SCIENTIFIC REPORTS OF THE NATIONAL UNIVERSITY OF LIFE AND ENVIRONMENTAL SCIENCES OF UKRAINE

Founder:
National University of Life and Environmental Sciences of Ukraine

Year of foundation: 2005

Recommended for printing and distribution
via the Internet by the Academic Council
of National University of Life and Environmental Sciences of Ukraine
(Minutes No. 14 of June 26, 2024)

State Registration:
Media identifier - R40-02082.
Decision of the National Council of Television and Radio Broadcasting of Ukraine
No. 1471, Minutes No. 28, dated 23.11.2023.

The journal is included in the list
of Professional Scientific Publications of Ukraine
Category "B". Specialties: 0511 – Biology, 0521 – Environmental Sciences,
0522 – Natural Environments and Wildlife, 0811 – Crop and Livestock Production,
0821 – Forestry, 0812 – Horticulture, 0841 – Veterinary
(Order of the Ministry of Education and Science of Ukraine No. 409 of 14 March 2020),
0715 – Mechanics and Metal Trades, 0716 – Motor Vehicles, Ships and Aircraft
(Order of the Ministry of Education and Science of Ukraine No. 886 of 02 July 2020).

The journal is presented international scientometric databases, repositories and scientific systems:
Google Scholar, Vernadsky National Library of Ukraine, BASE, AGRIS, Ulrichsweb, ERIH PLUS,
Dimensions, University of Oslo Library, OUCI (Open Ukrainian Citation Index),
Polska Bibliografia Naukowa

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НАУКОВІ ДОПОВІДІ НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ БІОРЕСУРСІВ І ПРИРОДОКОРИСТУВАННЯ УКРАЇНИ

Засновник:
Національний університет біоресурсів і природокористування України

Рік заснування: 2005

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Національного університету біоресурсів і природокористування України
(протокол № 14 від 26 червня 2024 р.)

Державна реєстрація:
Ідентифікатор медіа – R40-02082.
Рішення Національної Ради України з питань телебачення і радіомовлення
№ 1471, протокол № 28 від 23.11.2023 р.

Журнал входить до переліку
наукових фахових видань України
Категорія «Б». Спеціальності: 091 – Біологія, 101 – Екологія, 162 – Біотехнології та біоінженерія, 201 – Агрономія, 204 – Технологія виробництва і переробки продукції тваринництва, 205 – Лісове господарство, 206 – Садово-паркове господарство, 211 – Ветеринарна медицина, 212 – Ветеринарна гігієна, санітарія і експертиза (наказ МОН України № 409 від 14 березня 2020 року),
131 – Прикладна механіка, 133 – Галузеве машинобудування (наказ МОН України № 886 від 02 липня 2020 року).

Журнал представлено у міжнародних наукометричних базах даних, репозитаріях та пошукових системах:
Google Scholar, Національна бібліотека України імені В. І. Вернадського, BASE, AGRIS, Ulrichsweb, ERIH PLUS, Dimensions, University of Oslo Library, OUCI (Open Ukrainian Citation Index), Polska Bibliografia Naukowa

Адреса редакції:
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
E-mail: info@scireports.com.ua
https://scireports.com.ua/uk

Редакційна колегія

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Received 08.03.2024 Revised 06.06.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 636.087.7:633.14: 636.52/.58.082.35 DOI: 10.31548/dopovidi/3.2024.09

Chemical composition, energy content, and nutrient digestibility of rye grain in broiler chickens

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Abstract. The development of livestock farming is always associated with the search for new dietary components that increase feed efficiency or reduce feed costs. The maximum use of regional, conventional feed in the feeding of farm animals is quite relevant today. Furthermore, certain feeds, the production of which is accompanied by low greenhouse gas emissions, help reduce the carbon footprint of the diet as a whole. The purpose of this study was to determine the nutritional value of rye grain of the modern hybrid KWS Tayo and the digestibility of nutrients in poultry. The chemical composition of grain, digestibility of nutrients in broiler chickens, and total energy content were investigated. The chemical composition of feed, compound feed, and litter was determined according to the Wende method. Nutrient digestibility studies were conducted on broiler chickens of the ROSS-308 cross. For the physiological experiment, 5 chickens aged 22 days were selected. The experiment was carried out using a complex method, by replacing part of the basic diet. The experiment consisted of 2 parts. In the first experiment, the nutrient digestibility of the main diet was determined – compound feed containing 5% rye grain; in the second, the main diet with an additional 5% rye grain was used. The calculation was made on the assumption that the digestibility of nutrients in the main diet was the same in both experiments. The compound feed was balanced according to the recommendations of the cross developer. The energy content of rye grain was calculated in J of metabolisable energy by the regression equation, based on the data on the content

Suggested Citation:
Bilous, A., & Ilchuk, I. (2024). Chemical composition, energy content, and nutrient digestibility of rye grain in broiler chickens. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 9-19. doi: 10.31548/dopovidi/3.2024.09.

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of digestible protein, fat, fibre, and NFES determined in the physiological experiment. The average dry matter content of the rye samples was 87.4%. The content of the main nutrients in the grain of natural moisture was as follows: crude protein – 8.87 ± 0.484%; crude fat – 1.63 ± 0.105%; NFES – 73.95 ± 0.494%, and crude ash – 0.53 ± 0.109%. The nutrient digestibility of rye grain was as follows: crude protein – 76%; crude fat – 82%, crude fibre – 8%; NFES – 81% and organic matter – 78%. The total energy value of rye grain was 12.420 ± 0.2573 MJ/kg of metabolic energy for poultry. Nutritionists can use the nutritional and nutrient digestibility data of rye grain to develop practical recipes for poultry compound feed

Keywords: feeding; poultry; compound feed components; carbon footprint; feed efficiency

Introduction

The development of livestock farming is always associated with the search for new dietary components that increase feed efficiency or reduce feed costs. The maximum use of regional, conventional feed in the feeding of farm animals is quite relevant today. Chernozem soils cover up to 60% of Ukraine's territory. Sod-podzolic soils, which are found mainly in Polissia and contain up to 1.5% humus, are quite common. Grey forest soils in the southern part of Polissia and in the west and right bank of Ukraine also contain low humus content of up to 3% (Raza *et al.*, 2019). Oats and rye are conventional cereals that provide high yields under the prevailing soil and climatic conditions. Oats are a fairly conventional crop, but the situation with the use of rye in livestock feeding requires additional scientific research in Ukraine. Due to the rising cost of logistics, the existing local raw material base should be used as much as possible in feeding. The use of rye grain in livestock feeding will help reduce the carbon footprint of diets and the cost of logistics of feed components in conventional areas of its cultivation, as well as stimulate the development of livestock production.

According to the International Feed Industry Federation (n.d.), cereals, mainly maize, wheat, and sorghum, are the main components of poultry diets. Together with protein components, they form the basis of compound feed and meet the poultry's needs for essential nutrients and energy. The issue of using cheap local energy and protein sources is now very acute, as livestock production is expected to increase by 60% by 2050 amid population growth.

To meet the need for feed, a considerable number of alternative energy sources are being researched, including wheat, barley, and rye. D. Bederska-Łojewska *et al.* (2017) found that rye (*Secale cereale*) is resistant to fungal diseases, has a high tolerance to low temperatures, drought, and soil acidity, and provides high yields.

R. Lazaro *et al.* (2004) recognised rye as one of the crops with the most negative impact on performance when fed to poultry. The high concentration of soluble non-structural polysaccharides in rye increases the viscosity of feed masses in the gastrointestinal tract. Rye contains non-starchy polysaccharides, which leads to a decrease in the absorption of nutrients in the diet. This is conditioned by the fact that poultry have few or no endogenous enzymes capable of hydrolysing these non-starch polysaccharides. J.D. Latorre *et al.* (2014) found that exogenous carbohydrates are used as feed additives to reduce the negative effects of polysaccharides. D. Boros & M.R. Bedford (1999) showed that the nutritional value of rye for broiler chickens can be improved by breeding and growing rye varieties and hybrids with lower levels of anti-nutrients and by selecting suitable feed enzymes that can hydrolyse and reduce the viscosity of feed in the gastrointestinal tract and increase nutrient absorption. The work of breeders E. Makarska *et al.* (2007) focuses on

the development of new rye varieties and hybrids with reduced concentrations of antinutrients. They achieved reductions in alkylresorcinols, trypsin inhibitors, and ergot damage.

According to the findings of A. Arczewska-Wlosek *et al.* (2019), modern rye hybrids can be used at the level of 20% of the diet of broiler chickens aged 22 to 42 days of life, without any negative impact on growth performance. The additional use of enzyme additives (xylanase) has a positive effect on live weight gain and feed digestibility in chickens aged 1 to 21 days. Furthermore, according to L. Riedesel *et al.* (2022), rye is characterised by a low carbon footprint, and breeding in recent years has reduced this figure by 13-23% (rye is 8% lower than wheat).

Many researchers are investigating the effectiveness of feeding different levels of rye grain in broiler diets and their impact on growth and development. The effectiveness of feed additives and their impact on the gastrointestinal tract of poultry are widely covered. Therewith, little is known about the digestibility of various components of rye without the use of enzymes. This will allow for a better understanding of the selection of the best set of enzymes when formulating diets for broiler feeding, as well as assessing the effectiveness of their use in the future. Thus, the study of the digestibility of rye grain nutrients in broiler chickens is quite relevant.

The purpose of this study was to determine the nutritional value of rye grain of the modern hybrid KWS Tayo and the digestibility of nutrients in poultry.

Materials and Methods

Studies of the chemical composition and digestibility of nutrients of rye grain of the KWS Tayo hybrid were conducted in 2023-2024 in the research laboratory of feed additives of the P.D. Pshenychnyi Department of Animal Nutrition and Feed Technology of the National University of Life and Environmental Sciences of Ukraine in physiological experiments on broiler chickens of the *ROSS-308* cross, using a complex method, by replacing part of the main diet (Table 1).

Table 1. *Scheme of physiological experiment to determine the digestibility of rye grain nutrients in broiler chickens*

Experiment	Feeding	Experimental periods	Age, days
first	BR	preparatory	22-25
		accounting	26-30
second	95% BR + 5% rye grain	transitional	31-33
		preparatory	34-37
		accounting	38-42

Note: BR – basic ration (compound feed including 5% rye grain)
Source: developed by the authors of this study

All experimental studies were conducted following the modern methodological approaches and corresponding requirements and standards that follow DSTU ISO/IEC 17025:2005 (2006). The animals were kept and all manipulations were performed following the provisions of the Procedure for conducting experiments and experiments on animals by scientific institutions (European convention for the protection of vertebrate animals..., 1986; Law of Ukraine No. 249, 2012).

The physiological experiment was conducted on 5 broiler chickens aged 22-42 days. The chickens were kept in individual cages. The area per head was 0.2 m^2, the feeding front was 25 cm, and the watering front was 3 cm. The experiment consisted of 2 parts. In the first experiment, the

nutrient digestibility of the main diet was determined – compound feed containing 5% rye grain; in the second, the main diet with an additional 5% rye grain was used.

Each experiment consisted of a preparatory and a main period. During the preparatory period of the experiment, the chickens were accustomed to the consumption of the test feed and new housing conditions, and the level of feed consumption was established. During the accounting period, careful records were kept of the feed consumed by each animal, its residues, and the litter produced. The litter was collected from each animal separately in a corresponding container, weighed, and the samples were stored in glass jars, preserved with hydrochloric acid solution. Every day, samples of the feed and food consumed were taken into jars stored in the refrigerator. Between the first and second experiments, a 3-day transition period was introduced, during which the feed intake of the second experiment was checked. The nutrient digestibility of rye grains was calculated using two experiments. The calculation was made on the assumption that the digestibility of nutrients in the main diet was the same in both experiments.

The chemical composition of the compound feed was determined according to the Wende method. Laboratory analyses of feed and litter were performed according to current methodologies that follow Commission Regulation (EC) No. 152/2009 (2009) laying down methods of sampling and laboratory testing for official feed control. Dry matter was determined by drying in an oven, total moisture – at 65 ± 2 °C, hygroscopic moisture – at 103 ± 2 °C, using a Labexpert 3030 drying oven (Ukraine). The following was determined in dry matter:

- Crude ash – by burning the sample in a muffle furnace at 550 ± 20 °C. A muffle furnace SNOL-8.2/1100 (Lithuania) was used for combustion.
- Nitrogen was determined according to the Kjeldahl method. Gerhardt Turbotherm TT-625 (Germany) was used for ashing the feed, and Gerhardt Vapodest 300 (Germany) was used for distillation. Nitrogen was converted to crude protein by multiplying by a factor of 6.25. Urine nitrogen was separated from faecal nitrogen using the Dyakov method.
- Crude fat was determined according to the Soxhlet method using Gerhardt Soxtherm SOX 412 (Germany). Diethyl ether was used as an extractant.
- Crude fibre was determined according to the Henniberg and Stoeman method by washing the sample in dilute sulphuric acid and potassium hydroxide using the Gerhardt FibreBag-System FBS6 (Germany).
- Nitrogen-free extractables were determined by calculating the difference between the organic matter content and the sum of crude protein, crude fat, and crude fibre.

In the first experiment, the nutrient digestibility of the base compound feed was determined, the composition of which is presented in Table 2.

Table 2. *Composition of basic compound feed for experimental broiler chickens, %*

Component	Content
Rye grain (hybrid KWS Tayo)	5.00
Wheat grain	32.00
Maize grain	30.15
Soybean cake	19.00
Meat meal	12.00
Table salt	0.16
Limestone	0.40
DL-methionine for feed	0.29
Premix*	1.00

Note: the premix contained capillary wormwood (*Artemisia capillaris*) powder (Ibatullin *et al*., 2022)
Source: developed by the authors of this study

In the second experiment, chickens were fed a diet consisting of 95 parts of base compound feed and 5 parts of rye grain. The chemical composition and nutritional value of the compound feed is presented in Table 3. The compound feed was balanced according to the recommendations of the cross developer. The diets of experiments 1 and 2 differed in nutritional value by ± 1.83%. The energy content of rye grains was calculated in J of metabolic energy using the regression equation, based on the data on the content of digestible protein, fat, fibre, and nitrogen-free extractive substances (NFES) determined in the physiological experiment:

$$ME = (17.84\ dP + 39.78\ dF + 17.71\ dF + 17.71\ dNFES) \times 10^{-3}. \quad (1)$$

Table 3. *Nutritional value of 100 g of compound feed for broiler chickens in the first and second experiments*

Indicator	First experiment	Second experiment
Metabolic energy, MJ	1.300	1.235
Crude protein, g	20.65	20.06
Crude fat, g	4.56	4.41
Crude fibre, g	2.62	2.61
Nitrogen-free extractive substances, g	58.64	59.42
Calcium, g	0.91	0.86
Phosphorus, g	0.64	0.63
Sodium, g	0.26	0.24
Lysine, g	1.06	1.03
Methionine + cystine, g	0.83	0.80
Tryptophan, g	0.22	0.21

Source: developed by the authors of this study

The biometric processing of the data obtained during the study was performed using MS Excel 2013 software with built-in statistical functions. The results are presented as mean ± standard deviation (x ± SD). Differences between groups of birds were calculated using the t-test. The following significance levels were used for the study: $p < 0.05$, 0.01, and 0.001.

Results and Discussion

The results of the study of the chemical composition of rye grain are presented in Table 4.

Table 4. *Chemical composition of rye grain*

Indicator	Content, %	
	in the dry matter of the feed	in terms of natural humidity
Water	–	12.56 ± 0.456
Dry matter	100	87.44 ± 0.456
Crude protein	10.14 ± 0.581	8.87 ± 0.484
Crude fat	1.86 ± 0.112	1.63 ± 0.105
Crude fibre	2.82 ± 0.252	2.47 ± 0.231
Nitrogen-free extractives	84.57 ± 0.437	73.95 ± 0.494
Crude ash	0.60 ± 0.122	0.53 ± 0.109

Source: developed by the authors of this study

The average dry matter content of the rye samples was 874 g/kg, and the moisture content was 126 g/kg. The crude protein content was 101.4 g/kg in dry matter and 88.7 g/kg in natural moisture feed. M. Nilsson *et al.* (1997) obtained an analogous crude protein content in rye grain – 87 g/kg. However, most researchers report 3-35% more crude protein compared to the results obtained in the laboratory. Thus, in the feed nutrition guide for the Polissia Zone of Ukraine, the crude protein content of rye grain is 91 g/kg, which is 2.6% higher (Karpus *et al.*, 1994). For the natural and climatic zone of the Forest-Steppe of Ukraine, the crude protein content is 102 g/kg, which is 15.0% higher (Karpus *et al.*, 1995). For the Steppe zone, this figure is 117 g/kg, which is 31.9% higher than the data obtained in this experiment (Karpus *et al.*, 1993). I. Ibatullin & O.M. Zhukorskyi (2016) indicate a possible fluctuation in crude protein content from 90 to 110 g/kg with an average in Ukraine of 98 g/kg, but this figure also exceeds the one obtained in the experiment by 10.5%. Comparable data were obtained in studies of rye grain by D. Boros *et al.* (1995) and T. Antoniou & R.R. Marquardt (1981), where the crude protein content ranged within 94-99 g/kg. Somewhat higher values of crude protein content in rye grain were obtained by American scientists M.E. Ensminger *et al.* (1990) and M.H. Jurgens & K. Bregendahl (2007) – within 120 g/kg, which is 35% higher than the value obtained in this study.

The study of crude fat in rye grain showed its content of 18.6 g/kg dry matter and 16.3 g/kg natural moisture. The crude fat content of rye in the Polissia zone of Ukraine is 27 g/kg, which is 65% higher (Karpus *et al.*, 1994). In the Forest-Steppe zone, researchers report a slightly lower fat content of 15 g/kg (Karpus *et al.*, 1995). A comparable figure for rye was obtained in the Steppe zone of Ukraine – 16 g/kg (Karpus *et al.*, 1993). Researchers from the USA M.E. Ensminger *et al.* (1990) and M.H. Jurgens & K. Bregendahl (2007) report the same crude fat content in rye grain as in the Forest-Steppe zone of Ukraine – 15 g/kg. I. Ibatullin & O.M. Zhukorskyi (2016) indicate a possible crude fat content of up to 29.9 g/kg.

The crude fibre content of the natural moisture feed was 25 g/kg. This figure was slightly lower than previously published feed chemical composition data. In the Polissia zone of Ukraine, this figure was 34 g/kg, or 36% higher (Karpus *et al.*, 1994). In the Forest-Steppe zone of Ukraine, the crude fibre content is reported to be 45 g/kg, which is 80% higher than the research data (Karpus *et al.*, 1995). For the Steppe zone, the figure is 28% higher – 32 g/kg (Karpus *et al.*, 1993). I. Ibatullin & M.O. Zhukorskyi (2016) provide data on the possible crude fibre content in feed ranging within 20-47 g/kg, with the average for Ukraine being 33.7 g/kg. Researchers from the USA M.H. Jurgens & K. Bregendahl (2007) cite a fibre content of 22 g/kg.

The studied rye grain samples contained 739.5 g/kg of nitrogen-free extractive substances. This indicator corresponded to the highest possible values for Ukraine (Ibatullin & Zhukorskyi, 2016). However, the analysis of most of the data shows that the figure is 5-9% higher than the existing data. Thus, for the Polissia zone it is 675 g/kg, for the Forest-Steppe – 681 g/kg, and for the Steppe – 676 g/kg (Karpus *et al.*, 1993; 1994; 1995). Other researchers cite a slightly higher value of nitrogen-free extractive substances previously published for Ukraine, but lower than the one obtained by the laboratory – 700 g/kg (Ensminger *et al.*, 1990; Jurgens & Bregendahl, 2007).

The results of the study of nutrient digestibility of rye grains and the calculated digestibility coefficients are presented in Table 5.

Table 5. *Nutrient digestibility coefficients of rye grain, %*

Nutrient	Experimental animal No.					x ± SD
	1	2	3	4	5	
Crude protein	77.96	76.09	75.44	75.72	74.40	75.92 ± 1.164

Table 5. *Continued*

Nutrient	Experimental animal No.					x ± SD
	1	2	3	4	5	
Crude fat	85.90	84.96	80.58	79.93	79.08	82.09 ± 2.782
Crude fibre	13.82	8.59	8.73	6.47	4.01	8.33 ± 3.240
Nitrogen-free extractives	83.40	81.28	80.71	78.97	80.52	80.98 ± 1.432
Organic matter	79.91	78.04	77.19	76.09	76.59	77.56 ± 1.342

Source: developed by the authors of this study

Crude protein digestibility averaged 75.92%. The fluctuations in the index among the experimental broiler chickens ranged within 74.40-77.96%. There is a limited amount of data in the literature on the digestibility of rye nutrients for poultry, but I. Ibatullin *et al.* (2015) reported a slightly lower crude protein digestibility of 69%. Comparing the data obtained with the experiments conducted on monogastric animals, such as pigs, the digestibility coefficients of crude rye protein range within 80-82% (Karpus *et al.*, 1993; 1994; 1995). M. Ensminger *et al.* (1990) reported a comparable crude protein digestibility rate in pigs of 76%. The digestibility of crude fat averaged 82.09%, crude fibre – 8.33%, and nitrogen-free extractive substances – 80.98%. The data differ slightly from the digestibility coefficients for rye grain reported in the literature. I. Ibatullin *et al.* (2015) report crude fat digestibility coefficients of 25%, which is 57% lower, crude fibre digestibility of 3%, which is 5% lower, and nitrogen-free extractive substances of 85%, which is 3% higher than the data obtained.

The results of calculating the energy value of rye grain are presented in Table 6.

Table 6. *Energy content of rye grain, MJ of metabolisable energy*

Nutrient	Chemical composition, g/kg	Energy content, MJ					x ± SD
		1	2	3	4	5	
Crude protein	88.93	1.237	1.207	1.197	1.201	1.180	1.205 ± 0.0206
Crude fat	16.29	0.557	0.551	0.522	0.518	0.512	0.532 ± 0.0202
Crude fibre	24.73	0.061	0.038	0.038	0.028	0.018	0.036 ± 0.0159
Nitrogen-free extractives	742.40	10.965	10.687	10.612	10.383	10.587	10.647 ± 0.2107
Total energy content, MJ	–	12.819	12.482	12.369	12.131	12.297	12.420 ± 0.2573

Source: developed by the authors of this study

The total energy value of the rye grain was 12,420 MJ of metabolisable energy. The largest share of rye energy was provided by easily digestible carbohydrates of nitrogen-free extractive substances – 10,647 MJ, which was 85.7%. Crude protein energy accounted for 9.70%, or 1,205 MJ. Crude fat accounted for only 4.28%. Considering the low digestibility of raw fibre, it accounted for only 0.32%.

