrate	Phosphate Rock	Phosphoric Acid	Mono-ammonium Phosphate	Di-ammonium Phosphate	Muriate of Potash
Belarus	Production	0.59%	0.68%	0.71%	1.19%	0.00%	0.00%	0.43%	0.04%	0.00%	17.48%
	Exports	0.13%	0.42%	0.06%	0.00%	0.00%	0.00%	0.00%	0.06%	0.00%	20.51%
Russia	Production	10.53%	5.33%	6.27%	25.44%	3.74%	8.43%	7.93%	9.67%	4.24%	19.01%
	Exports	22.71%	13.91%	2.54%	45.81%	4.14%	9.18%	0.00%	14.52%	8.24%	20.66%
Ukraine	Production	1.51%	1.74%	0.19%	3.32%	1.33%	0.00%	0.00%	0.01%	0.00%	0.00%
	Exports	0.91%	2.94%	0.05%	0.84%	1.80%	0.00%	0.00%	0.00%	0.00%	0.00%

Countries/regions with greatest need for supply chain adjustment if trade is impacted

Nitrogen			Phosphates		Potash
Ukraine Belgium Finland Europe Middle East & Africa	Brazil Estonia Peru Europe North America Middle East & Africa	Brazil Estonia Latin America Europe Former Soviet Union Middle East & Africa	Brazil Estonia Latin America Europe Former Soviet Union Middle East & Africa	Belgium Latin America Europe Former Soviet Union North America	Brazil US Europe Latin America Middle East & Africa Southeast Asia

***Figure 1**. The vulnerability of the war on Ukraine, Russia, and Belarus on the global share of Nitrogen, potash, and phosphate production*

***Source**: IFA (2022)*

According to Ozil (2022) and Meena (2022), Nitrogen price has been on a sporadic rising scale since the war began, and this phenomenon can be explained using two factors and reasons. Firstly, potash (K) is supplied by three major countries which are Belarus, Ukraine, and Russia and sell to other importers, meaning that they have total control in determining and influencing the price of this fertilizer (Astrov *et al.,* 2022). Secondly, the sanctioning of Belarus due to the 2021 reports on the country suppressing and victimizing protest and now in support of Russia on its invasion of Ukraine has further impacted the supply and demand chain for these organic fertilizers, given that Belarus and Russia combined, control over 40% of the potash and nitrogen global exportations as shown in figure 1 (Paulson *et al.,* 2022; Hosseini, 2022).

To critically understand the severity of the Russia-Ukraine war, it is important to look at how the organic fertilizer rising prices will affect different countries. According to Nagarjuna (2022), the direct and severe impacts of the war on organic fertilizer have already been felt in India. India is at its peak of sowing for the next season to plant farm produce such as cotton, rice, and corn at the beginning of June. This process is likely to be sabotaged or delayed because all this production depends on Nitrogen, potash, and phosphate fertilizers whose prices have skyrocketed due to the war (McWilliams *et al*., 2022). Brazil is also starring indirect sabotage of its soybean production, which depends on the potash and Nitrogen fertilizers produced and imported from Russia and Ukraine. Brazil imports over 40% of its potash and Nitrogen fertilizers from Belarus, Russia, and Ukraine (Dent and Boincean, 2021; Gutiérrez-Moya *et al*., 2021). Latin America has also been impacted, especially in producing its large-scale wheat that depends on potash fertilizers from Russia and Ukraine.

The Russia-Ukraine war exposes the global market to greater food risks due to inadequate raw materials and subsequent unmet import and export demand (Oxford Analytica, 2022). Before the war began, Ukraine was scheduled to export more than 6million tons of wheat across the global market, while Russia was estimated to export more than 8 million tons of wheat across the global market (Alyukov, 2021). According to the Food and Agriculture Organization (FAO) estimates, before the war began, Ukraine and Russia were expected to export more than 14 million tones and 2.5 tons of maize across the global market (Finance, 2022; Lang and McKee, 2022). All these exportations have been hugely hindered either partially or completely, especially from the Ukraine side more than Russia.