The total energy value of rye grain calculated from the nutrient digestibility data obtained in these experiments differs slightly from that of other researchers. M. Ensminger *et al.* (1990) reported a 10.6% lower metabolisable energy

content for poultry in rye grain – 11.099 MJ/kg. M. Jurgens & K. Bregendahl, (2007) noted energy value of rye grain for poultry comparable to the findings of previous researchers – 11.103 MJ/kg. I. Ibatullin & O.M. Zhukorskyi (2016) report fluctuations in the energy value of rye grain within 11.34-14.22 MJ/kg, with an average value of 13.85 MJ in Ukraine, which is 12% higher than the data obtained.

Thus, the analysis of the chemical composition of a modern rye hybrid, its energy value, and nutrient digestibility allows revising the previously existing standards for its introduction into animal diets and compound feed. Lower crude fibre levels by 28-80% compared to previously published data, and low alkylresorcinols in modern rye hybrids (Milczarek *et al.*, 2020; Janiszewski *et al.*, 2021; Grabiński *et al.*, 2021) require further investigation.

The results of the chemical composition of rye grain showed that the content of the main nutrients, such as crude protein, crude fat, and crude fibre was lower than in the literature. The largest deviations were recorded in crude fibre content, which is 28-80% lower than previously published data, which may affect animal diets. The nutrient digestibility analysis confirmed that rye grain has good protein and carbohydrate digestibility, but low fibre digestibility. The findings underline the need to revise the standards for rye grain inclusion in animal diets.

Conclusions

The data on the chemical composition, energy value, and digestibility of nutrients of rye grain of the hybrid KWS Tayo in broiler chickens were obtained. 1 kg of rye grain contained: water – 12.56 ± 0.456%; dry matter – 87.44 ± 0.456%; crude protein – 8.87 ± 0.484%; crude fat – 1.63 ± 0.105%; crude fibre – 2.47 ± 0.231%; nitrogen-free extractive substances – 73.95 ± 0.494%, and crude ash – 0.53 ± 0.109%. The nutrient digestibility of rye grain was as follows: crude protein – 76%; crude fat – 82%; crude fibre – 8%; nitrogen-free extractive substances – 81%; and organic matter – 78%. The total energy value of rye grain was 12.420 MJ/kg of metabolisable energy for poultry. The obtained data on the chemical composition, energy value, and digestibility of nutrients of modern rye hybrid grain will be the basis for further research on the maximum levels of inclusion in poultry compound feed. Research also needs to be conducted on the impact of rye grain on the carbon footprint of broiler chicken compound feed.

The obtained findings confirm the possibility of using rye grain as an effective component of diets for broiler chickens, which has a significant potential in meeting their energy needs. However, the low digestibility of crude fibre can limit the share of rye in compound feed, especially for young poultry. The study also points to the need for more experiments on combining rye with other feed ingredients and enzyme preparations to ensure the best balance of nutrients. Specifically, this applies to determining the optimum levels of rye inclusion in diets depending on the age group of the poultry and the conditions of housing. Further research is needed to determine the maximum and effective levels of this component in broiler chicken compound feed, at different age periods, in combination with enzyme preparations, their impact on productivity, product quality, feed consumption and costs, production efficiency, and carbon footprint of diets.

Acknowledgements

The authors of this study would like to express their gratitude to KWS-UKRAINE LLC for the samples and support in the research.

Conflict of Interest

The authors of this study declare no conflict of interest.

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Хімічний склад, енергетична поживність та перетравність поживних речовин зерна жита у курчат-бройлерів

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Анотація. Розвиток тваринництва завжди пов'язується з пошуком нових компонентів раціону, які підвищують ефективність годівлі, або знижують вартість корму. Максимальне використання регіональних, традиційних кормів в годівлі сільськогосподарських тварин є досить актуальним в наш час. Крім того, окремі корми, виробництво яких супроводжується невисокими викидами парникових газів у атмосферу сприяють зниженню карбонового сліду раціону в цілому. Метою досліджень було визначити поживність зерна жита сучасного гібриду КВС Тайо та перетравність поживних речовин у птиці. Досліджено хімічний склад зерна, перетравність поживних речовин у курчат-бройлерів, розрахована загальна енергетична поживність. Визначення хімічного складу кормів, комбікормів та посліду проводили методом Венде. Дослідження перетравності поживних речовин проводили на курчатах-бройлерах кросу «РОСС-308». Для фізіологічного досліду було відібрано 5 курчат віком 22 доби. Дослід проводили складним методом, шляхом заміни частини основного раціону. Дослід складався із 2 частин. У першому досліді визначали перетравність поживних речовин основного раціону – комбікорму до якого входило 5 % зерна жита; у другому – основного раціону з введенням додатково 5 % зерна жита. Розрахунок вівся з умовою, що перетравність поживних речовин основного раціону під час обох дослідів була однаковою. Комбікорми були збалансовані за рекомендаціями розробника кросу. Енергетичну поживність зерна жита розраховували у Дж обмінної енергії за рівнянням регресії, за даними вмісту перетравних протеїну, жиру, клітковини та БЕР, визначеними у фізіологічному досліді. Середній вміст сухої речовини у дослідних зразках жита становив 87,4 %. Вміст основних поживних речовин у зерні натуральної вологості був наступним сирого протеїну – 8,87 ± 0,484 %; сирого жиру – 1,63 ± 0,105 %; БЕР – 73,95 ± 0,494 % та сирої золи – 0,53 ± 0,109 %. Перетравність поживних речовин зерна жита складала: сирого протеїну – 76 %; сирого жиру – 82 %, сирої клітковини – 8 %; БЕР – 81 % та органічної речовини – 78 %. Загальна енергетична цінність зерна жита склала – 12,420 ± 0,2573 МДж/кг обмінної енергії для птиці. Дані поживності і перетравності поживних речовин зерна жита можуть використовуватись нутриціоністами за складання практичних рецептів комбікормів для птиці

Ключові слова: годівля; птиця; компоненти комбікормів; карбоновий слід; ефективність використання корму

Received 28.02.2024 Revised 30.05.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 635.21:631.526.3:631.56 DOI: 10.31548/dopovidi/3.2024.20

Suitability of potato tubers of different varieties for processing

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Abstract. Drying is one of the most common ways to process potato tubers. To produce high-quality dried products, the quality of raw materials is crucial, and it depends on the varietal characteristics. The purpose of this study was to investigate the suitability of potato tubers of five varieties for convective drying without blanching. The study employed the experimental method according to the developed research scheme, the laboratory method was used to determine the organoleptic, morphological, and

Suggested Citation:
Zavadska, O., Iliuk, N., Ivanytska, A., Semenenko, S., & Mykhailyn, V. (2024). Suitability of potato tubers of different varieties for processing. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 20-30. doi: 10.31548/dopovidi/3.2024.20.

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biochemical quality indicators of fresh tubers and dry products, and the statistical method was used to process the research results mathematically. It was found that tubers of the Povin variety contained the greatest amount of dry matter and starch (24.6% and 18.4%, respectively), while vitamin C was found in Sante and Povin (over 11 mg%). The lowest amount of sugars was accumulated in the tubers of the Koroleva Anna variety – 0.32%. It was found that with an increase in the dry matter content of tubers, the starch content increases substantially (r = 0.98), and the sugar content significantly affects the degree of darkening of dry products (r = 0.74). The nitrate content of tubers of all varieties did not exceed the maximum permissible concentration. It was found that when potato tubers are used for convective drying, 17.1-24.5% of dry products can be obtained and 4.1-5.8 kg of prepared raw materials can be consumed. The dry matter content of the tubers and the amount of waste substantially affect the yield of the finished product. The most suitable for convective drying without blanching are the Koroleva Anna tubers, which provide a 24.5% yield of finished products with a tasting score of 5 on a 5-point scale. When using other varieties of tubers for convection drying, blanching or other methods should first be used to stabilise the colour. The materials of this study are of practical value for vegetable growers, breeders, and specialists of processing enterprises when choosing a potato variety for drying

Keywords: varietal characteristics; quality; tasting; darkening; drying; dry products

Introduction

Potato tubers, due to their high content of valuable compounds for consumers, their cost-effectiveness, and versatility, are of great global importance for food security. Ukraine is one of the world's five largest potato producers, growing 20-22 million tonnes of tubers annually. The breakdown of the tubers harvested is as follows: consumption by households is 33% (6.1 million tonnes); use for feed purposes is 20% (3.8 million tonnes); seeds are 27% (5 million tonnes); and processing is 1.0%. The number of fast-food outlets has grown considerably in Ukraine. In addition, due to Russia's aggression and frequent power cuts, demand for convenience foods, including dry mashed potatoes, has increased. Most potato products (over 90%) are imported. Only the creation of high-quality domestic products will help to displace imported products. Furthermore, the production of potato products will provide value-added products, filling the budgets of local communities and the country as a whole, which is important in the post-war reconstruction. Selecting potato varieties suitable for a particular processing method will not only guarantee quality products, but also reduce production costs (Davydenko *et al.*, 2020). According to H. Campos & O. Ortiz (2020), the versatility of potato tubers is determined by the content of a significant number of biochemical parameters. They accumulate about 26% of dry matter, of which 80-85% is starch and almost 3% is protein. Tuber carbohydrates are a valuable source of energy for the human body, while the protein is equivalent in quality to that of milk, eggs, and beef, and is superior to that of cereals, soybeans, and beans. M.M. Islam *et al.* (2022) note that the dry matter, starch, and reduced sugars content of tubers are crucial for the production of quality potato products.

Drying tubers is a relevant area of their processing. According to S. Chikpah *et al.* (2022), this is the way to preserve the biological valuable elements contained in fresh raw materials. Since the drying process removes free and some bound moisture, dry products are a stabilised concentrate of nutrients that can be easily transported and stored for a long time. In addition, the dry products do not contain any artificial or chemical preservatives, dyes, flavours, and after a short soak, they restore their properties. Dried tubers are used to produce dry mashed potatoes, chips, flakes, as additives for bakery products, etc.

There are many common points in the production technology of dried products. Specifically, both our long-term research and the studies of scientists from other countries have confirmed that their quality will significantly depend on the quality of raw materials, which is primarily determined by varietal characteristics, the content and ratio of macro- and microelements, drying methods, etc. O. Zavadska *et al*. (2020) found that one of the most common, cost-effective methods of drying vegetables, including potato tubers, is the convective method, which uses heated air. The quality and yield of dry products in convection drying depends primarily on the air temperature and the thickness of the cut pieces.

The most common defects in raw and processed tubers include darkening of the flesh. It is the appearance of food that affects commercial competitiveness and decisions about the suitability of its consumption. Furthermore, darkening of tubers can lead to a decrease in their nutritional and biological value. Scientists from different countries are investigating the causes of tuber flesh darkening and suggesting solutions to prevent it. Thus, S. Gunko *et al*. (2023) found a direct correlation between potassium content and the degree of darkening of potato tubers, namely, with an increase in potassium content in tubers, their resistance to darkening during heat treatment increases. Furthermore, the researchers argue that the ability to accumulate minerals in tubers is considerably influenced by varietal characteristics.

E. Wszelaczyńska *et al*. (2023) note that the tendency to darkening of tubers increases significantly due to stress factors arising during their cultivation and storage. Long-term storage leads to a 22% increase in total sugars and a 49% increase in reducing sugars. As noted by R. Hussain *et al*. (2022), it is the increase in the content of inverted sugars, including glucose, in tubers during their heat treatment (drying) that causes darkening of their flesh due to the appearance of dark-coloured melanoidins as a result of the reaction of sugars with amino acids. The conversion of starch to glucose also occurs during storage at low temperatures. A. Amjad *et al*. (2019) believe that the deterioration of tuber quality and an increase in the tendency to darkening is caused by non-compliance with the recommended temperature and humidity conditions during storage. The colour change of raw and cooked potatoes is also substantially affected by the temperature and duration of heat treatment (Syabana *et al.*, 2022).

To prevent colour changes or to obtain tubers that are more resistant to darkening, researchers suggest using biostimulants and hydrogels, which will reduce the effects of stress factors during plant cultivation. G. Bobo-García *et al*. (2020) note that the main enzyme regulating the tuber darkening is polyphenol oxidase. To reduce its activity, the researchers suggest using a variety of substances: chelating agents, inhibitors, natural extracts, and physical treatment.

Thus, darkening of the flesh of potato tubers is one of the key problems affecting the quality, nutritional value, and profitability of potato products. Therefore, the search for ways to solve this problem is relevant. Before drying, blanching of tubers is often used to prevent darkening of the finished product, but it leads to partial leaching and loss of nutrients and additional energy consumption, which increases production costs.

The purpose of this study was to investigate the suitability of potato tubers of different varieties for drying without additional processing. To fulfil the stated purpose, the tasks were identified as follows:

- to assess the quality of freshly harvested tubers and predict their suitability for processing;
- to determine the amount of waste in preparing tubers for drying and the yield of dried products;
- to assess the quality of dried products and the resistance of tubers to darkening without blanching before drying.

Materials and Methods

The study was conducted in 2022-2023. To fulfil the purpose and complete the objectives of the study, five potato varieties that are common in production were selected, namely: Svitanok

Kyivskyi, Koroleva Anna, Povin, Sante, and Tsyhanka. The Ukrainian variety Svitanok Kyivskyi, listed in the Register of Plant Varieties and recommended for the Polissia zone (State register of plant varieties…, 2020), was used as a control.

The economic, biological, and organoleptic analyses of potato tubers were performed in the scientific and educational laboratory of the Prof. B.V. Lesyk Department of Technology of Storage, Processing, and Standardisation of Crop Production of the National University of Life and Environmental Sciences of Ukraine according to generally accepted methods (Skaletska & Podpryatov, 2014). Freshly harvested tubers were evaluated for the content of the main biochemical parameters. Specifically, the dry matter content was determined by drying to a constant weight in an oven, starch – by specific weight, total sugars – by the cyanamide method, and vitamin C – by using a 2,6 dichlorophenolindophenol solution. A nitrate tester was used to determine the nitrate content.

To evaluate the suitability of potato tubers for drying, average samples of each variety weighing 4 kg were selected. Preparation of tubers for processing included weighing them, thoroughly washing, cleaning, and re-weighing (the difference was used to determine the amount of waste). The prepared tubers were cut into identical slices no more than 0.5 cm thick, evenly placed on the trays of a convective dryer DEXDFD-510P (TM DEX, DEXkee Elec-Technology Co. LTD, China) and loaded into the dryer chamber preheated to 60 °C (Fig. 1). The raw materials were dried until they were ready, which was determined organoleptically.

Figure 1. *General view of tubers prepared for drying and the convection dryer DEXDFD-510P*
Source: photographs taken by the authors of this study

The dry products were evaluated for a set of organoleptic and technological indicators, and their resistance to darkening was determined. The organoleptic evaluation of dry potatoes and the degree of their darkening were assessed on a 5-point scale according to the following gradation: 5 points – pieces are light, clean, white, or straw yellow, fully matching the colour of the raw material; 4 – up to 20% of the surface is slightly darkened; 3 – up to 40% of the surface is darkened; 2 – up to 60% of the surface is significantly darkened; 1 – pieces are darkened on the surface by more than 60%.

Determination of swelling dynamics and swelling coefficient of dried products. A 5 g sample was taken from the middle sample, 50 g of distilled water was added, and the sample was kept for one hour (60 min). After 20 min and 40 min of swelling, intermediate weighing was performed. The swelling coefficient was calculated as the ratio of the product weight after 60 minutes to the initial weight of the sample. The results were processed mathematically, and the least significant difference (LSD), correlations, and confidence intervals were calculated using generally accepted methods. The study was conducted following

the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992).

Results and Discussion

The formation of the chemical composition of potato tubers is a complex and lengthy process. It depends on a set of factors, the coincidence of which allows obtaining valuable or, conversely, unsuitable raw materials for processing. The yield and quality of dry products are substantially affected by the dry matter content of raw materials – high dry matter content ensures the profitability of processing and improves the quality of the finished product (Furrer *et al.*, 2018). According to A. Mazur (2013), an increase in the dry matter content of tubers by only 1% increases the yield of dried products by 1 kg per 100 kg of raw material, and the profitability of processing by 10-20%. French fries, crisps, or dried products made from tubers that contain little dry matter will be soft and watery (Amjad *et al.*, 2019). However, too high a content of dry matter will cause dryness, density, and brittleness of the finished products (Zavadska *et al.*, 2021). The most suitable tubers for drying are those containing at least 21% dry matter, including 14-16% starch and no more than 0.4% monosugars.

According to the results of the study, during the growing season, 19.5-24.6% of dry matter was accumulated in the tubers of the potato varieties under study (Table 1). The difference between the variants in this indicator reached 5.1%. It can be concluded that the dry matter content of tubers of all varieties, except for Tsyhanka, was suitable for drying. The highest dry matter content was found in tubers of the Povin variety – 24.6%, which is 2.2% greater than in the control.

Table 1. *The content of the main biochemical parameters in potato tubers of different varieties, average for 2022-2023*

Variety	Content in tubers				
	dry matter, %	starch, %	sugars (total), %	vitamin C, mg %	nitrates, mg/kg**
Svitanok Kyivskyi (control)	22.4 ± 0.8*	16.7 ± 0.4	0.36 ± 0.04	8.9 ± 2.2	138 ± 24
Koroleva Anna	23.1 ± 0.5	17.6 ± 0.2*	0.32 ± 0.03	8.5 ± 1.4	116 ± 18
Povin	24.6 ± 0.7	18.4 ± 0.3*	0.57 ± 0.04	9.6 ± 2.1	138 ± 16
Sante	21.9 ± 0.6	15.2 ± 0.3*	0.40 ± 0.03	11.4 ± 1.6	131 ± 26
Tsyhanka	19.5 ± 0.4*	13.7 ± 0.2*	0.62 ± 0.02	11.0 ± 1.8	107 ± 12

Note: * – values of biochemical parameters are mean values ± standard deviation (n = 3); ** – maximum permissible concentration (MPC) – 250 mg/kg
Source: developed by the authors of this study

K. Beals (2019) found that the basis of the dry matter of potato tubers is starch. Its share of the total dry matter content ranges within 70-80%. This pattern was confirmed in the present study. The starch content in tubers of the varieties under study ranged within 13.7-18.4%, which was 70-76% of the dry matter weight. The highest content of this element, as well as dry matter, was found in tubers of the Povin variety – 18.4%, which is 1.7% greater than in the control. The correlation analysis revealed a strong direct correlation between dry matter and starch content – r = 0.98, which confirms the data of A. Furrer *et al.* (2018) and previous findings of the authors of the present study.

According to E. Wszelaczyńska *et al.* (2023), the amount of sugars in tubers significantly depends on the varietal characteristics, their physiological state, growing conditions, and storage time. A. Amjad *et al.* (2019) found that freshly harvested tubers are typically characterised by a low sugar

content, averaging 0.5-0.6% per raw weight. The present study confirmed the dependence of sugar accumulation on varietal characteristics. Under the same growing conditions, the difference between the variants under study was substantial. Thus, in the tubers of the Koroleva Anna variety, they contained 0.32%, while in the Tsyhanka variety almost twice as much – 0.62% (0.26% more than in the control). According to this indicator, tubers of the Tsyhanka variety were unsuitable for drying without preliminary blanching and were predictably more prone to darkening compared to other variants under study.

O. Külen *et al.* (2020) proved that potato tubers also contain biologically valuable substances and vitamins, namely riboflavin, thiamine, pyridoxine, pantothenic and nicotinic acids, carotenoids, etc. However, only vitamin C, which can accumulate from 5 to 40 mg% in tubers, depending on the variety and growing conditions, has biological value. Ascorbic acid oxidises quickly and is quite sensitive to temperature, and therefore its amount is significantly reduced during heat treatment. In tubers of the varieties under study, the content of this element ranged within 8.9-11.4 mg%. Over 11 mg% of ascorbic acid was accumulated by fresh tubers of the Sante and Povin varieties. K. Hamouz *et al.* (2009) found that even the colour of tubers affects the content of this vitamin. The present study did not reveal such a pattern. Clearly, longer studies with more varieties are needed to confirm or refute this claim. As for the nitrate content, there was no significant difference between the variants, with an accumulation of 107-138 mg/kg. Tubers of Svitanok Kyivskyi and Povin varieties accumulated the most nitrates – 138 mg/kg. However, in none of the experimental variants did the actual nitrate levels exceed the MPC.

According to the previous findings of the authors of this study, the morphological characteristics of raw materials are also important for processing (Zavadska *et al.*, 2020). A. Mazur (2013) noted that the number of eyes in tubers suitable for processing should not exceed 7-8 and their depth should not exceed 1.5 mm. According to morphological parameters, tubers of all varieties under study met the requirements. The most suitable for processing in terms of the number of eyes were the Koroleva Anna (4.8 pcs.) and Povin (6.4 pcs.) tubers. The best performance in terms of the depth of the eyes was also achieved by tubers of the Koroleva Anna variety (0.57 mm) and Povin (0.87 mm). The amount of waste during tuber cleaning ranged within 15.0-23.3% and depended on the varietal characteristics (Fig. 2).

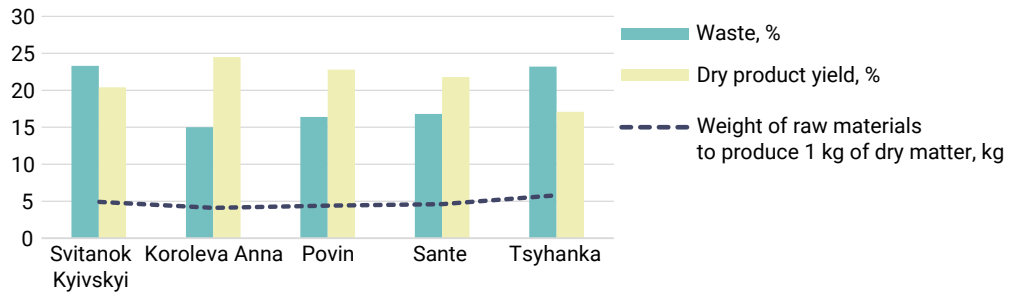

Figure 2. *Amount of waste, yield of dry products, and required weight of fresh raw materials to produce 1 kg of dry potato tubers of different varieties*

Note: * – control

Source: developed by the authors of this study

The largest amount of waste was obtained when cleaning tubers of Svitanok Kyivskyi (23.3%) and Tsyhanka (23.2%) varieties, while the smallest amount was obtained from Koroleva Anna (15.0%,

which is 8.3% less than in the control). This indicator was influenced by the number and depth of the eyes, as well as the presence of growths, mechanical damage, and pest damage. The yield of dried products significantly depended on the dry matter content of the raw materials and the amount of waste and ranged within 17.1-24.5%. Clearly, the largest amount of dry products was obtained from the Koroleva Anna variety tubers – 24.5%, which is 4.1% more than in the control variant. The calculations showed that 4.1 kg of fresh raw materials are required to produce 1 kg of dry products of this variety. The lowest yield of finished products was obtained using tubers of the Tsyhanka variety, which contained the lowest amount of dry matter – 17.1%, which is 3.3% less than the control. To produce 1 kg of dry products of this grade, 5.8 kg of raw materials were required. An important technological indicator of the quality of dried products, including potatoes, is their ability to recover, which is characterised by the swelling coefficient (Fig. 3).

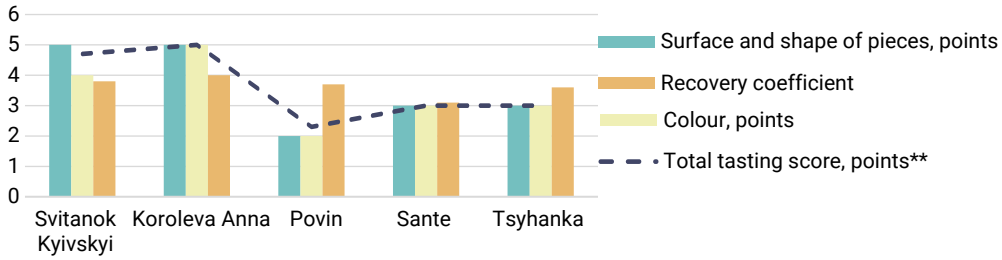

Figure 3. *Recovery factor, degree of darkening, and tasting evaluation of dried products from potato tubers of different varieties*

Note: * – control; ** – on a 5-point scale

Source: developed by the authors of this study

The results indicate that the best recovery rate was observed in samples of dry products of Koroleva Anna and Svitanok Kyivskyi varieties – the swelling coefficient was 4.0 and 3.8 units, respectively, the lowest was for the Sante variety (3.0). The most intensive recovery of dry products of all varieties occurred within 20 min from the beginning of soaking. To identify variants resistant to darkening of the flesh, the tubers were not blanched before drying. According to the study results, resistance to darkening significantly depended on the varietal characteristics. The most resistant to darkening without blanching before drying were the Koroleva Anna tubers. Dry and reconstituted products of this variety had a pleasant characteristic uniform cream colour, without darkening – 5 points (Fig. 4).

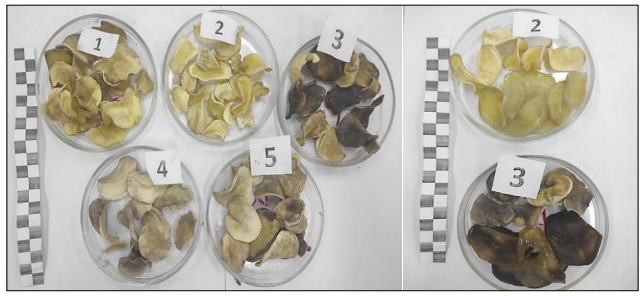

Figure 4. *General view of dried (A) and reconstituted (B) products from potato tubers of different varieties during tasting*

Note: 1 – Svitanok Kyivskyi; 2 – Koroleva Anna; 3 – Povin; 4 – Sante; 5 – Tsyhanka

Source: developed by the authors of this study

The organoleptic properties of dry and reconstituted products significantly depended on varietal characteristics, which is confirmed by C. Severini *et al.* (2010). Overall, the highest score in the finished product tasting was given to samples of the Koroleva Anna variety – 5.0 on a 5-point scale. The dry products of this grade were characterised by high resistance to darkening, fully retained the colour of the raw material, had a firm, elastic texture, and a uniform piece shape. During the tasting, the dry products of the control variety Svitanok Kyivskyi received quite high scores – 4.7 points on a 5-point scale. The least suitable for convection drying without blanching are Povin tubers. Dry samples of this variety received 2.3 points in the tasting. This low score was caused by the substantial darkening of dry and reconstituted products (1.8 points on a 5-point scale).

This study confirmed the findings of other researchers on the effect of sugar content in tubers on the degree of darkening of dry products, which is apparently caused by their interaction with amino acids and the formation of melanins (Bobo-García *et al.*, 2020; Hussain *et al.*, 2022), The correlation analysis revealed a significant direct relationship between these indicators – r = 0.74.

Thus, the findings of the present study suggest that the choice of potato variety substantially affects the quality of dry products and the efficiency of their production. The most suitable tubers for drying are those that accumulate the maximum amount of dry matter and starch, the minimum amount of sugars, have a small number of shallowly set eyes, and are highly resistant to darkening during heat treatment.

Conclusions

It was found that during the growing season, different amounts of reserve substances were accumulated in potato tubers of different varieties under the same growing conditions. The highest amount of dry matter and starch was contained in tubers of the Povin variety – 24.6% and 18.4%, respectively. The correlation analysis revealed a strong direct correlation between these indicators – r = 0.98. The dry matter content substantially influenced the yield of dried potatoes.

The amount of nitrates in the tubers of all the variants under study did not exceed the MPC and was even substantially lower than the established norm. The lowest amount of nitrates was accumulated in tubers of the Tsyhanka variety during the growing season – 107 mg/kg. There was no effect of varietal characteristics on nitrate accumulation.

The number of eyes and their depth also depended on the variety characteristics and affected the amount of waste and dry product yield. The smallest number of eyes was formed by tubers of Koroleva Anna and Povin varieties – 4.8 pcs./tuber and 6.4 pcs./tuber, respectively. The depth of their occurrence in tubers of these varieties was the smallest. The lowest waste in preparing tubers for drying and the highest yield of finished products were found in these variants – the amount of waste was 15.0% and 16.2%, and the yield of dry products was 24.5% and 22.8%, respectively. The calculations revealed that to produce 1 kg of dry products of these varieties, 4.1 kg and 4.4 kg of fresh raw materials are required.

The dry and reconstituted pieces made from Povin tubers were the most prone to darkening and upon tasting received 2.3 points and 1.8 points on a 5-point scale, respectively. When using tubers of this variety for convection drying, blanching, or other methods should be used to prevent discolouration.

Dry products from Koroleva Anna and Svitanok Kyivskyi tubers had the best recovery rate, with a swelling coefficient of 4.0 units and 3.8 units, respectively. The most intensive recovery process occurred within 20 min after soaking.

Thus, according to the complex of studied indicators, the most suitable for convective drying without blanching are tubers of the Koroleva Anna variety, which accumulate 23.1% dry matter, 17.6% starch, and 0.32% sugars during the growing season. The amount of waste when using tubers of this variety will be 15%, the yield of dry products will be 22.8%, and its tasting score will be 5.0 points on a 5-point scale.

Further research can be aimed at identifying the impact of growing conditions on the quality of fresh tubers and dry products, as well as improving drying technologies, specifically, investigating the impact of drying methods and temperatures.

Acknowledgements

None.

Conflict of Interest

None.

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Придатність бульб картоплі різних сортів до переробки

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Анотація. Сушіння – один з найпоширеніших способів переробки бульб картоплі. Для отримання якісної сушеної продукції вирішальне значення має якість сировини, яка суттєво залежить від сортових особливостей. Метою дослідження було вивчення придатності бульб картоплі п'яти сортів до конвективного сушіння без проведення бланшування. Під час проведення досліджень було використано метод експерименту, згідно з розробленою схемою досліджень, лабораторний метод – для визначення органолептичних, морфологічних і біохімічних показників якості свіжих бульб та сухої продукції, статистистичний – для математичної обробки результатів досліджень. Виявлено, що найбільше сухої речовини та крохмалю містили бульби сорту «Повінь» – 24,6 та 18,4 % відповідно, а вітаміну С – «Санте» та «Повінь» (понад 11 мг%). Найменше цукрів накопичувалося у бульбах сорту «Королева Анна» – 0,32 %. Виявлено, що зі збільшенням вмісту в бульбах сухої речовини суттєво зростає вміст крохмалю (r = 0,98), а вміст цукрів істотно впливає на ступінь потемніння сухої продукції (r = 0,74). Вміст нітратів бульбах всіх сортів не перевищував гранично допустимої концентрації. Встановлено, що при використанні для конвективного сушіння бульб картоплі можна отримати 17,1-24,5 % сухої продукції й витратити 4,1-5,8 кг підготовленої сировини. На вихід готової продукції суттєво впиває вміст сухої речовини у бульбах та кількість відходів. Найпридатнішими для конвективного сушіння без проведення бланшування є бульби сорту «Королева Анна», використання яких забезпечить вихід готової продукції на рівні 24,5 % з дегустаціної оцінкою 5 балів за 5-ти бальною шкалою. При використанні для конвективного сушіння бульб інших досліджуваних сортів необхідно попередньо проводити бланшування чи застосовувати інші способи для стабілізації забарвлення. Матеріали статті становлять практичну цінність для овочівників, селекціонерів, фахівців переробних підприємств під час вибору сорту картоплі для сушіння

Ключові слова: сортові особовості; якість, дегустація; потемніння; сушіння; суха продукція

Received 21.02.2024 Revised 17.05.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 612.357.15; 612.357.32; 616.36-003.826 DOI: 10.31548/dopovidi/3.2024.31

Influence of milk phospholipids on microstructural changes in rat liver under tetracycline-induced hepatosis

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Abstract. The growing number of cases of adverse effects of medicines on the liver leads to hepatopathology and the development of complications such as cirrhosis, necrosis, liver failure, and liver carcinoma. Therefore, the purpose of this study was to determine the characteristic structural changes in the liver of rats with tetracycline damage and to find out the corrective effectiveness of milk phospholipids. The study performed histological examination of sections from different parts of the liver in experimental rats, which were stained with haematoxylin and eosin according to the conventional method. It was found that in case of artificial modelling of tetracycline-induced hepatosis in rats, the general architecture of the liver is preserved. At the same time, large-scale damage to hepatocytes and the development of fatty and granular dystrophy were recorded in the affected animals. Some of the damaged cells were destroyed, followed by lysis of fragments of the destroyed cells. The described microscopic changes were most pronounced in the areas of the liver under its capsule. As a result, there was partial or complete disorganisation of the liver lobes in all lobes of the organ. The use of milk phospholipids in the form of a biologically active additive "FLP-MD" as a corrective therapy in sick rats prevented the development of hepatocyte dyscomplexity, contributed to a substantial reduction in the count of destroyed cells in a state of dystrophy with isolated cases of disordered organisation of the liver laminae. This suggests a pronounced stimulatory effect of milk phospholipids on the processes of hepatocyte regeneration and repair in tetracycline-induced

Suggested Citation:
Pototskyi, A., & Gryshchenko, V. (2024). Influence of milk phospholipids on microstructural changes in rat liver under tetracycline-induced hepatosis. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 31-41. doi: 10.31548/dopovidi/3.2024.31.

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liver damage in rats. In case of separate administration of a milk phospholipid-based supplement to clinically healthy animals, the microscopic structure of liver samples did not differ from that of the control group. The findings of this study are of practical value for pathologists, clinicians, and therapists in case of development of drug-induced hepatopathology in animals, especially when using tetracycline antibiotics, and for determining the strategy in the treatment of such patients

Keywords: histological examination; corrective therapy; dystrophy; hepatopathology; complications; milk phospholipids

Introduction

The liver ensures the stability of the body's internal environment, supporting vital functions such as immunity, haematopoiesis, haemostasis, energy production, and detoxification of toxic substances. However, many pharmaceuticals can be hepatotoxic, leading to liver damage and even functional failure.

Tetracycline drugs are known for their ability to cause liver damage, which indicates the relevance of investigating their effects on this organ. According to P.B. Watkins *et al.* (2021), over 900 drugs provoke the development of hepatotoxic reactions, which often leads to the withdrawal of these drugs from therapeutic use. Damage to functional liver cells is usually accompanied by an increase in the activity of liver-specific enzymes in the blood, which reflects substantial structural and functional pathological changes in hepatocytes.

S. Thakur *et al.* (2024) found that individual differences, age, gender, xenobiotic intake, chronic or acute pathological processes, as well as environmental and genetic factors increased the risk of developing severe liver disease, such as cirrhosis, necrosis, liver failure, and cancer. M. Martin-Grau & D. Monleon (2023) analysed the results of metabolic studies of sex differences in the development and progression of pathological fat accumulation in the liver, the role of metabolic profiles in understanding the mechanisms and identifying sex-dependent biomarkers, and how this evidence may help in the future treatment of patients with fatty liver disease in its toxic damage. N.V. Bergasa (2022) found that 5% of all clinical complications and half of acute liver failure cases are the result of drug-induced hepatocyte damage.

H. Jaeschke & A. Ramachandran (2024) classified hepatotoxicity according to the severity and intensity of hepatocyte damage in the case of synthetic drugs, including antibiotics, against the background of simultaneous assessment of hepatic biomarkers. M. Sherman (2021) distinguished between distinct stages of liver damage, which are assessed as initial damage and severe disease. The stage of pathological changes in the liver parenchyma and their clinical manifestation depends on various specific and non-specific risk factors, the duration of their action on the organ and the aggressiveness of the lesion factor.

H. Jaeschke & A. Ramachandran (2024) argued that hepatotoxicity can also manifest itself in the form of mitochondrial dysfunction, decreased cellular respiration, or changes in the intensity of fatty acid oxidation. According to N.K. Björnsson & E.S. Björnsson (2022) and M. Machiels *et al.* (2022), hepatocellular, cholestatic, or mixed liver damage is distinguished. It was noted that, considering the significance of the full functioning of the liver for the body as a whole, damage to hepatocytes would inevitably affect the functional state of other organs and their systems. At the same time, V. Gryshchenko *et al.* (2019) reported on the general consequences of hepatopathology development due to the use of tetracycline hydrochloride, namely damage to the plasma membrane and intracellular membranes of hepatocytes. Another prominent target of possible therapeutic effects is opened for doctors – the restoration

and protection of cell membranes. This area of treatment is called membrane therapy. Since the lipid component of hepatocyte cell membranes is represented by essential phospholipids, the use of these biologically active substances in the treatment of patients with diffuse liver damage is of great interest to scientists and clinicians. D. Wupperfeld *et al.* (2022) found that essential phospholipids increased hepatocyte membrane fluidity, prevented apoptosis, and increased the intensity of hepatocellular export, which substantially improved the functional state of the liver.

A. Ortega-Alonso & R.J. Andrade (2018) investigated structural and functional changes in the liver upon liver disease, which helped to improve the diagnosis of hepatotoxicity of certain groups of xenobiotics and the effectiveness of corrective therapy. Assessing the unique signs of liver damage, F. Ezquer *et al.* (2022) argued that it is possible to quickly and accurately detect pathological changes in the liver and determine their severity. To counteract the pathological events that occur in drug-induced liver damage by means of cellular and molecular mechanisms associated with the therapeutic effects of membranotropic and hepatoprotective agents, it is important to reduce oxidative damage and the intensity of the inflammatory response, increase the regeneration of functional liver cells, restore energy balance, and maintain a suitable level of adenosine triphosphate (ATP) production in hepatocytes. Such a comprehensive effect on the recovery processes in damaged hepatocytes will help to ensure effective therapeutic support in case of drug-induced hepatopathology, which will reduce the risk of chronic liver damage and prevent the occurrence of complications that threaten animal health.

The relevance of the present study lies in the need for an in-depth investigation of the mechanisms of hepatotoxicity, especially using models that can reflect microstructural changes in the liver. This will enable a prompt and reliable assessment of the degree of damage to the organ and help to find innovative approaches to its protection and treatment.

The purpose of this study was to determine the nature of structural changes in the liver parenchyma during the experimental reproduction of tetracycline injury in rats and the corrective effectiveness of milk phospholipids.

Materials and Methods

The experimental studies were conducted at the laboratories of the Faculty of Veterinary Medicine of the National University of Life and Environmental Sciences of Ukraine during 2022-2023. To determine the corrective efficacy of milk-derived phospholipids in the form of a biologically active additive (BAA) "FLP-MD" on the microstructure of the liver parenchyma, laboratory rats (males) of the *Wistar* line with a body weight of 210 ± 40 g (n = 24), which M. Martin-Grau & D. Monleon (2023) explained as sex differences in the occurrence of hepatopathology and the specific features of the course in animals of different sexes.

The laboratory animals were kept in standard vivarium conditions at an indoor temperature of 22-24 °C and were fed a standardised complete food diet with free access to water. All necessary surgical interventions in the experiments were performed according to the ARRIVE guidelines, following the guidelines of Council Directive 2010/63/EU (2010) on the protection of animals used for scientific purposes.

According to the proposed scheme of V. Gryshchenko *et al.* (2019), tetracycline-induced hepatosis was reproduced in laboratory rats. For this, a 4% solution of tetracycline hydrochloride at the rate of 0.25 g/kg body weight was administered daily intragastrically to the animals for 7 days using an oral gavage tube. The "Self-Rehabilitation" group (n = 6) was formed from these animals. Animals that received a 1% solution of dietary supplement "FLP-MD" containing milk phospholipids intragastrically for seven days before intragastric administration of tetracycline hydrochloride and for the next two days after the antibiotic administration were classified as animals of the "Correction" group (n = 6). The daily dose of the supplement corresponded to 13.5 mg/kg body

weight (Litvinenko *et al.*, 2009). Animals were intragastrically injected with an equivalent volume of distilled water to the volume of antibiotic and supplement formed the "Control" group (n = 8). A separate group of healthy animals received only a phospholipid-containing dietary supplement, the main components of which (phospholipids) were produced from milk (the "Preparation" group, n = 6) in the dose specified above. At the end of the experiment, immediately after the animals were euthanised, liver samples were taken.

Notably, additional studies were aimed at investigating the dynamics of liver microstructure recovery in the "Correction" group and comparing the results with the "Self-Rehabilitation" group. This helped to assess not only the direct effect of phospholipids on the affected tissue, but also to determine their potential ability to accelerate regeneration processes. Furthermore, the study considered the possible side effects of the dietary supplement on other organs, which helped to draw more comprehensive conclusions regarding its safety and effectiveness.

At least 5 pieces of liver from different parts of the parenchyma – from its peripheral and central parts – were obtained from each animal. All pieces of the organ were to be fixed in formalin and then embedded in paraffin. Histological sections were prepared using a MS-2 sled microtome (Ukraine) and subsequently stained with Carazzi's haematoxylin and eosin (Goralskij *et al.*, 2015). The prepared histological specimens were examined and photographed using a microscope model MC 100 LED (Austria).

Results and Discussion

In laboratory rats of the control group, the microscopic structure of the liver corresponded to the typical microstructure of this organ in mammals. Specifically, the liver was constructed from individual lobules. In the centre of each lobule is a central vein surrounded by hepatocytes (Fig. 1a). The wall of central veins is represented by a single layer of endothelial cells (Fig. 1b). Rows of hepatocytes extend from the central veins to form the liver lobules. Intrahepatic blood capillaries passed between adjacent liver laminae. Their wall was also represented by a single layer of endothelial cells. Apart from the central vein, micrographs of liver samples showed the location of triads, including an artery, a vein, and a bile duct.

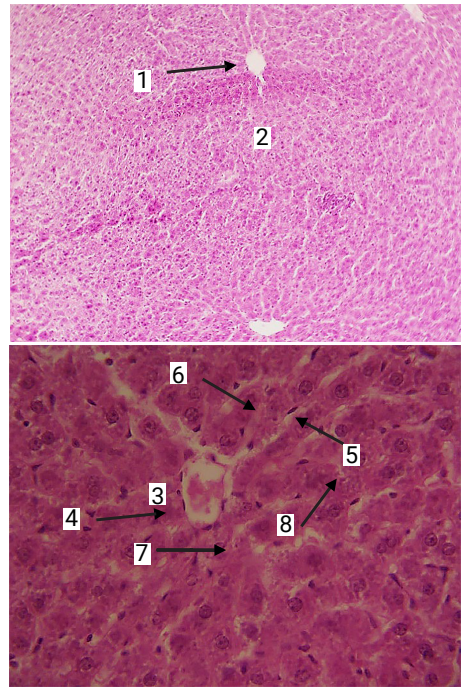

Figure 1. *Liver of a rat in the control group*
Note: a – 1 – central vein; 2 – hepatocytes. Carazzi's haematoxylin and eosin, x300; b – 3 – central vein; 4 – central vein endothelium; 5 – liver lamina; 6 – endothelium of intrahepatic blood capillary; 7 – hepatocyte; 8 – bile capillary. Carazzi's haematoxylin and eosin, x400
Source: authors' photo

Hepatocytes are polygonal cells characterised by a large, homogeneous cytoplasm and a large, rounded nucleus, which usually contains a single nucleolus. In functional liver cells in preparations obtained from clinically healthy experimental rats ("Control" group), the nuclei were located in the centre of the cell, and sporadic binucleated hepatocytes were observed. In the liver laminae, bile capillaries passed between adjacent hepatocytes (Fig. 1b).

As reported by S. Thakur *et al.* (2024), the liver is one of the crucial internal organs that protects the body from the negative effects of various toxins, acting as a universal metabolic barrier. Furthermore, in the liver, the enzymatic systems of hepatocytes fully or partially neutralise toxic substances, specifically, tetracycline antibiotics. The morphological and functional picture of the tissue microsection of the liver parenchyma contains common elements that are found in other structures of the mammalian body. These include lymphatic and blood microvessels, interstitium (loose connective tissue), and functional cells (hepatocytes), which reflect not only the functional tension of the organ itself, but also may indicate the body's overall response to a pathological factor.

There are thin, hardly visible strips of fibrous connective tissue between the lobes of the liver (Fig. 2). In some places, they form overgrowths, which housed the hepatic triads, including the hepatic triad artery, hepatic triad vein, and bile duct.

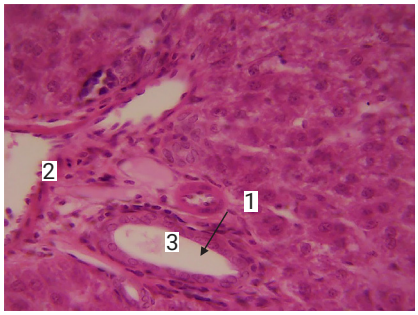

Figure 2. *Hepatic triad in a rat of the control group*

Notes: 1 – artery of the hepatic triad; 2 – vein of the hepatic triad; 3 – bile duct. Carazzi's haematoxylin and eosin, x400

Source: authors' photo

In clinically healthy rats, which were additionally intragastrically administered milk phospholipids in the form of the BAA "FLP-MD" ("Preparation" group), the microscopic structure of the liver did not differ from that of the control group. Analogously, lobules and hepatic triads of typical microscopic structure with all their structural elements were found in the organ (Fig. 3a; 3b). The above suggests the absence of toxic effects of the BAA "FLP-MD" on specialised liver cells in the experimental rats of the corresponding group.