Given the uncertainty of the war in regards to the scale of destruction, damage, and the duration that the war will last, researchers have pointed out two essential scenarios that are likely to play out in regards to organic fertilizers and agricultural production in the coming months and years (Zhongming and Wei, 2022). The majority of these researchers have made diverse scenarios assuming that the price of natural oil, which is the primary raw material for organic fertilizer, will continue rising. One of the real scenarios is that the rise in natural oil prices will subsequently increase the price of organic fertilizers for the next five years (Oxford Analytica, 2022). This scenario provides a complete projection from the one that has been previously given based on the COVID-19 recovery and growth rate for both countries. Before the war, the two countries had projected a rise in growth and development of the national gross domestic product (GDP) over the next five years, a projection which has failed due to the eruption and continuity of the war till now (Blinnikov, 2021).

According to E. Mammadov (2022), another scenario is that even though there would be alternative producers that will respond to the higher prices of organic fertilizers and agricultural products to replace Russia and Ukraine, there would still be a considerable supply gap in the global market (Hunt *et al.,* 2021). Additionally, even though most of both countries' cereals will be ready for harvesting from June, the uncertainty at the end of the war poses a huge risk in harvesting thus causing a huge threat to the global food security (Lun *et al.,* 2021). The war threatens the availability of labor and farmers to tend the crops in cultivating, sowing, harvesting, marketing, and selling the farm produce (Boincean and Dent, 2019).

CONCLUSIONS

The Russia-Ukraine War has escalated the supply shock to organic fertilizers for agricultural growth and food production across the global market. The research results indicate that the supply shock of organic fertilizers due to the war has negative impact due to increased inflationary pressures. It will lead to a sharp rise in prices for fertilizers and food. This is due to the fact that Ukraine and Russia are the leading producers of agricultural products worldwide. Additionally, Russia is the leading producer and exporter of natural gas, the primary raw material for manufacturing organic fertilizer.

With the war and many sanctions imposed on Russia, the production and exportations operations have been heavily affected by being disrupted or temporarily stopped. This means that Ukraine and Russia largely control the food and fertilizer in the global market, and therefore, the war has a direct impact on food production, hence the skyrocketing prices being experienced. Nitrogen, potash, and phosphate prices have been on a rising scale since the war began as these countries are the main producers and exporters of these fertilizers. The war has caused civil unrest, population displacement, and migration. There are great risks in cultivating and harvesting farm produce and uncertainty in marketing and sales.

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Шок пропозиції органічних добрив для сільського господарства, що спричинені наслідками російсько-української війни

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Анотація. Україна та Росія є одними з провідних світових виробників сільськогосподарської продукції, на них припадає мільйони тонн світових продуктів харчування, а також виробництво та експорт органічних добрив. З огляду на це, російсько-українська війна спричинила величезний зрив і великий шок у постачанні органічних добрив і сільськогосподарського виробництва, а також цін на продукти харчування по всьому світу. Метою авторів було проаналізувати вплив російсько-української війни на сільське господарство, зокрема на органічні добрива та сільськогосподарське виробництво. У дослідженні використовувався метод систематичного дослідження для збору даних про масштаби впливу війни на органічні добрива та виробництво харчових продуктів. Результати дослідження свідчать про те, що війна призвела до порушення поставок органічних добрив, скорочення сільськогосподарської продукції та подальшого зростання цін на сільськогосподарську продукцію. Дослідження показують, що зростання вартості добрив безпосередньо впливає на виробництво та постачання продуктів харчування. Війна порушила життєздатне середовище для сільськогосподарського та органічного виробництва та експорту з інших країн, спричинивши зростання цін на продукти харчування та загрозу продовольчій безпеці в усьому світі. Необхідно забезпечити, щоб міжнародна торгівля стала більш гнучкою та відкритою у сфері виробництва та експорту добрив, харчових продуктів. Існує також потреба сприяти політичному діалогу та ринковому контролю, а також прозорості, особливо в умовах невизначеності світового продовольчого ринку через зриви, спричинені російсько-українською війною. Результати дослідження можуть бути використані науковцями, економістами та громадськими діячами для побудови подальших прогнозів стану сільського господарства, а також для побудови стратегій покращення економіки деяких країн, зокрема України

Ключові слова: шок ланцюга поставок, сільськогосподарське виробництво, ціни на продукти харчування, сировина, експорт добрив

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