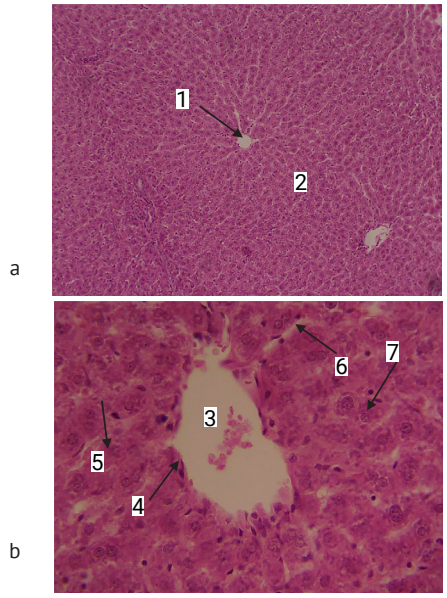

Figure 3. *Liver of a rat treated with milk phospholipids in the form of the BAA "FLP-MD" ("Preparation" group)*

Note: a – 1 – central vein; 2 – hepatocytes. Carazzi's haematoxylin and eosin, x300; b – 3 – central vein; 4 – central vein endothelium; 5 – liver lamina; 6 – endothelium of intrahepatic blood capillary; 7 – hepatocyte. Carazzi's haematoxylin and eosin, x400

Source: authors' photo

As reported by R. Ramachandran & S. Kakar (2009), the diagnosis of drug-induced liver injury is extremely challenging due to insufficient clinical information and difficulties in identifying the effects of non-prescription preparations and toxins.

In the modelling of hepatosis in experimental rats ("Self-Rehabilitation" group), it was found that the general architecture of the liver was preserved (Fig. 4a). Analogously to the control, lobules and hepatic triads of typical microscopic structure with all their structural elements were found in the liver. However, distinct microscopic changes were found in the liver lobules, which primarily involved damage to hepatocytes.

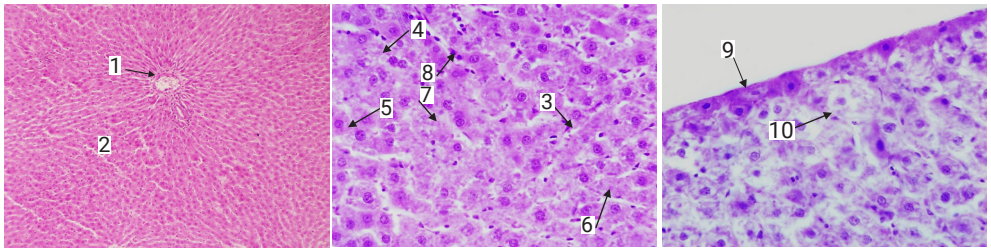

Figure 4. *Rat liver in the model of tetracycline-induced hepatosis ("Self-Rehabilitation" group)*
Note: a – 1 – central vein; 2 – hepatocytes. Carazzi's haematoxylin and eosin, x300; b – 3 – liver lamina; 4 – disorganisation of liver laminae; 5 – separation of hepatocytes from each other; 6 – granular dystrophy of hepatocytes; 7 – destruction of hepatocyte; 8 – hyperplasia of Kupffer cells. Carazzi's haematoxylin and eosin, x400; c – 9 – liver capsule; 10 – destruction and lysis of hepatocytes. Carazzi's haematoxylin and eosin, x400
Source: authors' photo

In case of tetracycline-induced hepatosis in laboratory rats, hepatocytes were separated from each other in many parts of the liver. A considerable share of liver cells were in a state of fatty and granular dystrophy. Some of the dystrophically altered hepatocytes were destroyed with subsequent lysis of fragments of destroyed cells. The destruction and lysis of hepatocytes was particularly pronounced in some areas of the liver under its capsule. All these changes led to partial or complete disorganisation of the liver laminae in all lobes of the organ (Fig. 4b; 4c). Comparable microscopic changes in the liver parenchyma were also observed by H.Y. Yong *et al.* (2020), specifically, the steatogenic effect of tetracycline hydrochloride, which was associated with a decrease in the intensity of mitochondrial β-oxidation of fatty acids by affecting the expression of genes related to lipid metabolism. Furthermore, according to these researchers, tetracycline reduces the expression of acylcarnitine transferase I, responsible for carnitine acylation in mitochondrial fatty acid transport, which leads to a decrease in β-oxidation of fatty acids. Subsequently, this leads to an increase in the intensity of triacylglycerol and cholesterol biosynthesis. The researchers suggest that the direction of fatty acids to the synthesis of triacylglycerols is the result of the inhibitory effect of the antibiotic as part of the mechanism of tetracycline-induced steatosis with a characteristic high content of lipid molecules in hepatocytes.

At the same time, D. Pessayre *et al.* (2012) noted that a frequent mechanism for the development of drug-induced hepatopathology is the development of reactive metabolites that exhibit direct toxicity or immune reactions. These pathological phenomena provoke damage to the mitochondrial membrane. Tetracycline has a direct cytotoxic effect, which is expressed in damage to the mitochondrial membrane or inhibition of the mitochondrial energy-producing function through various mechanisms. Such mechanisms may include blocking coenzyme A or inhibiting the activity of mitochondrial β-oxidation enzymes, electron transport in the respiratory chain, or ATP synthase. It is also possible to destroy mitochondrial DNA, inhibit its replication, or block the synthesis of mitochondrial protein. Tetracycline has many different effects on mitochondrial function. A severe impairment of oxidative phosphorylation reduces the hepatic ATP pool, which leads to functional disorders or cell necrosis. This drug is capable of secondary inhibition of ß-oxidation, provoking steatosis, and can also block the catabolism of pyruvate, which causes lactoacidosis. Like the previous researchers, they point to a substantial impairment in β-oxidation of fatty acids in this situation, which leads to liver fatty acidosis. At the same time, insufficient gluconeogenesis and increased use of glucose as an alternative to the inability to oxidise fatty acids, combined with mitochondrial toxicity of accumulated free fatty

acids and lipid peroxidation products, can drastically reduce energy production, which can lead to irreversible consequences. Therefore, scientists recommended that all new drugs be tested for mitochondrial side effects. The microscopic structural changes in the liver parenchyma, along with the cytotoxic side effects of tetracycline drugs already known from the literature, convince of the need to use corrective therapy with reparative properties in animals suffering from drug-induced hepatosis.

Furthermore, a distinct activation of fixed hepatic phagocytes (Kupffer cells) was recorded everywhere in the liver parenchyma, which was morphologically manifested by a considerable increase in their count, i.e., hyperplasia of these cells (Fig. 4b). We assume that this activation of hepatic phagocytes was caused by the need to eliminate fragments of destroyed hepatocytes from the organ. Histological examination of the liver samples of the "Self-Rehabilitation" group animals revealed no microscopic changes in the central veins, intrahepatic blood capillaries, as well as arteries, veins, and bile ducts of the hepatic triads. Therewith, no manifestations of any inflammatory reaction in the liver were recorded.

As noted in the previous study by V.A. Gryshchenko *et al*. (2018), most cellular functions are determined by the physicochemical properties of the lipid component of biological membranes, which is mainly represented by phospholipids. In this study, the development of a deficient level of phospholipids of both the total fraction and individual phospholipids (phosphatidylethanolamine, phosphatidylcholine, sphingomyelin, phosphatidylserine, phosphatidylinositol, and other representatives) was noted, which is important for elucidating the molecular basis of the pathogenesis of the pathological process in the drug-induced form of hepatopathology. Overall, this suggests the expediency of searching for biologically active substances that eliminate the negative effects of xenobiotics at the cellular level.

That is why a separate group of sick animals was administered milk phospholipids in the form of the BAA "FLP-MD" ("Correction" group). When these rats were administered corrective therapy in the form of a phospholipid-containing dietary supplement, the overall liver architecture was also preserved (Fig. 5a). In this parenchymal organ, as in the control group, lobules and hepatic triads of typical microscopic structure with all their structural elements were detected. Therewith, microscopic changes were found in some liver lobules, which consisted of damage to the microstructure of hepatocytes. However, in liver samples from animals of this group, in contrast to the microscopic picture in the modelling of hepatosis ("Self-Rehabilitation" group), no hepatocyte dyscomplexity was recorded in case of treatment with milk phospholipids. The count of liver cells in the state of fatty and granular dystrophy was noticeably lower (Fig. 5b).

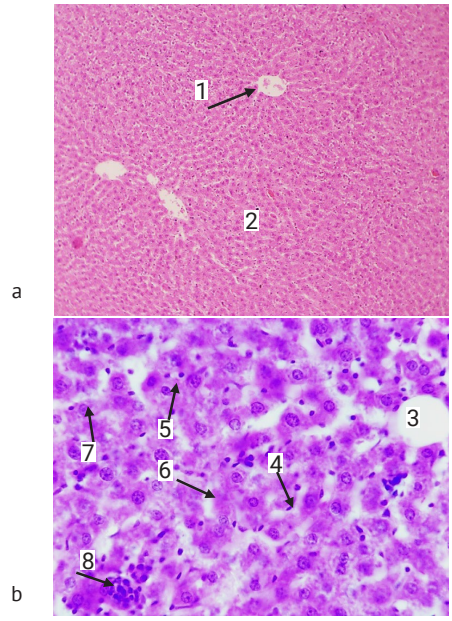

Figure 5. *Liver of a sick rat in the case of corrective therapy ("Correction" group)*

Note: a – 1 – central vein; 2 – hepatocytes. Carazzi's haematoxylin and eosin, x300; b – 3 – central vein; 4 – liver lamina; 5 – disorganisation of liver laminae; 6 – fatty and granular dystrophy of hepatocyte; 7 – destruction of hepatocyte; 8 – hyperplasia of Kupffer cells. Carazzi's haematoxylin and eosin, x400

Source: authors' photo

Notably, only single hepatocytes were destroyed, while the disruption of the orderly organisation of the liver laminae was substantially less pronounced than in the case of tetracycline-induced hepatosis in animals ("Self-Rehabilitation" group). This fact suggests a positive effect of phospholipids on the processes of hepatocyte regeneration and repair, which is consistent with the findings described in other studies.

Specifically, D.O. Melnychuk *et al.* (2014) reported the efficacious influence of milk phospholipids of the BAA "FLP-MD" in the restoration of quantitative indicators of pigment metabolism (unconjugated bilirubin, bilirubin glucuronide, bilirubin sulphate, stercobilin, and urobilin), which were studied in the liver, whole blood, contents of the caecum and faeces under conditions of exposure to ecopathogenic factors (cadmium and ionising radiation). Therewith, the components of the phospholipid-containing dietary supplement had a reparative effect on damaged membrane structures with simultaneous restoration of bile secretion and bile-forming functions of the liver.

At the same time, X. Zhang *et al.* (2018) provided evidence that the use of nanocarriers can exacerbate the side toxic effects of drugs, and therefore serious attention should be paid to the safe use of nanotechnology in drug delivery. M. Mitrovic *et al.* (2022) described potential mechanisms of the corrective effect of omega-3 phospholipids. Moreover, the results of preclinical studies showed that omega-3 phospholipids had a more pronounced antisteatotic effect on the liver compared to the use of omega-3 fatty acids administered as triacylglycerols alone. This antisteatotic effect is likely to involve numerous internal mechanisms that involve not only the liver, but also the intestines and adipose tissue. The need for further research on the possible impact of omega-3 phospholipids on progressive fatty liver disease was noted.

As stated in their studies by M. Yin *et al.* (2021) and D. Wupperfeld *et al.* (2022), the main functions of phospholipids are cell membrane repair, antioxidant action, protection of mitochondrial and microsomal enzymes from damage, as well as slowing down collagen synthesis, and increasing collagenase activity. The complex effect of phospholipids, according to D. Wupperfeld *et al.* (2022), was responsible for their physiological antifibrotic effect. In these animals, hyperplasia of Kupffer cells was also markedly pronounced (Fig. 5b). Microscopic changes in the central veins, intrahepatic blood capillaries, as well as arteries, veins, and bile ducts of the hepatic triads were not observed. There were no signs of any inflammatory reaction in the liver.

Thus, the use of milk phospholipids in the form of the BAA "FLP-MD" ("Correction" group) as a corrective therapy in rats with tetracycline-induced liver damage contributed to a noticeable reduction in dystrophic changes in the liver parenchyma, prevented the destruction of hepatocytes and disorganisation of hepatic beams in the liver lobules.

Conclusions

In the experimental studies, the corrective effectiveness of milk phospholipids in the form of the BAA "FLP-MD" was determined by analysing microstructural changes in liver samples from experimental rats. Specifically, the liver parenchyma of the control group was found to have a typical microscopic structure inherent in healthy animals. In clinically healthy rats, which were additionally intragastrically administered milk phospholipids in the form of the BAA "FLP-MD" ("Preparation" group), the microscopic structure of the liver did not differ from that of the control group. Analogously, lobules and hepatic triads of typical microscopic structure with all their structural elements were found in the organ. In the modeling of tetracycline-induced hepatosis in experimental rats ("Self-Rehabilitation" group), it was found that the general architecture of the liver was preserved. However, distinct microscopic changes were found in the liver lobules, which primarily involved damage to hepatocytes. Therewith, a considerable proportion of liver cells were in a state of fatty and granular dystrophy. Some of

the dystrophically altered hepatocytes were destroyed with subsequent lysis of fragments of destroyed cells. The destruction and lysis of hepatocytes was particularly pronounced in some areas of the liver under its capsule. All these changes resulted in partial or complete disorganisation of the liver lobes in all lobes of the organ. In the case of application of corrective therapy in the form of milk phospholipids of the BAA "FLP-MD" to sick rats ("Correction" group), no hepatocyte dyscomplexity was recorded, only sporadic hepatocytes were destroyed, a noticeably smaller count of liver cells were in a state of fatty and granular degeneration, while the disordered organisation of the liver laminae was substantially less pronounced than in the case of tetracycline-induced hepatosis modelling in animals ("Self-Rehabilitation" group). This fact suggests a positive effect of milk phospholipids on the processes of hepatocyte regeneration and repair in tetracycline-induced liver damage in rats.

In the future, it is planned to investigate the biochemical markers of the effectiveness of milk phospholipids on the structural and functional state of the liver in experimental hepatopathology.

Acknowledgements

The authors of this study would like to express their gratitude to Borys Borysevych, Doctor of Veterinary Sciences, Professor of the V. G. Kasianenko Department of Vertebrate Biomorpholog, for his consultancy support in analysing the microscopic picture of the liver histopreparations studied.

Conflict of Interest

None.

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Вплив фосфоліпідів молока на мікроструктурні зміни у печінці щурів за тетрацикліндукованого гепатозу

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Анотація. Зростання випадків негативного впливу лікарських препаратів на печінку призводить до гепатопатології і розвитку ускладнень, таких як цироз, некроз, печінкова недостатність і карцинома печінки. Тому метою цієї роботи було визначення характерних структурних змін у печінці щурів за тетрациклінового ураження та з'ясування коригувальної ефективності фосфоліпідів молока. Проведено гістологічне дослідження зрізів з різних ділянок печінки у піддослідних щурів, які фарбували гематоксиліном та еозином за загальноприйнятою методикою. Встановлено, що у разі штучного моделювання в щурів тетрацикліндукованого гепатозу загальна архітектоніка печінки зберігається. Водночас у хворих тварин зафіксовано масштабне пошкодження гепатоцитів та розвиток жирової і зернистої дистрофії. Частина пошкоджених клітин зазнавала руйнування з подальшим лізисом фрагментів зруйнованих клітин. Описані мікроскопічні зміни найбільше проявлялися на ділянках печінки під її капсулою. У результаті відмічалась часткова або повна дезорганізація печінкових пластинок в усіх часточках органу. Застосування хворим щурам фосфоліпідів молока у вигляді біологічно активної добавки «FLP-MD» в якості коригувальної терапії запобігало розвитку дискомплексації гепатоцитів, сприяло істотному зменшенні кількості зруйнованих клітин у стані дистрофії з поодинокими випадками порушення впорядкованої організації печінкових пластинок. Це свідчить про виражений стимулювальний вплив фосфоліпідів молока на процеси регенерації та відновлення гепатоцитів за тетрацикліндукованого ураження печінки в щурів. У випадку окремого застосування клінічно здоровим тваринам біодобавки на основі фосфоліпідів молока мікроскопічна будова зразків печінки не відрізнялася від такої у тварин контрольної групи. Результати дослідження мають практичну цінність для лікарів-патоморфологів, клініцистів і терапевтів за розвитку в тварин медикаментозної форми гепатопатології, особливо у разі застосування антибіотиків тетрациклінової групи, та для визначення стратегії у лікуванні таких хворих

Ключові слова: гістологічне дослідження; коригувальна терапія; дистрофія; гепатопатологія; ускладнення; фосфоліпіди молока

Received 04.03.2024 Revised 03.06.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 658.7+334.012

DOI: 10.31548/dopovidi/3.2024.42

Models for optimising the volume of material flows in the technological chain of corporate vertically integrated structures of the agricultural sector

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Abstract. The relevance of this study lies in the need to optimise supply cycles and volumes in value chains, which helps to reduce costs and increase the profitability of agricultural enterprises. The purpose of this study was to investigate and optimise the costs of initial material flows in the production subsystems of corporate vertically integrated structures of the agricultural complex under conditions of non-stationary demand. To fulfil this purpose, the study investigated the relationship between the amount of raw material stock stored in the production subsystem and the time of its consumption, based on which an extended model of the economic order quantity (EOQ) was considered, which, apart from the defined costs, also considers the costs of raw material shortages associated with the inability to fulfil deliveries and losses associated with supply failures caused by the unpredictability (stochasticity) of the order flow itself. It was found that in continuous

Suggested Citation:

Zagurskiy, O., Sobczuk, H., & Lisetskyi, V. (2024). Models for optimising the volume of material flows in the technological chain of corporate vertically integrated structures of the agricultural sector. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 42-56. doi: 10.31548/dopovidi/3.2024.42.

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production systems there is an opportunity to reduce the costs associated with failures by using an additional regular supply batch. For this, the mathematical "point-of-order" model was built based on the theory of mass service, which allows determining not only the best point to order, but also the optimal amount of the safety stock. A model for optimising the volume of material flows was proposed, which combines the model of the economic order quantity order adapted for use in product subsystems of corporate integrated structures of the agricultural complex and the "point-of-order" model, which allows calculating the minimum size of the insurance stock of raw materials using the tools of operations research. As an example, the material flow was optimised for Kivshovata Agro LLC. The findings of the study, such as the use of analytical tools and models for determining the economic order quantity and safety stock, can be used by the management of agricultural enterprises to improve the efficiency of material flow management

Keywords: production systems; economic order quantity; demand; queuing system; stock management

Introduction

One of the most pressing issues in value chain management is optimising the number of cycles and batch sizes of the initial material flow. The required annual volume of raw materials and financial resources to support the production programme is calculated based on product demand. With one delivery cycle providing an annual volume of raw materials, the production subsystem faces the problem of storing the incoming volume and increasing the costs associated with this process. In contrast, organising deliveries in smaller batches increases organisational costs. For the entire process chain to function smoothly, the required amount (volume) of raw materials or semi-finished products, i.e., stock, must be present at the inlet of the chain links at any given time.

Optimisation of material flows reduces the cost of transporting, storing, and handling raw materials and finished products. This helps to reduce overall production costs and increase the profitability of enterprises. Effective material flow management helps to reduce waste, optimise resource use, and reduce the negative impact on the environment. Modern optimisation models consider the latest technologies, which helps to increase productivity and reduce the impact of the human factor. This is especially true for large corporate structures with a complex logistics network.

T. Kovtun (2020) considered the problem of forming reverse material flows and proposed a model of a reverse linkage logistics system, which should solve the problem of optimising material flows using circular economy processes and achieve maximum benefit from the implementation of circular processes. F.F. Galimulina & N.V. Barsegyan (2024), raising the problem of optimising economic systems to improve the efficiency of material flows management, proposed to apply an interdisciplinary approach that allows tools and methods from different fields of knowledge to be combined into a single methodology. A. Ghasemi *et al.* (2024) developed a methodology for radically improving the efficiency of industrial systems, which proposed the use of an optimally designed production scheduling (PS) module that can actively control the budget, timing, and volume of deliveries and which can improve the efficiency of material flow management in the supply chains of many production systems. M. Pekarcikova *et al.* (2020) developed a simulation model of production and supply of goods based on the control logic of the Kanban system to track the movement of material flows in real time and optimise delivery times.

Both Ukrainian and foreign researchers have addressed the problems of optimising material

flows in agricultural production and the impact of stock management on the efficiency of corporate agrarian structures V. Matsiuk *et al.* (2023) developed an agent-based simulation model in the AnyLogic environment to improve the transport and technological system for the supply of material resources of an agricultural enterprise under conditions of partial uncertainty. O. Zagursky (2021) proposed a model of a technological system for the supply of perishable food products, which considers compatibility of technical means; technological parameters of technical systems; adaptability of technical systems to environmental conditions and technological properties of perishable food products; parameters of transport and technological cycles, etc. Among the main challenges of supply chains for perishable agricultural products, S. Osman *et al.* (2023) identified the lack of scheduling for product shelf life, lack of product characteristics that affect shelf life, difficulties in storing the product during deliveries, and difficulties in tracking and monitoring the product throughout the supply chain. Exploring the possibilities of a closed-loop economy in small farms, H. Fernandez-Mena *et al.* (2020) propose a new agent-based model, Flows in Agri-Food Networks (FAN), which simulates the optimum exchange of material flows (feed, fertiliser, food) and agricultural waste between farms and partners at different levels (food industry, fertiliser and feed suppliers, waste recyclers, etc.)

Therewith, despite the sufficient elaboration of the subject, the issue of managing the dynamics of changes in the volume of material flows of corporate structures of the agricultural complex with a multi-nomenclature assortment in the conditions of non-stationary demand for products is still understudied in Ukrainian and foreign literature.

The purpose of this study was to investigate and optimise the costs of input material flows in the production subsystems of corporate vertically integrated structures of the agricultural complex under conditions of non-stationary demand.

To fulfil this purpose, the following objectives had to be met:

- to investigate the relationship between the amount of raw materials stored in the production subsystem and the time of their consumption;
- to determine the optimal point of order based on queuing theory;
- to optimise the material flow using the "point-of-order" model for an existing agricultural enterprise.

Materials and Methods

In studying the influence of stock management on the efficiency of corporate vertically integrated structures of the agrarian complex, the study employed general scientific methods: analysis and synthesis – in collecting research materials; systemic – when assessing the interaction of individual elements of the supply system, their impact on the functioning and overall costs of the system and optimisation of supply chain resources as a whole; process – when forming a sequence of actions and working within the supply process to minimise the cost of material flows; synergistic – when considering the dynamics and changes in the supply of vertically integrated structures of the agricultural complex in conditions of non-stationary demand, which are in a state of changing equilibrium, when small changes can lead to large effects; economic and quantitative – to assess the quality of supply processes of the enterprise under study.

To improve the accuracy of the analysis, mathematical modelling techniques were employed to assess the impact of various factors on the behaviour of inventories over time, including linear programming methods to optimise the allocation of resources in the supply chain; simulation modelling to analyse possible scenarios and determine the best stock management strategies; and discrete optimisation methods to minimise costs and maximise the efficiency of logistics operations.

To accommodate the complexity of the processes taking place in production subsystems, a multi-criteria optimisation approach was applied, which allows simultaneously considering several conflicting goals, such as cost minimisation and

service level maximisation. This approach used Pareto-optimisation methods to identify the optimal points for managerial decision-making.

Specialised methods of operations research were also used, namely: queuing systems to represent the process of ordering stocks; determining the "point-of-order" to establish the relationship between the amount of raw materials stored in the production subsystem and the time of its consumption; economic order quantity (Harris–Wilson model) to determine the size and interval of delivery batches.

To verify the correctness of the results, additional modelling was performed based on real data from an agricultural enterprise, which helped to confirm the adequacy of the proposed models and methods. A multivariate analysis was performed to investigate the relationships between various elements of the logistics system, such as storage costs, lead times, and service levels.

The findings of this study were experimentally confirmed based on the operational data on the dynamics of changes in material flows for 2023 at the agricultural enterprise Kivshovata Agro LLC, which engages in agricultural production activities in the Kyiv Oblast (Ukraine).

To collect the data, the study employed the methods of questionnaires and expert interviews, which helped to obtain valuable information on the specifics of stock management at the enterprise. Data from automated enterprise management systems (ERP systems) were also used, which ensured high accuracy and reliability of the results.

To ensure the scientific reliability and validity of the results, a comprehensive approach to data collection and analysis was used. The study covered the entire production and logistics process of the agricultural enterprise, from the receipt of raw materials at the warehouse to the delivery of finished products to the consumer. A detailed analysis of the dynamics of raw material stocks was performed, the optimum ordering intervals were determined, and the impact of various factors, such as seasonality and demand fluctuations, on the efficiency of stock management was assessed. The use of statistical methods helped to assess the probabilistic characteristics of supply chain processes, which helped to conclude on the stability and reliability of the stock management system in the face of volatile demand. The use of correlation analysis helped to identify the crucial factors affecting the efficiency of stock management, which became the basis for developing recommendations for improving logistics processes.

Results and Discussion

Agricultural production is specific and has a series of features related to the biological nature of production, as biological organisms, land, and other natural resources are used as the main means of production, and therefore material flows in agro-logistics also have their specific features related to the following:

- diversification – the ability to generate 2 or more streams that differ significantly from each other in terms of their properties, promotion routes, and end users;
- seasonality – the need to store products due to seasonality;
- duality – the ability of a material flow at any stage to act as both a raw material for the next stage and a final product;
- transformation – a significant change in the material flow on the way towards the end consumer, which requires relevant changes in the storage and transportation regime;
- range – expanding the range of material flow as it moves through the supply chain, which requires increased efforts to maintain it.

This specificity in the production subsystems of the full technological cycle of production in the market conditions causes (especially in crop production) the movement of certain volumes of annual financial, material, and information flows. In Figure 1, the financial flow (d_1) compensates for the cost of purchasing raw materials $M_1=k_1d_1$, where k_1 is considered as the conversion factor of the financial flow (d_1) into the material flow (M_1).

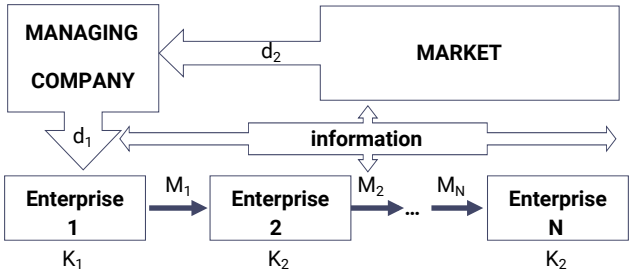

Figure 1. *General scheme of the technological chain of vertically integrated structures of the agricultural sector*

Note: d – financial; M – material; I – information flows

Source: compiled by the authors of this study based on O.M. Zagurskiy (2021)

Determining the volume of material flow (M_2) and the number of cycles (m) in the production subsystems of vertically integrated structures of the agricultural complex requires additional information (I) and the application of the stock management methodology on its basis. Therewith, the need for stocks of these structures is characterised by random processes, as the probability of receiving the required amount of raw materials at the input of the technological link at the time of the requirement is not high. And in case of a stock shortage, the production process may stop or slow down, leading to financial losses.

Accordingly, the production subsystems of vertically integrated structures of the agricultural sector need to strike a balance between the processes of raw material shortages and the processes of increasing stocks, which entails an increase in storage costs (Yablonskyi *et al.*, 2024).

Notably, the stock management methodology allows making an optimal (suboptimal) decision under certain conditions and strategic constraints (Volokha *et al.*, 2023). Therefore, the issue of optimising the output material flows in production subsystems comes down to the following issues:

- what volume (quantity) of goods should be periodically delivered to the warehouse to create the required stock (delivery lot size);
- at what time (at what minimum stock level) should the stocks be replenished ("point-of-order").

Thus, there is a need to establish a link between the quantity or volume of raw materials (Q) stored in the production subsystem and the time (t) of its consumption, i.e., the study of the following function:

$$Q = f(t), \quad (1)$$

where Q is the stock of one type of raw material.

The classic Harris-Wilson (Wilson, 1934; Harris, 2013) model for calculating the economic order quantity (Formula 2) relates ordering costs to stock storage costs:

$$EOQ = \sqrt{\frac{2S \times D}{H}}, \quad (2)$$

where S is the ordering cost (per year, per unit), which includes the cost of delivery, processing, and settlement of orders; D is the demand coefficient or resource requirement (number of units sold per year); H is the stock storage cost (per year, per unit), which includes the cost of storing materials or goods in a warehouse and losses due to stock-outs.

It involves the continuous consumption of raw materials, as well as their immediate receipt, which is impossible in practice (Rogovskii *et al.*, 2022). Even if a continuous production process is organised in corporate integrated structures, to maintain its rhythm, the rate of supply of raw materials (p) must exceed the rate of resource consumption (a). That is, the condition ($p > a$) must

be met. Therefore, in contrast to the classical approach, when formulating the task of stock management in corporate vertically integrated structures of the agricultural sector, it is assumed that batches of raw materials will arrive evenly at the rate of delivery (*p*) rather than instantly, and within the interval (t_p), as presented in Figure 2.

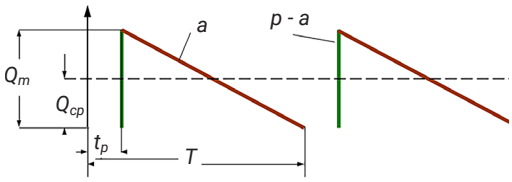

Figure 2. *Diagram of the dynamics of production stocks of corporate vertically integrated structures of the agricultural sector*

Note: *Q* is the stock of raw materials; *t* is the time of consumption; *p* is the rate of supply of raw materials; *a* is the rate of resource consumption

Source: compiled by the authors of this study based on I. Rogovskii *et al*. (2022)

In this regard, the following types of expenses arise:

1. Organisational costs associated with the processing and delivery of goods that are required for each warehousing cycle and are subject to recycling.

2. Expenses related to storage and depreciation of goods subject to deterioration, ageing, and reduction in quantity during storage.

3. Raw material shortage costs associated with the inability to deliver raw materials, which results in lost profits.

Figure 3 shows an approximate graph of the cost function as a function of the quantity of stocks C = f(q) for corporate vertically integrated structures of the agricultural sector. Figure 3 shows that the process of stock management for corporate vertically integrated structures of the agricultural sector is based on assumptions analogous to the Harris-Wilson model and differs in that if the stock in the warehouse approaches zero, deliveries will be started and continued until one batch is available. Therewith, the supply of raw materials to the technological process, i.e., its shipment, will not be interrupted. Thus, the presented classification of the costs of the process under study can be defined by the following formula (3):

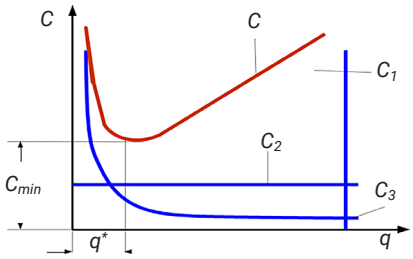

Figure 3. *Diagram of changes in costs of corporate vertically integrated structures of the agricultural sector*

Note: C – the costs; C_1 – the total stock storage costs; C_2 – the cost of goods; C_3 – the total organisational costs; C_{min} – the minimum costs

Source: compiled by the authors of this study

$$C = C_1 + C_2 + C_3 = h\frac{Q_m}{2} + C_a + S\frac{a}{q}, \quad (3)$$

where $C_1 = h\frac{Q_m}{2}$ is the total stock storage costs; $C_2 = C_a$ is the cost of goods; $C_3 = S\frac{a}{q}$ is the total organisational costs.

The modified Harris-Wilson formula for finding the optimal lot size for delivery (Q^*), which corresponds to the volume of the original material flow, will have the following form:

$$Q^* = \sqrt{\frac{2pSa}{h(h-a)}}. \quad (4)$$

However, the Harris-Wilson stock management model and its modifications are deterministic and do not accommodate the stochastic nature of the flow of requirements (requests) in a vertically integrated production system (Rogovskii *et al.*, 2021). To accommodate stochastic processes in stock management in the production chain (especially in the sales unit), it is proposed to use the mathematical model of the "point-of-order" based on the theory of mass service (Nobil *et al.*, 2016; Balestra *et al.*, 2021; Utama *et al.*, 2022).

According to this model, for any queuing system, the stock ordering process can be represented by two functions:

1. Number of applications received by the system by time t: *x(t)*.

2. Number of applications that have left the system by t: *y(t)*.

The above functions are characterised by a jump (an increase by one at the moments of arrival and departure of orders). Graphically, the functions x(t) and y(t) are presented in Figure 4:

- lines representing functions are stepped;
- the upper bound is x(t);
- the lower bound is y(t).
- the difference z(t) = x(t) – y(t) at any time t is the number of orders in the system. If z(t) = 0, there are no orders in the system.

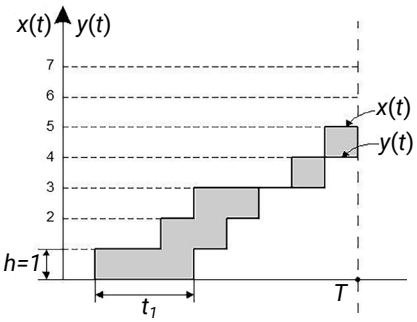

Figure 4. *Graphical representation of the functions x(t) and y(t)*

Note: *x*(*t*) is the number of orders that entered the system by time *t*; *y*(*t*) is the number of orders that have left the system by time *t* – orders in the system at a given time

Source: compiled by the authors of this study based on S. Minkevičius *et al*. (2021)

To apply the queuing theory in solving this problem, the study investigated the flows of requirements that differ in their internal structure and performed their quantitative description. The simplest flows are characterised by the following properties: ordinariness; stationarity; and absence of after-effects.

An ordinary request flow is one where more than one request will be received in the system in a short period of time *(*Δ*t*) with probability *R* > *1*(Δ*t*), which is quite small compared to the fact that only one request will be received in the same period of time, as expressed by the following:

$$R > 1(\Delta t) << R1(\Delta t). \quad (5)$$

A flow is called stationary if the probability of occurrence of some requirements (*k*) in a time interval *(*Δ*t*) depends on the length of the interval and does not depend on the location of the interval on the time axis, i.e., in a stationary flow of requirements, the probability characteristics are not subject to changes on the time scale. The average number of claims, expressed as (*λ*), received per unit of time and characterising the intensity or density of the flow. In a stationary flow, the intensity value (*λ*) will be the same at any interval (Δ*t*).

If the number of demands entering the system in a non-overlapping time slot does not depend on the number of demands in another time slot, then such a flow is characterised by no consequences. The Poisson's law is used to describe the simplest requirement flow with a certain parameter (*λ*):

$$R_{k(t)} = \frac{(\lambda t)^k}{k} e^{-\lambda t}, \quad (7)$$

where: $R_{k(t)}$ is the probability that reflects the process of receipt of (*k*) claims at an arbitrary time interval with duration (*t*).

Then, according to Poisson's law, the probability of no claims at a time interval (*t*) after one of the claims enters the system will be as follows:

$$R_0(t) = e^{-\lambda t}. \quad (8)$$

However, the given probability corresponds to the probability that the value (*t*) will be no more than a random variable *T*. Then:

$$R_0(T \geqslant t) = e^{-\lambda t}, \quad (9)$$

Accordingly:

$$F(T) = 1 - e^{-\lambda}{}_t, \quad (10)$$

where: F(*T*) is a function that distributes a random variable *T*.

The distribution for a random variable *T* will be carried out with density as follows:

$$f(t) = \lambda_e^{-\lambda t}. \quad (11)$$

Thus, for the simplest flow, the time interval between any two neighbouring demands will be distributed according to the exponential law and using the parameter (*λ*). In addition, the simplest flow is characterised by a higher probability of short intervals between events than long ones. Approximately 63% of the time intervals between events in the system are characterised by a length that is less than the average and equal to (*1/λ*).

Furthermore, the Harris-Wilson model does not consider the losses associated with failures during order processing due to the unpredictability of the order flow itself (stochasticity). In practice, it may happen that an order is received at a time when the current batch has already been exhausted and the next delivery has not yet taken place. To account for such losses, it is proposed to introduce a cost coefficient (*g*), the value of which is determined by the probability of failure when servicing an incoming request (*R*), and determines the probability of failure and the amount of costs associated with this process for the Harris-Wilson model of production supply.

Accordingly, there is a probability, expressed as *Ri(t)*, that at the time of the next arrival of a batch of goods, there is a stock of units of goods in the amount from 0 to Q_m. Moreover, the probability of a decrease in the current batch ($Q_m - i$) of units of goods corresponds to or is equal to the probability *Ri(t)*. The probability of reducing the current batch $RQ_m - i(t)$ is determined by Poisson's law, and the probability of no failure during maintenance is as follows:

$$R_{00}(t) = \sum_{i=1}^{Q_m} R_i(t), \quad (12)$$

or

$$R_{00}(t) = \sum_{i=1}^{Q_m} R_{Q_{m-i}}(t). \quad (13)$$

Consequently, the probability of a failure to service the order will be as follows:

$$R_f(t) = 1 - \sum_{i=1}^{Q_m} R_{Q_{m-i}}(t), \quad (14)$$

and the amount of costs incurred in case of a failure is determined by the following expression:

$$I_f(t) = g[1 - \sum_{i=1}^{Q_m} R_{Q_{m-i}}(t)]. \quad (15)$$

If one replaces the following variables with $j = q^* - i$, one gets that when $i = 1$, the value of (*j*) is equal to $Q_m - 1$, and when (*i*) is equal to Q_m, the value of (*j*) is 0. Then, changing the bounds of the sum in places, the resulting expression is brought to a standard form as follows:

$$I_f(t) = g[1 - \sum_{j=1}^{Q_m - 1} R_j(t)]. \quad (16)$$

The parameters of the Harris-Wilson model for production conditions are substituted into the formula. Poisson's formula for *Rj(t)*, where the parameter λ is the annual demand intensity expressed as a, which characterises the intensity of the flow of applications on average during the year. And the time interval for considering the probabilistic characteristics of the stock management system is the interval between the receipt of batches of goods, expressed as $Q_{m/a}$. Thus, for the process described, the Poisson's formula will take the following form:

$$R_j(t) = \frac{\left(a\frac{Q_m}{a}\right)^j}{j!} exp\left(-a\frac{Q_m}{a}\right). \quad (17)$$

Substituting the formula for I_f (t) instead of Rj(t) in expression (17), one obtains the following:

$$I_f = g[1 - \sum_{j=0}^{Q_m - 1} \times \frac{\left(a\frac{Q_m}{a}\right)^j}{j!} exp\left(-a\frac{Q_m}{a}\right)], \quad (18)$$

where Q_m is the maximum volume of stocks; a is the intensity of the annual flow of applications; $Q_{m/a}$ is the time interval during which one delivery batch is consumed, year.

By simplifying expression (18), the final formula is obtained:

$$I_f = g[1 - \sum_{j=0}^{Q_m-1} \times \frac{(Q_m)^j}{j!} exp(-Q_m)]. \quad (19)$$

Notably, in continuous production systems, it is possible to reduce the costs associated with I_f failures by using an additional regular supply batch (Zagurskiy *et al.*, 2024) in the time interval Δt. A graphical description of the process is presented in Figure 5.

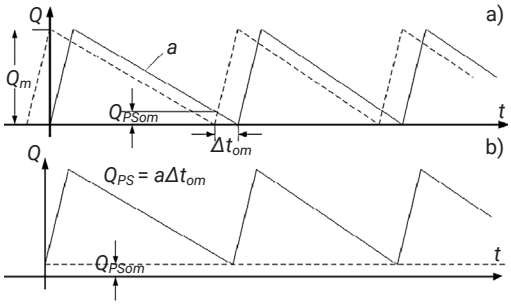

Figure 5. *Supply shift by* Δt_{om}

Note: a – the delivery with failures in the time interval Δt; b – the delivery with the use of an additional regular batch

Source: compiled by the authors of this study

The application of this adjustment requires a change in expressions (18) and (19):

$$I_f = g[1 - \sum_{j=0}^{Q_m-1} \frac{\left(a\left(\frac{Q_m}{a} - \Delta t\right)\right)^j}{j!} exp\left(-a\left(\frac{Q_m}{a} - \Delta t\right)\right)], \quad (20)$$

or

$$I_f = g[1 - \sum_{j=0}^{Q_m-1} \frac{(Q_m - a\Delta t)^j}{j!} exp\big(-(Q_m - a\Delta t)\big)]. \quad (21)$$

An analysis of Figure 5 shows that such a change in supply is equivalent to a process of increasing the shelf life by (1 + Δ*t*). Accordingly, the storage costs will be as follows:

$$I_x = h * \frac{Q_m}{2*(1+\Delta t)}, \quad (22)$$

while the total costs will be equal.

$$I = I_x + I_f. \quad (23)$$

Thus, with the optimum precautionary supply interval Δt_{op}, the total costs are minimal:

$$min(I) = g\left[1 - \sum_{j=0}^{Q_m-1} \frac{(Q_m - a\Delta t_{on})^j}{j!} exp(-(Q_m - a\Delta t_{on}))\right] + h\frac{Q_m}{2}(1 + \Delta t_{on}), \quad (24)$$

and the optimum ordering point (optimum safety stock volume) Q_{PSt}, which is defined as follows:

$$Q_{PSt} = a\Delta_{top}. \quad (25)$$

Table 1 and Figure 6 show an example of considering the dependences that reflect the dynamic result of all the functions of the stock storage unit of the integrated agricultural supply chain for the operating agricultural enterprise of Ukraine Kivshovata Agro LLC.

Table 1. *Results of material flow optimisation using the "point-of-order" model for Kivshovata Agro LLC*

Intensity of application flow per year, I	Stock storage costs, h	Maximum stock level, Qm	Interval of validity of one delivery batch, Δt	Storage costs, Ix	Failure costs, If	Total costs, I
20	6	150	1	900	0.0000000	900.0
20	6	150	2	1350	0.0000000	1350.0
20	6	150	3	1800	0.0000000	1800.0

Table 1. *Continued*

Intensity of application flow per year, *I*	Stock storage costs, h	Maximum stock level, Qm	Interval of validity of one delivery batch, Δt	Storage costs, Ix	Failure costs, If	Total costs, I
20	6	150	4	2250	0.0000000	2250.0
20	6	150	5	2700	0.01897892	2700.0
20	6	150	6	3150	0.00000003	3150.0
20	6	150	7	3600	0.0000000	3600.0
20	6	150	8	4050	0.0000453	4050.0
20	6	150	9	4500	22026.460	26526.5
20	6	150	10	4950	38026.460	42976.5

Source: compiled by the authors of this study

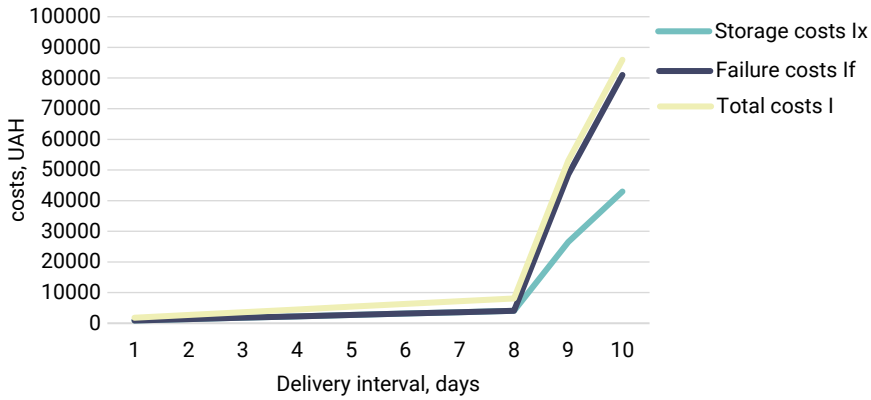

Figure 6. *Schedule for determining the optimum interval for the advance delivery ofthe next batch (Δt_{op})*

Source: compiled by the authors of this study

As Figure 6 shows, the minimum value of the total cost is maintained up to Δt_{op} = 8, when the delivery interval of one delivery batch reaches eight days, while increasing the delivery interval of batches to nine or ten substantially increases the total cost of supply.

Comparing the obtained approaches and results with other comparable studies, all of them, like the present study, are devoted to building effective stock management models and investigating the relationship between the amount of stock stored at the enterprise and the time of its consumption. Thus, H. Starushenko (2022) proposed a digital model for calculating the economic order quantity developed based on the Harris-Wilson EOQ stock management model. The researcher used the minimisation of total expected costs of the enterprise as the optimisation criteria, while organisational and storage costs were used as constraints, and did not consider the possible shortage of stocks. The present study, apart from the above costs, also considered the costs of raw material shortages associated with the inability to supply raw materials, which results in lost profits.

T. Nestorenko *et al.* (2020) conducted a thorough investigation of stock management models

with uncertain demand (variations of the Harris formula based on the Markov equation and the Wilson formula developed to minimise expected replenishment costs and stock-outs). Their model considers fluctuations in demand, lead time, and price, among other criteria. Therewith, the model does not accommodate the possibility of potential supply failures. In the present study, for vertically integrated production systems, the possibility of failures is allowed, and therefore during the servicing of orders, the losses associated with failures caused by the unpredictability (stochasticity) of the order flow itself are also considered, and therefore the possibility of reducing the costs associated with failures by means of an additional regular supply batch is calculated.

To ensure supply sustainability, S. Zeng *et al.* (2019) presented a modified version of the Wilson model that considers consumer demand trends and provides flexibility in re-ordering time, which allows determining the economic order quantities and intervals between them. In contrast to S. Zeng *et al.* (2019), the current study proposes to use a mathematical model of the "point-of-order" based on the theory of queuing to account for stochastic processes in stock management in the supply chain of a vertically integrated agricultural production system, which allows determining not only the optimum point of order but also the optimum amount of safety stock.

C. Çalışkan (2021) proposed an extended classical Harris-Wilson model for stock management and compound interest accounting, which, according to the researcher, is an intuitive closed-form equation for the economic order quantity, but, like previous studies, it also does not consider possible stock-outs and losses associated with supply failures.

Notably, some modern researchers consider the problem of stock optimisation from the standpoint of sustainable economic development and, apart from economic components, include environmental and social components in stock management models. Thus, N. Liao & Q. Deng (2018) propose an environmental sustainability model (EES-EOQ), which uses benefit-cost ratios to indirectly control production to overcome the limitations of the classical EOQ model. To this end, the researchers derive three optimum strategies: (I) minimise stock costs, (II) maximise the overall environmental benefit in a dedicated recovery model, and (III) coordinate forward logistics and reverse logistics to achieve environmental optimisation in a combined recovery model. Using stochastic analysis, they mathematically prove the existence and uniqueness of the optimum ratio in each strategy. S. Turki *et al.* (2020) also propose an EOQ model that considers the costs of waste disposal. A. Jokar & S.-M. Hosseini-Motlagh (2020) and S. Pattnaik *et al.* (2021), defining the stock management policy of companies in the face of demand volatility, included corporate social responsibility issues in models for determining optimum stock quantities in supply chains. Therewith, this model is more in line with the development of optimum restoration strategies to mitigate environmental problems caused by excessive carbon emissions and is suitable for restoration enterprises.

Conclusions

Determination of the volume of the required material flow and the number of cycles in the production subsystems of vertically integrated structures of the agricultural complex requires the application of the stock management methodology. The frequent need for stocks of these structures is characterised by random processes, as the probability of receiving the required amount of raw materials at the input of the technological link at the time of the requirement is not high. Moreover, in case of a stock shortage, the production process may stop or slow down, leading to financial losses. Therefore, the production subsystems of vertically integrated structures of the agricultural sector need to strike a balance between the processes of raw material shortages and the processes of increasing stocks, which entails an increase in storage costs.

It was found that optimisation of material flows is a critical aspect of ensuring uninterrupted

operation and reducing the cost of transporting, storing, and handling raw materials and finished products. This helps to reduce overall production costs and increase the overall profitability of subsystems of vertically integrated structures in the agricultural sector. The integration of classic stock management models such as the economic order quantity and point-of-order models allows for more accurate calculations and reduced costs.

Optimisation of material flows reduces the cost of transporting, storing, and handling raw materials and finished products. This helps to reduce overall production costs and increase the overall profitability of subsystems of vertically integrated structures in the agricultural sector.

A model of optimisation of volumes of material flows in subsystems of corporate integrated structures of the agrarian complex was proposed, which combines two classical models: the model of economic order quantity adapted for use in product subsystems of corporate integrated structures of the agrarian complex and the "point-of-order" model, which allows calculating the minimum size of the insurance stock of raw materials using the tools of operations research.

For example, the material flow was optimised for the operating agricultural enterprise Kivshovata Agro LLC. The above calculations showed that the total costs stay at a minimum value up to $\Delta t_{op} = 8$, when the delivery interval of one batch of supplies does not exceed eight days; an increase in the interval by even a day or two substantially increases the total cost of supplies.

Prospects for further research are related to improving the models of stock management of agricultural enterprises, considering current trends in sustainable economic development.

Acknowledgements

The authors of this study express their gratitude to the soldiers of the Armed Forces of Ukraine, who, through their courage, enable the scientists to do science in Ukraine.

Conflict of Interest

None.

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Моделі оптимізації обсягів матеріальних потоків у технологічному ланцюзі корпоративних вертикально-інтегрованих структур аграрного комплексу

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Анотація. Актуальність дослідження полягає в необхідності оптимізації циклів та обсягів поставок у ланцюгах створення доданої вартості, що сприяє зниженню витрат і підвищенню рентабельності аграрних підприємств. Метою статті було дослідження та оптимізація витрат вихідних матеріальних потоків у виробничих підсистемах корпоративних вертикально-інтегрованих структур аграрного комплексу в умовах нестаціонарного попиту. Для досягнення поставленої мети в роботі досліджено зв'язок між обсягом запасу сировини, що зберігається у складі виробничої підсистеми і часом його споживання на основі якого розглянуто розширену модель оптимального розміру замовлення EOQ, у якій окрім визначених витрат враховуються ще й витрати дефіциту сировини, пов'язані із неможливістю виконання постачання і втрати пов'язані з відмовами у постачаннях обумовленими непередбачуваністю (стохастичністю) самого потоку заявок. Визначено, що у безперервних виробничих системах існує можливість зменшення витрат, пов'язаних із відмовами за допомогою додаткової чергової партії постачання. Для цього на засадах теорії масового обслуговування побудовано математичну модель «точка замовлення», що дає можливість визначити не тільки оптимальну точку замовлення, а й оптимальний обсяг страхового запасу. Запропоновано модель оптимізації обсягів матеріальних потоків, що поєднує модель оптимального розміру замовлення EOQ адаптовану до використання в продуктових підсистем корпоративних інтегрованих структур аграрного комплексу та модель «точка замовлення», що дозволяє розраховувати мінімальні розміри страхового запасу сировини з використанням інструментів дослідження операцій. Для прикладу проведено оптимізацію матеріального потоку для ТОВ «Ківшовата Агро». Результати дослідження, такі як застосування аналітичних інструментів і моделей визначення оптимального розміру замовлення та страхового запасу можуть бути використані менеджментом аграрних підприємствами для підвищення ефективності управління матеріальними потоками

Ключові слова: виробничі системи; оптимальний розмір замовлення; попит; система масового обслуговування; управління запасами

Received 28.01.2024 Revised 30.04.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 629.359, 681.513.1

DOI: 10.31548/dopovidi/3.2024.57

Development of a mathematical model of stabilisation of device for small-sized cargo transportation

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Abstract. The relevance of the study is conditioned by the need to improve the efficiency and safety of transportation of small-sized cargo. The purpose of this study was to build a mathematical model of the dynamics of stabilisation of device for small-sized cargo transportation. For this, the equations of motion of the system were formulated in the form of a system of second order Lagrange differential equations of the second kind. A grey box approach was used to determine the unknown coefficients of the equations of motion. To implement the approach, an optimisation criterion was constructed that reflected the parameters of the root-mean-square and maximum absolute errors of the differences between theoretical and experimental data of the tilt angle and angular velocity of the device. A modified Ring-Rot-PSO particle swarm method was used to minimise the criterion. The unknown parameters of the device model were found, and the adequacy of the obtained mathematical model was assessed by individual components of the criterion, which proved the adequacy of the obtained mathematical model. To find the unknown parameters, namely the coefficients of the equation of

Suggested Citation:
Loveikin, V., Romasevych, Yu., & Zarivnyi, O. (2024). Development of a mathematical model of stabilisation of device for small-sized cargo transportation. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 57-71. doi: 10.31548/dopovidi/3.2024.57.

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motion of the device, a grey box approach was applied. For this, experimental studies of the device stabilisation were performed, and the difference function was formed as an objective function of theoretical, obtained based on analytical equations of motion and experimental data. The objective function was minimised using the modified particle swarm method Ring-Rot-PSO. As a result of the optimisation, the unknown parameters of the system were obtained: the moments of inertia of the frame $I_{1c} = 5.52 \cdot 10^{-4}$ kg·m² and the wheel $I_{wc} = 2.75 \cdot 10^{-3}$ kg·m², the wheel mass $m_w = 3.31 \cdot 10^{-1}$ kg. These data allowed obtaining an adequate mathematical model model of the stabilisation of the device, which underlies further solving of the problem of synthesising optimal control of its motion

Keywords: two-wheeled vehicle; equations of motion; motion control; unstable dynamic system; Ring-Rot-PSO

Introduction

Transportation of cargo forms an integral part of any commodity production, the delivery of goods, and everyday life. Small-sized automated systems for the transportation and courier delivery of small-sized cargo, goods, and products are becoming increasingly widespread. The designs of such devices are represented by both aircraft and ground wheel systems. One of the key tasks of developing such devices is to synthesise optimal control of their motion, which requires the development of an adequate mathematical model of the motion of such devices. This study is dedicated to this issue.

Stable configurations of four to six wheels are commonly used as wheel propulsion systems. Two-wheeled devices are represented by systems where the wheels are on the same axis of rotation. Such devices cannot stabilise their position in static conditions.

The dynamics of ensuring the stability of two-wheeled devices (such as a scooter) has been understudied. To maintain transverse stability in static, such devices require additional mechanisms, such as gyroscopes (Lin *et al.*, 2018), jet wheels (Hongyang & Ruizhi, 2020), etc.

In any case, the synthesis of control systems for such devices is based on adequate mathematical models (Aulin *et al.*, 2024). Thus, the synthesis of optimal motion control of a device for transporting small-sized cargo, which is a non-linear dynamic system, necessitates the construction of an adequate mathematical model. To obtain such a mathematical model, the problem of measuring the dynamic parameters of the system with a given accuracy arises (Rogovskii, 2021). Such measurements are not always possible, and therefore the problem of estimating such parameters based on experimental data obtained during the stabilisation of the device position becomes relevant.

Usually, scientists use the classical method of developing a mathematical model, including finding the parameters of the device, building a dynamic model, and designing of differential equations of motion. Specifically, V. Mudeng *et al.* (2020) describes a method for constructing a mathematical model of a two-wheeled device, such as a segway, which is an unstable dynamic "inverse pendulum" system. To build the mathematical model, the equilibrium method was used, which is based on the d'Alembert's principle of dynamic equilibrium. Some geometric and dynamic characteristics were specified, while others were found theoretically using a computer model of the system. The results of the test were performed only theoretically, without verification on a physical model of the device.

J. Velagic *et al.* (2021) describe a method for constructing a mathematical model using second order Lagrange equations for a two-wheeled device such as a segway. The dynamic characteristics of the device were determined approximated from the kinematic diagram of the device. As a

result, the model was used to select the coefficients of the PD controller and an experiment was conducted to assess the quality of the model. There were significant discrepancies between the theoretical and experimental data on the position stabilisation of the device. The researchers explained this discrepancy by referring to inaccuracies in the definition of the dynamic parameters of the device.

M.A. Tofigh *et al*. (2021) describe a two-wheeled device that works on a principle comparable to that of a reverse pendulum. However, two gyroscopes provide stability. The composite mathematical model of the device is presented in the form of second order Lagrange equations. The parameters of the device were determined theoretically using its idealised computer model. O. Obadina *et al*. (2022) described the application of the "grey box" and "white box" approaches and their comparison with experimental data on the device's performance. Thus, the unknown parameters of the model were found from the experimental data of the device operation by applying an optimisation criterion containing the root mean square error values. The criterion was minimized using the GWO-WOA optimization algorithm. This resulted in an error that, compared to the conventional "white box" approach, was an order of magnitude smaller than the one obtained based on theoretically determined values of the model's dynamic parameters. E. Cachaya *et al*. (2024) investigated the stabilisation of the position of a two-wheeled device with a balancing mechanism in the form of a jet wheel. The mathematical model was developed using the equilibrium method. It was later used to optimize the parameters of controllers.

D. Vasilevski *et al*. (2023) considered the problem of synthesising optimal control of the position stabilisation of a two-wheeled device such as a motorcycle, where the balancing mechanism is implemented in the form of a jet wheel. To solve the problem, a mathematical model with two degrees of freedom was proposed, the kinematic scheme of which was presented in the form of an inverse pendulum with a flywheel. The mathematical model of the device was represented in the state space of the system. The dynamic parameters of the system were determined by theoretical methods. M. Horoub *et al*. (2023) considered the mechanism of balancing a two-wheeled vehicle such as a bicycle using propeller thrust. A two-stage process of concept development and testing was presented, first on a simple model and then on a full-scale vehicle. The result was a mathematical model in the form of a matrix of system states. The dynamic parameters of the system were determined approximately. As a result, when checking the adequacy of the model in comparison with the experiment, the model poorly describes the damped self-oscillations when the position of the device changes.

The purpose of the present study was to obtain a mathematical model of the dynamics of the position stabilisation of a device for small-sized cargo transportation.

To fulfil this purpose, the following objectives had to be met:

1) to build a kinematic scheme of the device in the mode of stabilisation of its position and, on its basis, to wright the equations of motion of the device in the form of a system of second order Lagrange equations;

2) to develop an optimization criterion that reflects the difference between theoretical and experimental data on the angle and angular velocity of the device as a function of unknown parameters of the equation of motion of the device and find its minimum by using the Ring-Rot-PSO algorithm;

3) to analyse the quality of the developed mathematical model.

Materials and Methods

To build a mathematical model of a device for small-sized cargo transportation, a kinematic scheme of the device's operation in the balancing mode was presented (Fig. 1). When building the model, a partial mode of operation was considered, namely balancing the device, provided that the wheels of the device do not rotate.

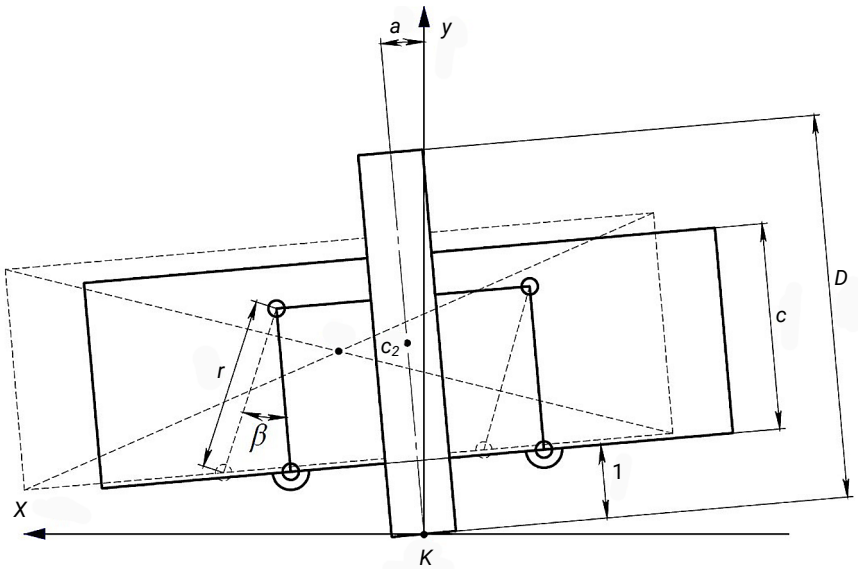

Figure 1. *Kinematic scheme of the device in balancing mode*

Note: α is the angle of inclination of the device in the vertical plane; β is the angle of displacement of the crank of the balancing mechanism from the initial position; c_1 and c_2 is the centre of mass of the frame and the rear wheel, respectively; r is the radius of the crank; c is the frame height; D is the wheel height; l is the distance from the frame to the point of contact K of the wheel with the ground

Source: compiled by the authors of this study

Assumptions were made in developing the model:

1) the frame and rear wheel have an even weight distribution;

2) the centres of gravity of the frame and wheels coincide with the geometric centres of their profiles (marked respectively by points c_1 and c_2);

3) the wheel is in contact with the ground at a point K.

To build a mathematical model of the device, the expression of the kinetic T is compiled:

$$T = \frac{1}{2}\left(\left(I_m + I_p\right) \cdot u^2 + I_p + I_{wc}\right) \cdot \dot{\beta}^2 + \frac{m_1}{2} \cdot \cdot \left(\dot{x}_{c1}^2 + \dot{y}_{c1}^2\right) + m_w \cdot \frac{1}{2}\left(I_{lw} + I_{wc}\right) \cdot \dot{\alpha}^2, \quad (1)$$

where I_p is the moment of inertia of the pulleys in the belt transmission; I_m is the moment of inertia of the step motor; u is the gear ratio of belt transmission ($u = 1$); I_{wc} is the moment of inertia of the wheel relative to the point of contact with the surface K (Fig. 1); m_1 is the mass of the frame; m_w is the mass of the wheel; I_{lc} is the moment of inertia of the frame relative to the point of contact with the surface K; x_{c1}, y_{c1} are the coordinates of the centre of mass of the device frame. The potential energy of the system is as follows:

$$P = m_1 g y_{c1} + m_k g y_{c2}, \quad (2)$$

where g is the acceleration of free fall; y_{c2} is the coordinate of the centre of mass of the wheel, which is found as follows:

$$y_{c2} = \frac{D}{2} \cos\alpha \approx \frac{D}{2}, \quad (3)$$

where D is the diameter of the wheel. Hereafter, since the angle α varies within a small range (+-5°), we assume $\cos(\alpha) = 1$, $\sin(\alpha) = \alpha$. The coordinates of the centre of mass of the frame are obtained from the following expressions:

$$x_{c1} = r \cdot \sin\beta + y_1 \cdot \sin\alpha, \quad (4)$$

where r is the radius of the crank;

$$y_{c1} = y_1 \cdot \cos\alpha, \quad (5)$$

where y_1 is the height of the centre of the frame under the condition $\alpha = 0$. It is found as follows:

$$y_1 = l + \frac{c}{2} + r \cdot (1 - \cos\beta), \quad (6)$$

where l is the distance from the bottom of the frame to the ground at $\alpha = 0$; c is the height of the frame. The first derivative of y_1 in time is found as follows:

$$\dot{y}_1 = \dot{\beta} \cdot r \cdot \sin\beta, \quad (7)$$

By substituting y_1 in equations (4) and (5), we obtain:

$$x_{c1} = r \cdot \sin\beta + y_1 \cdot \sin\alpha \approx r \cdot \sin\beta + \alpha \cdot \cdot \left(l + \frac{c}{2} + r \cdot (1 - \cos\beta)\right), \quad (8)$$

$$y_{c1} = y_1 \cdot \cos\alpha = \cos\alpha \cdot \cdot \left(l + \frac{c}{2} + r \cdot (1 - \cos\beta)\right) \approx \approx l + \frac{c}{2} + r \cdot (1 - \cos\beta). \quad (9)$$

The first derivative of the frame's centre of mass coordinates was found as follows:

$$\dot{x}_{c1} = \dot{\beta} \cdot r \cdot \cos\beta - \dot{y}_1 \cdot \sin\alpha + y_1 \cdot \dot{\alpha} \cdot \cos\alpha = = \dot{\beta} \cdot r \cdot \cos\beta - \dot{\beta} \cdot r \cdot \sin\beta \cdot \sin\alpha + \left(l + \frac{c}{2} + r \cdot (1 - \cos\beta)\right) \cdot \dot{\alpha} \cdot \cos\alpha = = \dot{\beta} \cdot r \cdot (\cos\beta - \sin\beta \sin\alpha) + \left(l + \frac{c}{2} + r \cdot (1 - \cos\beta)\right) \cdot \dot{\alpha} \cdot \cos\alpha \approx \approx \dot{\beta} \cdot r \cdot (\cos\beta - \alpha \cdot \sin\beta) + \dot{\alpha} \cdot \left(l + \frac{c}{2} + r \cdot (1 - \cos\beta)\right); \quad (10)$$

$$\dot{y}_{c1} = \dot{y}_1 \cdot \cos\alpha - y_1 \cdot \dot{\alpha} \cdot \sin\alpha = = \dot{\beta} \cdot r \cdot \sin\beta \cdot \cos\alpha - \dot{\alpha} \cdot \sin\alpha \cdot \left(l + \frac{c}{2} + r \cdot (1 - \cos\beta)\right) \approx \approx \dot{\beta} \cdot r \cdot \sin\beta - \dot{\alpha} \cdot \alpha \cdot \left(l + \frac{c}{2} + r \cdot (1 - \cos\beta)\right). \quad (11)$$

To build a mathematical model, the second order Lagrange equation was used as follows:

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{\alpha}} - \frac{\partial T}{\partial \alpha} = -\frac{\partial P}{\partial \alpha}; \quad (12)$$

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{\beta}} - \frac{\partial T}{\partial \beta} = M_u \cdot \eta - \frac{\partial P}{\partial \beta}, \quad (13)$$

where M_u is the torque on the step motor shaft; η is the efficiency ratio of the belt transmission ($\eta = 0.9$). To find the partial derivatives of the potential and kinetic energies, the corresponding partial derivatives are taken as follows:

$$\frac{\partial T}{\partial \alpha} = m_1 \left(\dot{x}_{c1} \cdot \frac{\partial \dot{x}_{c1}}{\partial \alpha} + \dot{y}_{c1} \cdot \frac{\partial \dot{y}_{c1}}{\partial \alpha}\right); \quad (14)$$

$$\frac{\partial T}{\partial \dot{\alpha}} = m_1 \left(\dot{x}_{c1} \cdot \frac{\partial \dot{x}_{c1}}{\partial \alpha} + \dot{y}_{c1} \cdot \frac{\partial \dot{y}_{c1}}{\partial \alpha}\right) + (I_{lc} + I_{wc}) \cdot \dot{\alpha}; \quad (15)$$

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{\alpha}} = m_1 \left(\ddot{x}_{c1} \cdot \frac{\partial x_{c1}}{\partial \alpha} + \dot{x}_{c1} \cdot \frac{\partial \dot{x}_{c1}}{\partial \alpha} + + \ddot{y}_{c1} \cdot \frac{\partial y_{c1}}{\partial \alpha} + \dot{y}_{c1} \cdot \frac{\partial \dot{y}_{c1}}{\partial \alpha}\right) + (I_{lc} + I_{wc}) \cdot \ddot{\alpha}; \quad (16)$$

$$\frac{\partial T}{\partial \beta} = m_1 \left(\dot{x}_{c1} \cdot \frac{\partial \dot{x}_{c1}}{\partial \beta} + \dot{y}_{c1} \cdot \frac{\partial \dot{y}_{c1}}{\partial \beta}\right); \quad (17)$$

$$\frac{\partial T}{\partial \dot{\beta}} = I_{cm} \cdot \dot{\beta} + m_1 \left(\dot{x}_{c1} \cdot \frac{\partial \dot{x}_{c1}}{\partial \dot{\beta}} + \dot{y}_{c1} \cdot \frac{\partial \dot{y}_{c1}}{\partial \dot{\beta}}\right), \quad (18)$$

where I_{cm} is the combined moment of inertia of the device relative to the point of contact with the ground K (Fig. 1) ($I_{cm} = I_m + I_p + I_c$);

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{\beta}} = I_{cm} \cdot \dot{\beta} + m_1 \cdot \left(\ddot{x}_{c1} \cdot \frac{\partial x_{c1}}{\partial \beta} + \dot{x}_{c1} \cdot \frac{\partial \dot{x}_{c1}}{\partial \beta} + \ddot{y}_{c1} \cdot \frac{\partial y_{c1}}{\partial \beta} + \dot{y}_{c1} \cdot \frac{\partial \dot{y}_{c1}}{\partial \beta}\right); \quad (19)$$

$$\frac{\partial P}{\partial \alpha} = m_1 \cdot g \cdot \frac{\partial y_{c1}}{\partial \alpha} + m_w \cdot g \cdot \frac{\partial y_{c2}}{\partial \alpha}; \quad (20)$$

$$\frac{\partial P}{\partial \beta} = m_1 \cdot g \cdot \frac{\partial y_{c1}}{\partial \beta} + m_w \cdot g \cdot \frac{\partial y_{c2}}{\partial \beta}. \quad (21)$$

Substituting the results of (14)-(21) into expressions (12) and (13), the following system of differential equations is obtained:

$$\begin{cases} I_{cm}\cdot\ddot{\beta}+m_1\cdot\left(\ddot{x}_{c1}\cdot\frac{\partial x_{c1}}{\partial\beta}+\dot{x}_{c1}\cdot\frac{\partial x_{c1}}{\partial\beta}+\ddot{y}_{c1}\cdot\frac{\partial y_{c1}}{\partial\beta}+\dot{y}_{c1}\cdot\frac{\partial\dot{y}_{c1}}{\partial\beta}\right)-m_1\cdot\left(\dot{x}_{c1}\cdot\frac{\partial x_{c1}}{\partial\beta}+\dot{y}_{c1}\cdot\frac{\partial\dot{y}_{c1}}{\partial\beta}\right)= \\ =M_u\cdot\eta-m_1\cdot g\cdot\frac{\partial y_{c1}}{\partial\beta}+m_w\cdot g\cdot\frac{\partial y_{c2}}{\partial\beta}; \\ (I_{lc}+I_{wc})\cdot\ddot{\alpha}+m_1\cdot\left(\ddot{x}_{c1}\cdot\frac{\partial x_{c1}}{\partial\alpha}+\dot{x}_{c1}\cdot\frac{\partial x_{c1}}{\partial\alpha}+\ddot{y}_{c1}\cdot\frac{\partial y_{c1}}{\partial\alpha}+\dot{y}_{c1}\cdot\frac{\partial\dot{y}_{c1}}{\partial\alpha}\right)-m_1\cdot\left(\dot{x}_{c1}\cdot\frac{\partial x_{c1}}{\partial\alpha}+\dot{y}_{c1}\cdot\frac{\partial\dot{y}_{c1}}{\partial\alpha}\right)= \\ =-m_1\cdot g\cdot\frac{\partial y_{c1}}{\partial\alpha}-m_w\cdot g\cdot\frac{\partial y_{c2}}{\partial\alpha}. \end{cases} \quad (22)$$

Having opened the brackets and performing simplifications in the system of equations (22), the following system of equations is obtained:

$$\begin{cases} I_{cm}\cdot\ddot{\beta}+m_1\cdot\left(\ddot{x}_{c1}\cdot\frac{\partial x_{c1}}{\partial\beta}+\ddot{y}_{c1}\cdot\frac{\partial y_{c1}}{\partial\beta}\right)=M_u\cdot\eta-m_1\cdot g\cdot\frac{\partial y_{c1}}{\partial\beta}+m_w\cdot g\cdot\frac{\partial y_{c2}}{\partial\beta}; \\ (I_{lc}+I_{wc})\cdot\ddot{\alpha}+m_1\cdot\left(\ddot{x}_{c1}\cdot\frac{\partial x_{c1}}{\partial\alpha}+\ddot{y}_{c1}\cdot\frac{\partial y_{c1}}{\partial\alpha}\right)=-m_1\cdot g\cdot\frac{\partial y_{c1}}{\partial\alpha}-m_w\cdot g\cdot\frac{\partial y_{c2}}{\partial\alpha}. \end{cases} \quad (23)$$

To find the unknown parts of (23), consider the following:

$$\frac{\partial x_{c1}}{\partial\alpha}=\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)\cos\alpha\approx \approx l+\frac{c}{2}+r\cdot(1-\cos\beta); \quad (24)$$

$$\frac{\partial y_{c1}}{\partial\alpha}=\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)\sin\alpha\approx \approx-\alpha\cdot\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right); \quad (25)$$

$$\frac{\partial y_{c2}}{\partial\alpha}=\frac{D}{2}\sin\alpha\approx\frac{D}{2}\alpha; \quad (26)$$

$$\frac{\partial y_{c2}}{\partial\beta}=r\cdot\cos\beta+r\cdot\sin\beta\sin\alpha\approx \approx r\cdot(\cos\beta+\alpha\cdot\sin\beta); \quad (27)$$

$$\frac{\partial y_{c1}}{\partial\beta}=r\cdot\sin\beta\cos\alpha\approx r\cdot\sin\beta; \quad (28)$$

$$\frac{\partial y_{c2}}{\partial\beta}=0. \quad (29)$$

To find the second derivative for the coordinate x_{c1} of the centre of mass of the frame, the following expression is formulated:

$$\ddot{x}_{c1}=\beta\cdot r\cdot(\cos\beta-\sin\beta\cdot\sin\alpha)-\beta\cdot r\cdot\left(\dot{\beta}\cdot\sin\beta-\beta\cdot\cos\beta\sin\alpha-\dot{\alpha}\cdot\sin\beta\cos\alpha\right)+ +\ddot{\alpha}\cdot\cos\alpha\cdot\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)+\dot{\alpha}\cdot\left(\dot{\beta}\cdot r\cdot\sin\beta\cos\alpha-\dot{\alpha}\cdot\sin\alpha\cdot\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)\right). \quad (30)$$

The brackets are opened, and the equation is simplified:

$$\ddot{x}_{c1}=\ddot{\beta}\cdot r\cdot(\cos\beta-\alpha\cdot\sin\beta)-\dot{\beta}\cdot r\cdot\left(\dot{\beta}\cdot(\sin\beta-\alpha\cdot\cos\beta)-\dot{\alpha}\cdot\sin\beta\right)+ +\ddot{\alpha}\cdot\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)+\dot{\alpha}\cdot\left(\dot{\beta}\cdot r\cdot\sin\beta-\dot{\alpha}\cdot\alpha\cdot\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)\right); \quad (31)$$

$$\ddot{x}_{c1}\approx\ddot{\beta}\cdot r\cdot(\cos\beta-\alpha\cdot\sin\beta)+\ddot{\alpha}\cdot\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)-\dot{\beta}^2\cdot r\cdot(\sin\beta-\alpha\cdot\cos\beta)- -\dot{\alpha}^2\cdot\alpha\cdot\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)+2\dot{\alpha}\cdot\dot{\beta}\cdot r\cdot\sin\beta. \quad (32)$$

The second derivative of the coordinate y_{c1} of the centre of mass of the frame is determined:

$$\ddot{y}_{c1}=\beta\cdot r\cdot\sin\beta\cdot\cos\alpha+\beta\cdot r\cdot\left(\dot{\beta}\cdot\cos\beta\cdot\cos\alpha-\dot{\alpha}\cdot\sin\beta\sin\alpha\right)- -\ddot{\alpha}\cdot\sin\alpha\cdot\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)-\dot{\alpha}\cdot\left(\dot{\beta}\cdot r\cdot\sin\beta\sin\alpha-\dot{\alpha}\cdot\cos\alpha\cdot\left(l+\frac{c}{2}+r\cdot(1-\cos\beta)\right)\right). \quad (33)$$

Having performed the transformation, let us reduce expression (33) to the following form:

$$\ddot{y}_{c1} \approx \ddot{\beta} \cdot r \cdot sin\,\beta - \ddot{\alpha} \cdot \alpha \cdot \left(l + \frac{c}{2} + r \cdot (1 - cos\,\beta)\right) + \dot{\beta}^2 \cdot r \cdot cos\,\beta$$
$$-2\dot{\alpha} \cdot \dot{\beta} \cdot \alpha \cdot r \cdot sin\,\beta - \dot{\alpha}^2 \cdot \alpha \cdot \left(l + \frac{c}{2} + r \cdot (1 - cos\,\beta)\right). \quad (34)$$

Substituting all the results obtained into the system of equations (20), a system of differential equations is obtained:

$$\begin{cases} I_{cm} \cdot \ddot{\beta} + m_1 \cdot \left(\ddot{x}_{c1} \cdot \frac{\partial x_{c1}}{\partial \beta} + \ddot{y}_{c1} \cdot \frac{\partial y_{c1}}{\partial \beta}\right) = M_u \cdot \eta - \left(m_1 \frac{\partial y_{c1}}{\partial \beta} + m_w \frac{\partial y_{c2}}{\partial \beta}\right) \cdot g; \\ (I_{lc} + I_{wc}) \cdot \ddot{\alpha} + m_1 \cdot \left(\ddot{x}_{c1} \cdot \frac{\partial x_{c1}}{\partial \alpha} + y_{c1} \cdot \frac{\partial y_{c1}}{\partial \alpha}\right) = -\left(m_1 \frac{\partial y_{c1}}{\partial \alpha} + m_w \frac{\partial y_{c2}}{\partial \alpha}\right) \cdot g, \end{cases} \quad (35)$$

The system of differential equations (35) is a mathematical model of the dynamics of balancing a device for small-sized cargo transportation.

In model (35), the coefficients in equations (35) are known, but some need to be determined, i.e., identified. This allows obtaining an adequate mathematical model that would correspond to the dynamics of device stabilisation. An adequate mathematical model underlies the synthesis of a controller that would ensure the optimised stabilisation of the device.

Results and Discussion

The individual device parameters included in equation (35) can be easily measured. Their numerical values are given in Table 1.

Table 1. *Numerical values of known parameters of a device for small-sized cargo transportation*

Parameter name	Unit of measurement	Symbol	Numeric value
Frame mass	kg	m_1	9.5
Crank radius	m	r	0.047
Distance from ground to the frame	m	l	0.040
Frame height	m	c	0.080
Wheel diameter	m	D	0.136

Source: developed by the authors of this study

Since the stabilisation process of the device is controlled by the angular velocity $\dot{\beta}$ of the balancing mechanism, let us consider the second equation of the system (35), which includes the desired (unknown) parameters of the device. They were found by using experimental data from the device by using "grey box" approach (Romlay *et al.*, 2019; Komor *et al.*, 2020).

The experimental data were collected in the stabilisation mode of the device in the form of an array of numerical data. The array data was collected with a time step of $\Delta t = 0.006$ s. The duration of data acquisition when the device was in stabilisation mode was 15 s. At each time interval, the following were read: tilt angle α, angular velocity of the device tilt $\dot{\alpha}$, angular velocity of the balancing mechanism rotation $\dot{\beta}$, and the current program operation time t.

The stability of the device was achieved using a proportional-differential controller (PD controller), the coefficients of which were selected empirically:

$$\dot{\beta} = 3 \cdot a - 3 \cdot \dot{\alpha}. \quad (36)$$

Accordingly, the values of the slope angle β and its second-time derivative were found in the components of equation (35):

$$\beta = \int (3 \cdot \alpha - 3 \cdot \dot{\alpha})\, dt; \quad (37)$$

$$\ddot{\beta} = 3 \cdot \dot{\alpha} - 3 \cdot \ddot{\alpha} \quad (38)$$

Having made all the substitutions, the second equation of the system (35) takes the following expanded form:

$$\begin{aligned} &2 \cdot g \cdot \alpha \cdot (c \cdot m_1 - D \cdot m_w + 2 \cdot m_1 \cdot (l + r)) + 6 \cdot m_1 \cdot r^2 \times \\ &\times sin(6 \cdot \int (\alpha + \dot{\alpha}) \cdot \mathrm{dt}) \cdot (\alpha + \dot{\alpha}) \cdot (3 \cdot \alpha + 5 \cdot \dot{\alpha}) = \\ &= 4 \cdot g \cdot \alpha \cdot m_1 \cdot r \cdot cos(3 \cdot \int (\alpha + \dot{\alpha})\, dt) + 6 \cdot m_1 \cdot r \cdot \\ &\cdot (c + 2 \cdot (l + r)) \times sin(3 \cdot \int (\alpha + \dot{\alpha})\, dt) \cdot (\alpha + \dot{\alpha}) \cdot \\ &\cdot (3 \cdot \alpha + 5 \cdot \dot{\alpha}) + 4 \cdot \ddot{\alpha} \cdot (I_{lc} + I_{wc}) + m_1 \cdot (c + 2 \cdot (l + r) - \\ &- 2 \cdot r \cdot cos(3 \cdot \int (\alpha + \dot{\alpha}) \cdot dt)) \times (\ddot{\alpha} \cdot (c + 2 \cdot (l + r)) - \\ &- 2 \cdot r \cdot cos(3 \cdot \int (\alpha + \dot{\alpha}) \cdot \mathrm{dt}) \cdot (3 \cdot \dot{\alpha}) + 4 \cdot \ddot{\alpha})). \quad (39) \end{aligned}$$

To find the solution to equation (39), the initial conditions were set as follows: the tilt angle of the device α_0=-0.033 rad, the angular velocity of the tilt $\dot{\alpha}$ = 0.109 rad·s^{-1}. The sought parameters of the device are as follows: 1) moment of inertia of the wheel I_{wc}; 2) moment of inertia of the frame I_{lc}; 3) mass of the wheel m_w. The optimisation criterion J, which corresponds to the degree of deviation of theoretical data (obtained using model (39)) from experimental data, is the following expression:

$$J = E_{RMS\alpha} + E_{RMSd\alpha} \cdot T + E_{max\alpha} + E_{maxd\alpha} \cdot T, \quad (40)$$

where $E_{RMS\alpha}$ is the root-mean-square value of the difference between the deviations of theoretical and experimental data by angle α; $E_{RMSd\alpha}$ is the root-mean-square value of the difference between the deviations of theoretical and experimental data in terms of angular velocity $\dot{\alpha}$; T is the period of forced oscillations of the device during the experiment (T = 0.744 s); $E_{max\alpha}$ is the maximum value of the difference between the deviations of the theoretical data and the experimental data at the angle α; and $E_{maxd\alpha}$ is the maximum error value of the difference between the deviations of theoretical and experimental data in terms of angular velocity $\dot{\alpha}$. In formula (40), the $E_{RMS\alpha}$ value was found as follows:

$$E_{RMS\alpha} = \sqrt{\frac{1}{2500} \cdot \sum_{j=1}^{2500} E_{\alpha.j}^2}, \quad (41)$$

where $E_{\alpha.j}$ is the j^{th} difference between theoretical data and experimental data for the angle α:

$$E_{\alpha.j} = \alpha_{t\_j} - \alpha_{e\_j}, \quad (42)$$

where α_{t_j} is the j^{th} value of the inclination angle α obtained theoretically (solution of equation (39)); α_{e_j} is the j^{th} value of the angle α of the array of experimental data. In formula (40), the root-mean-square value of the angular velocity error $E_{RMSd\alpha}$ was found as follows:

$$E_{RMSd\alpha} = \sqrt{\frac{1}{2500} \cdot \sum_{j=1}^{2500} E_{d\alpha\_j}^2}, \quad (43)$$

where $E_{d\alpha.j}$ is the j^{th} difference between theoretical data and experimental data in terms of angular velocity $\dot{\alpha}$:

$$E_{d\alpha.j} = \dot{\alpha}_{t.j} - \dot{\alpha}_{e.j} \quad (44)$$

where $\dot{\alpha}_{t.j}$ is the j^{th} value of the angular velocity , which is obtained theoretically (the first-time derivative of the solution of equation (39)); $\dot{\alpha}_{e\_j}$ is the j^{th} value of the angular velocity $\dot{\alpha}$ array of experimental data.

To reduce the elements of the expression to one dimension, the value T is used in expression (40). The maximum values of the differences in angles and angular velocities of the theoretical and experimental data $E_{max\alpha}$ and $E_{maxd\alpha}$ are found according to the following formulas:

$$E_{max\alpha} = max(|E_{\alpha.j}|); \quad (45)$$

$$E_{maxd\alpha} = max(|E_{d\alpha.j}|). \quad (46)$$

To minimise criterion (40), a modified Ring-Rot-PSO particle swarm method was applied (Romasevych *et al.*, 2021). As a result of its use, numerical values of the parameters were obtained (Table 2).

Table 2. *Numerical values of the found arguments of the criterion J (parameters of the dynamic system)*

Parameter	Dimensions	Numerical value
I_{wc}	kg·m²	$5.52 \cdot 10^{-4}$
I_{lc}	kg·m²	$2.75 \cdot 10^{-3}$
m_w	kg	$3.31 \cdot 10^{-1}$

Source: developed by the authors of this study

The values of the parameters presented in Table 2 allow minimising the value of the criterion *J*, and therefore the difference between the data of the theoretical model (39) and the experimental data is minimal. To analyse the constituent elements of criterion *J*, a plot was built. In Figures 2 and 3, the solid grey curves correspond to theoretical data, the dashed curves – to experimental data, while the red curves – to the difference between theoretical and experimental data.

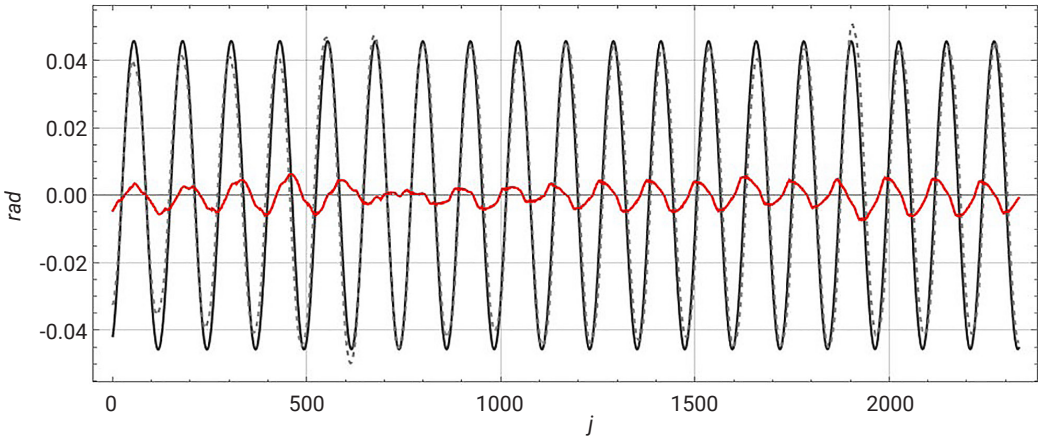

Figure 2. *Plots of the angle of inclination α obtained theoretically and experimentally, as well as their difference*

Source: developed by the authors of this study

Figure 2 shows that the difference between the values of the theoretical and experimental data for the angle α is much smaller than the values of the angle itself (both theoretical and experimental data) and they change almost synchronously. That is, the maximums and minimums of the error plot practically coincide with the maximum and minimum values of the device's tilt angle. The values of the difference between the theoretical and experimental data for the angular velocity $E_{d\alpha}$ (Fig. 3) are much smaller than the values of the experimental and theoretical data themselves. This plot varies proportionally with the values of the angular velocity . Furthermore, the numerical values of the components of the *J* criterion were calculated, which show certain categories of discrepancies between theoretical and experimental data (Table 3)

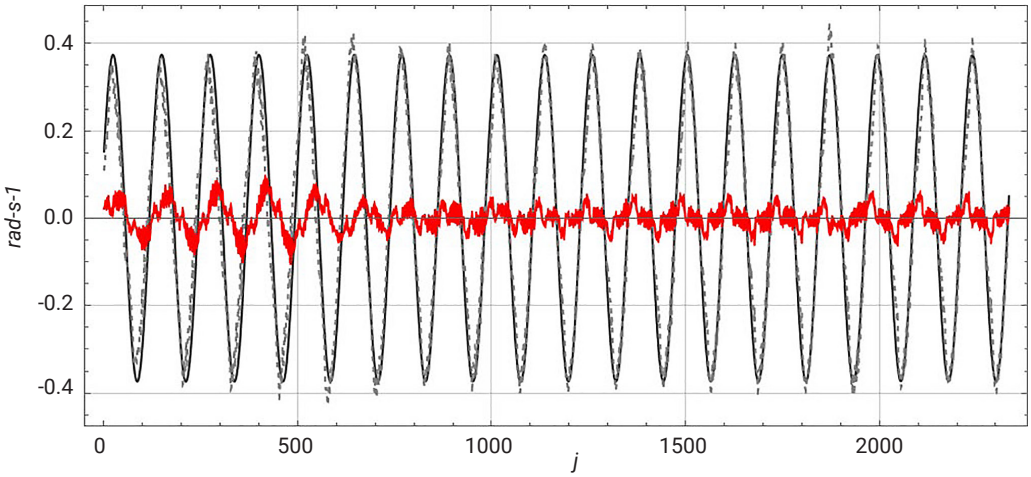

Figure 3. *Plots of angular velocity , obtained theoretically and experimentally, as well as their difference*

Source: developed by the authors of this study

Table 3. *The numerical values of the components of the criterion J*

Component of criterion J	Dimensions	Value
$E_{max\alpha}$	rad	$7.31 \cdot 10^{-3}$
$E_{maxd\alpha}$	$rad \cdot s^{-1}$	$9.91 \cdot 10^{-2}$
$E_{RMS\alpha}$	rad	$3.11 \cdot 10^{-3}$
$E_{RMSd\alpha}$	$rad \cdot s^{-1}$	$2.78 \cdot 10^{-2}$

Source: developed by the authors of this study

Considering the values of $E_{RMS\alpha}$ and $E_{RMSd\alpha}$, which are insignificant (Table 3), it can be concluded on the good quality of identification of the parameters of the mathematical model (39). It can then be used to synthesise the optimal motion control for a small cargo transport device in stability mode.

Comparing the results and approach with other researchers, the following characteristics can be obtained. Z. Pluta & T. Hryniewicz (2013) described a method for determining the moment of inertia of the body mass relative to the desired axis experimentally using a physical pendulum with a rigid suspension at the end of which the test body is fixed. The moment of inertia was found by the oscillation parameters (deflection angle, oscillation period, and suspension length). In our case, the moments of inertia of the frame and wheel were found from the experimental data of the device stabilisation by using „grey box" approach, the parameter optimisation criterion, and the Ring-Rot-PSO optimisation algorithm. This allowed simplifying the construction of a mathematical model without the need to build a pendulum system and perform additional calculations of the device's moments of inertia measurements.

B. Rao *et al.* (2022) put the simple physical pendulum method into practice to determine the moment of inertia for a model aircraft. This methodology allows obtaining fairly accurate results: the researchers noted that the error is 1% when comparing theoretical and experimental data of mass inertia moments. This method is not well-suited for the cases described in the present study since the moment of inertia of

the frame during the balancing process is not constant. It varies depending on the position of the balancing mechanism, which changes the height of the frame's centre of mass relative to the point of contact of the wheel with the ground, relative to which the frame's moment of inertia is found.

In some cases, it is sufficient to estimate the unknown system parameters, or even to empirically find the required control action to stabilise the position of the device. To ensure the stability in the static of a two-wheeled device (such as a scooter), P. Gogoi *et al*. (2017) used a balancing mechanism in the form of a jet wheel. Its parameters were sought empirically by changing the diameter and weight of the disc, and relevant experiments were conducted to determine the optimised diameter of the jet wheel disc. In our case, the balancing mechanism works on the principle of shifting the mass relative to the centre of mass to ensure static stability. An empirical approach to synthesise the optimal control would take an exceedingly long time and, if the parameters (weight of the cargo, inclination of the road) changed, the balancing would be of questionable quality or even impossible.

L. Nehaoua *et al*. (2013) conducted a thorough study and proposed to use the differential-variational principle of Jourdain to build a mathematical model of a two-wheeled device (such as a motorcycle), accommodating the suspension, elastic properties of the wheels, and the force on the steering wheel. It showed good prediction performance, but this is an example of a theoretical problem without practical verification. In contrast to the Jourdain principle, the present study constructed a mathematical model of the device in the form of second order Lagrange equations, and the use of the „grey box" approach made it possible not to determine the stiffness of the suspension, the elasticity of the wheels, the deformation in the links and the shape of the ground contact patch. These and many other parameters were found from the experimental data of the device.

To ensure the stability of the position of a two-wheeled device (such as a motorcycle) in static and in motion, R. Lot & J. Fleming (2018) proposed to use a gyroscope in two modes (passive and active). The active mode proved to be much better than the passive mode and ensured that the stability was maintained in static. The mathematical model of the device was developed in the form of a system state space. The quality of the device model has not been assessed in practice. This approach requires accurate measurements of the device parameters, which is not always possible. Unlike R. Lot & J. Fleming (2018), the current study is tied to a real device and thus allows not only theoretical verification, but also experimental verification.

Y. Lin *et al*. (2024) considered the problem of maintaining stability in motion for a two-wheeled device (such as a scooter) by controlling the rotation of the front wheel. To solve this problem, a dynamic model of the device's motion was constructed in the form of second order Lagrange equations. The method of determining the dynamic parameters of the device was not described. To ensure stability, the parameters of various variations of the PD controller were found based on the dynamic model. In the cited study, the process of creating a mathematical model partially repeats the methodology presented in the current study, except that the former did not consider ensuring high-quality dynamic parameters of the device. In our case, a more thorough study was carried out, which involved determining the unknown parameters of the model.

M. Khan *et al*. (2022) described a method for constructing a mathematical model of a two-wheeled device (such as a segway) by using the „black box" approach. It is implemented using neural network technologies based on time-series data arrays generated on a known mathematical model of the device. To fulfil this purpose, it was proposed to use two models: simple autoregressive (ARX) and non-linear autoregressive (NLARX). The modelling result showed high quality forecasting with a relative error of less than

0.05%. Compared to the current study, the cited study describes a solution to the second part of the process of creating a mathematical model. It uses experimental data in the form of a time series to determine the dependence of some system parameters on each other.

M. Garziad *et al.* (2024) describe a method for constructing a mathematical model of a two-wheeled device (such as a motorcycle) based on graph theory. In this method, the dynamic model is represented as a system of graphs. The results of the forecasting quality check presented by the researchers, in comparison with other studies, show good prediction quality. Comparing the methodology for creating a mathematical model based on graph theory with the „grey box" approach implemented in the current study, the following differences can be observed. Representation of the dynamic model of the device in the form of graphs and the subsequent process of creating a mathematical model is complex, novel, and requires high qualification of the researcher, unlike the classical methods used in the present study.

Conclusions

A kinematic scheme of a device for small-sized cargo transportation was constructed. A system of differential equations for the dynamics of the device stabilisation was developed by using second order Lagrange equations. To find the unknown parameters (coefficients of the equation of motion of the device), a „grey box" approach was applied. For this, experimental studies of the device stabilisation were conducted, and a difference function (objective function) between theoretical (obtained from the equations of motion) and experimental data was formed. The objective function is minimised using the modified particle swarm method Ring-Rot-PSO. As a result of the optimisation, the unknown parameters of the system were found as follows: moments of inertia of the frame $I_{lc} = 5.52 \cdot 10^{-4}$ kg · m² and wheels $I_{wc} = 2.75 \cdot 10^{-3}$ kg · m², wheel mass $m_w = 3.31 \cdot 10^{1}$ kg. The quality of the mathematical model was evaluated according to the following parameters: the maximum values of the difference between theoretical and experimental data for the angle of inclination of the device $E_{\max\alpha} = 7.31 \cdot 10^{-3}$ rad and for the angular velocity $E_{\max d\alpha} = 9.91 \cdot 10^{-2}$ rad·s^{-1}; root mean square values for the tilt angle of the device $E_{RMS\alpha} = 3.11 \cdot 10^{-3}$ rad and for the angular velocity $E_{RMSd\alpha} = 2.78 \cdot 10^{-2}$ rad·s^{-1}. The findings give grounds to consider the obtained mathematical model of stabilisation of the device suitable for further synthesis of optimal control of device position stabilisation. This will enable development of a control algorithm and implement it in software on a prototype device.

The obtained methodology for developing a mathematical model of a device is not limited to this example and can be applied to other dynamic systems. The generality of the methodology is grounded by the use of the classical approach to constructing a dynamic model in the form of Lagrange equations, while the „grey box" approach simplifies the search for unknown system parameters. The findings allow considering this methodology as one of the ways to solve the problem of developing an adequate mathematical model of movement devices such as a segway, scooter, motorcycle, bicycle, and a series of other wheeled unstable mobile platforms. The application of this methodology in other fields of technology and engineering opens new opportunities for the analysis and optimisation of dynamic systems. It will also help to develop more efficient and stable mechanisms in various industries, from transport to robotics.

Acknowledgements

None.

Conflict of Interest

None.

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Розробка математичної моделі стабілізації пристрою для транспортування малогабаритних вантажів

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Анотація. Актуальність дослідження обумовлена необхідністю підвищення ефективності та безпеки транспортування малогабаритних вантажів Метою дослідження було побудувати математичну модель динаміки стабілізації пристрою для транспортування малогабаритних вантажів. Для цього складено рівняння руху системи у вигляді системи диференціальних рівнянь Лагранжа другого роду. Для визначення невідомих коефіцієнтів рівнянь руху застосовано підхід «сіра скриня». Для реалізації підходу було побудовано критерій оптимізації, який відображав параметри середньоквадратичних та максимальних абсолютних похибок різниць теоретичних та експериментальних даних кута нахилу та кутової швидкості нахилу пристрою. Для мінімізації критерію було застосовано модифікований метод рою часточок Ring-Rot-PSO. Знайдено невідомі параметри моделі пристрою та проведено оцінку адекватності отриманої математичної моделі за окремими складовими критерію, яка показала адекватність отриманої математичної моделі. Для знаходження невідомих параметрів, а саме коефіцієнтів рівняння руху пристрою, застосовано підхід сіра скриня. Для цього проведено експериментальні дослідження стабілізації пристрою та сформовано функцію відмінності, як цільову функцію, теоретичних, які отримані на основі аналітичних рівнянь руху, і експериментальних даних. Проведено мінімізацію цільової функції за допомогою модифікованого методу рою часточок Ring-Rot-PSO. В результаті оптимізації отримано невідомі параметри системи: моменти інерції рами $I_{1к} = 5{,}52 \cdot 10^{-4}$ кг · м² та колеса $I_{кк} = 2{,}75 \cdot 10^{-3}$ кг · м², масу колеса $m_к = 3{,}31 \cdot 10^{-1}$ кг. Ці дані дозволили отримати адекватну математичну модель стабілізації пристрою, яка є основою для подальшого розв'язання задачі синтезу оптимального керування його рухом

Ключові слова: двоколісний пристрій; рівняння руху; керування рухом; нестійка динамічна система; Ring-Rot-PSO

Received 16.02.2024 Revised 21.05.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 504.55.054:553.982

DOI: 10.31548/dopovidi/3.2024.72

Phytoremediation of soils contaminated as a result of military and anthropogenic impact

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Abstract. Military conflicts and anthropogenic accidents cause significant soil contamination with heavy metals, oil products, pesticides, and other toxic substances. The purpose of this study was to highlight the factors of influence of military-anthropogenic load on soils and to analyse the available methods of their remediation. The study summarised the available and promising phytoremediation methods with an assessment of their impact on soil contamination by chemicals that are typical pollutants during military conflicts. The study summarised, classified, and compared the groups of pollutants that are most common during military operations; analysed the impact of pollutants on the fertile soil layer and their mobility; and analysed the available remediation methods. It was found that the available soil remediation technologies, which can be used individually or in combination, provide the necessary tools to address the problem of chemical contamination of soils due to toxic products such as explosive derivatives and heavy metals. The degree of economic feasibility was considered, which, accordingly, suggested that soil phytoremediation may be the most economically feasible under certain conditions. This opens wide possibilities for further investigations, where the synergy of ecology, economics, and agrobiology will enable the development of mechanisms for optimising soil phytoremediation methods, considering their type, profile, and intended use. An algorithm of actions for remediation of soils as a result of military-anthropogenic load was proposed, which includes a related set of related actions on zoning, demining, assessment, and return of land to industrial use. The findings of this study can be used to clean industrial areas that have been contaminated during production processes or accidents

Keywords: soil remediation; phytoremediation; anthropogenic impact; soil degradation; chemical soil pollution; energy-intensive substances; propellants

Suggested Citation:
Melnychenko, V. (2024). Phytoremediation of soils contaminated as a result of military and anthropogenic impact. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 72-84. doi: 10.31548/dopovidi/3.2024.72.

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Introduction

Restoring soil fertility affected by military operations, as one of the most aggressive anthropogenic factors, and protecting it from pollution is a complex scientific challenge of modern time that requires a balanced approach and covers physical, chemical, and biological aspects. The development of new methods of remediation of soils contaminated with both explosives and fuels and lubricants is relevant and significant both in practical and theoretical terms. Phytoremediation is one of the most promising ways to decontaminate xenobiotics in soil using phytoremediation plants. This method does not require physical soil movement, helps preserve the natural environment and soil ecosystem, improves soil quality, protects it from erosion, and can be applied on an industrial scale with a positive economic effect.

Issues related to the impact of anthropogenic military activity on ecological systems continue to be comprehensively investigated by both Ukrainian and foreign scientists. Iu. Boretska *et al*. (2021) investigated the problem of restoring soil fertility and protecting it from pollution using phytoremediation methods and provided recommendations for the use of crops as phytoremediation agents. The researcher noted the effectiveness of some plant species in absorbing heavy metals and toxic substances, which allows not only cleaning the soil but also increasing its fertility for further agricultural use. V. Dudar (2023) covers the issue of military-anthropogenic impact on the environment, considering explosives and their impact on the soil ecosystem. The study noted that explosive remnants of war have a significant negative impact on the environment. They contaminate soil and water resources with toxic chemicals released during explosions and ammunition decomposition. This leads to degradation of natural ecosystems and loss of biodiversity in the affected regions. Furthermore, the presence of explosive remnants of war makes it difficult to access land resources and use them for agricultural and recreational purposes.

Ya. Tsytsiura *et al*. (2022) covered the issues related to the redistribution of heavy metals in the agricultural landscape under the influence of anthropogenic factors and the specific features of their accumulation in plants. The researchers conducted a comprehensive assessment of existing factors, their grouping, and classification. The researchers analysed approaches to phytoremediation and phytoremediation in modern farming systems, which include the use of genetically modified plants that can absorb and neutralise pollutants more effectively. The cited study also used multi-component plant complexes to help clean soils more quickly and comprehensively. These techniques not only increase agricultural productivity but also help to restore ecological balance in agricultural landscapes. Along with Ukrainian scientists, the problem of the impact of military-anthropogenic load is being studied by their foreign counterparts. J.J. Pichtel (2012) examined the distribution and ways of spreading chemical pollutants in the soil, paying special attention to explosives, which are most often used during military and anthropogenic impact. C.R. Müller *et al*. (2022) analysed the impact of mechanical factors on the soil during military exercises, which to some extent serves as a simulation of military-anthropogenic load on the soil system. The study showed that such factors cause considerable changes in the soil structure, including compaction, reduced porosity, and disturbance of the water regime. These changes can lead to soil degradation, reduced fertility, and a negative impact on vegetation and microbiological processes. D. Averin *et al*. (2024), in collaboration with the OSCE (Organisation for Security and Cooperation in Europe) and the Conflict and Environment Observatory, thoroughly examined the environmental consequences of the war in Ukraine. The report analysed the factors of influence, the scale and consequences of ecosystem contamination, including land, and provided recommendations on the possibility of remediation.

To analyse the existing military-anthropogenic impact on soil in Ukraine, it is considered that this impact is not static and is constantly changing. This creates the need for further monitoring of both the factors of influence and its consequences. The purpose of this study was to highlight the factors of phytoremediation impact on soils subjected to military-anthropogenic load. The objectives of the study were to summarise phytoremediation techniques and analyse their impact on soil contamination by chemicals, which are typical pollutants during military conflicts.

For this, a series of general scientific methods were employed, including classification, which was used to group the factors of military-anthropogenic impact and sources of pollution. Using the analytical method, the study investigated the totality of the consequences of negative impact on the soil ecosystem, dividing the latter into mechanical, chemical, and biological. The use of a combination of analytical and theoretical methods helped to propose an action algorithm designed to ensure remediation of soils damaged as a result of military and anthropogenic impact.

Considering the dynamism of military-anthropogenic impact processes and a wide series of factors, the issue of their assessment and classification is a task that aims to create standardised mechanisms for remediation that optimises the process of returning contaminated land to industrial production. Considering that Ukraine's agricultural land is the mainstay of agricultural production, remediation of contaminated soils will have a positive impact on the global food security situation. Thus, soil remediation should be considered not only as a technique, but also as a tool that will serve to improve food security (UNCG 2022).

Types of Soil Damage Depending on the Factors of Influence

Soil damage resulting from military operations is mainly of three main types: mechanical, chemical, and biological – as a result of direct damage or, more often, indirect impact (Certini *et al.*, 2013).

Mechanical damage to the soil includes compaction resulting from the construction of defence infrastructure and facilities, the construction of trench systems, compaction caused by the movement of military equipment, or the formation of craters from detonations of highly explosive substances. Such actions drastically change the structure of the soil profile. Bombardment and shelling create sinkholes, mix soil horizons, and disrupt the water balance. The consequences of such actions are changes in the topography and landscape of the ecosystem (Anderson & Walker, 2000). Almost always, considerable fires occur near the sites of hostilities, causing the burning of fertile soil and the destruction of protagonistic microflora (Agrilab, 2022). The main types of mechanical damage to soils during military operations are (but are not limited to) listed in Table 1:

Table 1. *The effects of mechanical damage on the soil ecosystem*

Root cause of mechanical soil damage	Implications for the soil ecosystem
1. Movement of heavy machinery	➤ soil compaction; ➤ aeration disorder; ➤ fuel and lubricants entering the soil.
2. Digging fortifications (trenches, dugouts, emplacements)	➤ disturbance of the soil profile; ➤ aeration disorder; ➤ soil erosion; ➤ change in relief; ➤ destruction of habitats.
3. Explosions of ammunition	➤ disturbance of the soil profile; ➤ mixing of soil horizons; ➤ fires.

Source: compiled by the author of this study based on R.M. Iverson (1981), P.S. Althoff & S.J. Thien (2005)

Chemical damage is caused by the ingress of harmful substances into the soil, such as oil and its derivatives, heavy metals, explosives, organophosphates, radioactive elements, etc. Chemical compounds that get into the soil cause serious pollution. Typically, chemicals are not biodegradable and contain a wide range of chemical compounds that are toxic to plants, animals, and humans. They lead to soil contamination, slow plant growth, and threaten the entire ecosystem (Table 2). Such contamination can have long-term effects on the soil ecosystem, the environment, and human health. The impact of chemical soil contamination on both plants - for which access to water and nutrients is impaired – and human health is noted, due to the entry of chemical contaminants into food chains through contaminated plants and water sources (Boretska *et al*., 2021).

Table 2. *Effects of chemical damage on the soil ecosystem*

Root cause of chemical soil damage	Implications for the soil ecosystem
1. Fuel and lubricants entering the soil	➤ entry into ground, groundwater, and surface water; ➤ impact of chemical toxicity; ➤ disruption of the water-air balance; ➤ reduction of the water retaining capacity of the soil; ➤ hydrophobic treatment of soil particle surfaces with heavy hydrocarbon fractions; ➤ inhibition of biological processes in the soil; ➤ reduction of soil pore space; ➤ excessive absorption of solar radiation.
2. Explosions of ammunition	➤ chemical products of the explosion reaction entering the soil; ➤ soil contamination with heavy metals; ➤ thermal and chemical burns of plants; ➤ disturbance of the soil profile; ➤ mixing of soil horizons.
3. Fires	➤ emission of pollutants into the atmosphere (products of organic synthesis, phosphorus); ➤ contamination of ground and underground water with heavy metal salts (cadmium, etc.); ➤ soil contamination with dioxins, phosgenes, polycyclic aromatic organic compounds; ➤ destruction of vegetation.

Note: FL – fuels and lubricants

Source: compiled by the author of this study based on Iu. Boretska *et al*. (2021)

Biological damage to soil can occur as a result of actions that affect the chemical and physical properties of the soil, as well as through the deliberate introduction of pathogenic cultures of microorganisms that can be deadly to higher animals and humans, such as botulinum or anthrax. Soil is an environment where such pathogens can stay virulent for decades. The presence of pathogens in soil can cause diseases in plants, animals, and humans (Table 3).

Table 3. *The effects of biological damage on the soil ecosystem*

Root cause of biological soil disturbance	Implications for the soil ecosystem
1. Deliberate introduction of pathogenic microorganisms into the soil	➤ pollution of groundwater and surface water; ➤ increase in the virulence of the soil; ➤ soil intoxication due to pathogenic microorganisms; ➤ changes in the soil microbiome and an increase in the population of pathogens in it.
1. Decomposition of organic residues	➤ contamination of groundwater and surface water with pathogens; ➤ epidemic consequences; ➤ soil contamination.

Source: compiled by the author of this study based on O. Angurets *et al*. (2023)

Considering the above, the areas affected by active hostilities can be considered as having suffered from contamination of both terrestrial and soil ecosystems.

Typical Pollutants During Military-Anthropogenic Impact on Soil

Scientific research suggests that wars or even military exercises leave behind large areas contaminated mainly with toxic substances such as explosives, ammunition, and their residues (Beckmann & Vykhor, 2022). Examples of such contaminants, which include a large list of organic and inorganic toxic substances in the soil and pose significant risks to agriculture and, subsequently, to human health, are toxic elements released in explosion reactions. Typically, most of these elements are resistant to biodegradation and stay in the ecosystem and become a source of environmental pollution, exerting toxic effects on soil microbiota and water resources (Reuveny *et al.*, 2010). When oxidised in contact with the environment, these toxic elements sometimes become available in the context of their mobility to agricultural plants, and thus potentially dangerous to humans and animals. The consequences of the ingestion of toxins accumulated by plants into living organisms can be damage to vital organs and functions of the organism (Gorecki *et al.*, 2017). Notably, the so-called "Energy materials" are considered a generalised category of pollutants. Energy-intensive substances include both the explosives themselves and the fuels and lubricants mentioned above. When explosives enter the soil, they become xenobiotic pollutants that pose a toxic hazard to the ecosystem (Table 4). Many soils in the world are contaminated with energy-intensive materials as a result of military conflicts, military training exercises at training grounds and demining with open detonations of unexploded ordnance. When energy-intensive materials enter the soil, they undergo varying degrees of chemical and biochemical transformations depending on the chemical compounds they contain and environmental factors. Particular attention should be paid to the most common explosives 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (Hexagen or RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (Octogen or HMX), as well as rocket fuel components: (Nitroglycerin or NG), (Nitroguanidine or NQ), (Nitrocellulose or NC), (DNT or Dinitrotoluene), and perchlorate. These energy-intensive substances are most often used in the production of conventional ammunition, and subsequently – in combat operations or military training.

Table 4. *Explosive decay products and their mobility in soil*

Explosive substance (Energy-intensive substance)	Chemical class of the substance	Type of explosive	Degradation products	Mobility in the soil	Research
2,4,6-trinitrotoluene (TNT)	Organic nitrobenzene	Secondary / explosive filler	Degrades to (2-amino-4,6-dinitrotoluene, 4-amino-2,6-dinitrotoluene)	Often found in the upper soil layers	J.C. Pennington & J.M. Brannon (2002), F. Monteil-Rivera *et al*. (2009), H. Ryu *et al*. (2009), J. Pichtel (2012)
2,4-Dinitrotoluene (DNT)	Organic nitrobenzene	Secondary/ explosive filler or TNT degradation product	Degrades to (2-amino-4-nitrotoluene, 2,4-diaminotoluene, 4-amino-2-nitrotoluene, dinitrophenol)	Mobile in the soil. Enters groundwater. More mobile in sandy soils	ATSDR (n.d.), F. Monteil-Rivera *et al*. (2009), R. Reuveny *et al*. (2010), J. Akhavan (2011), J.D. Arthur *et al*. (2017), T. Temple *et al*. (2018)

Table 4. *Continued*

Explosive substance (Energy-intensive substance)	Chemical class of the substance	Type of explosive	Degradation products	Mobility in the soil	Research
Picric acid	Organic nitrobenzene	Secondary / explosive filler	Stable in water, degrades to toxic and mutagenic degradation products	High mobility in the soil, will stay in the environment for a long time	S.L. Yost *et al*. (2007), F. Monteil-Rivera *et al*. (2009), R.M. Hebert & A. Jackovitz (2015), Q.J. Zhao (2020)
2,4,6-Trinitrophenyl-methyl-nitramine (Tetryl)	Organic nitrobenzene	Secondary / explosive filler	Rapid degradation in soil, comparable to other nitrobenzene products: within a few weeks in some soil types	Mobile in the soil. Enters groundwater	ATSDR (n.d.), F. Monteil-Rivera *et al*. (2009); J.C. Lipcomb (2013), D. DeTata *et* al. (2013)
Cyclotrimethylene trinitramine RDX (Hexogen)	Organic nitramine	Secondary / explosive filler	Degrades to (mono-, di- and trinitroso products MNX, TNX and DNX	Mobile in the soil. Enters groundwater	J.C. Pennington & J.M. Brannon (2002), US Army Corps of Engineers, Environmental Research and Development Center (2006), H. Ryu *et al*. (2009), F. Monteil-Rivera *et al*. (2009)
1,3,5,7- tetranitro -1,3,5,7- Tetrazocaine HMX (Octogen)	Organic nitramine	Secondary / explosive filler	Very slow/ Inconsiderable degradation.	Can enter groundwater and persist for a long time	J.C. Pennington & J.M. Brannon (2002), E.T. Urbansky (2002), US Army Corps of Engineers, Environmental Research and Development Center (2006), H. Ryu *et al*. (2009), F. Monteil-Rivera *et al*. (2009), Technical Fact Sheet Perchlorate (2014), M.R. Sijimol *et al*. (2015)
Nitrocellulose	Polymer	Propellant	Degradation to nitrate and nitrite	Mobility in the soil is improbable	H. Ryu *et al*. (2009), M. Williams (2015), Integrated Risk Information System (1990)
Nitroguanidine	Organic	Propellant	Degrades to less harmful minerals	Mobile in the soil. Enters groundwater	Integrated Risk Information System (1990), F. Monteil-Rivera *et al*. (2009), T. Temple *et al*. (2018)

Source: compiled by the author of this study based on the data of the sources cited in the table

The absorption of pollutants by plants from the soil is influenced by two groups of factors: mobile forms of pollutant elements in the soil, which are regulated by the biological characteristics of plants and the properties of the soil with respect to pollutant ions. The absorption of heavy metals by plants and the simultaneous impact of this process on the soil is twofold. On the one hand, during absorption, the soil reduces the amount of accumulated elements in the plant. However, on the other hand, the accumulation of occluded elements in the upper layers, where the highest concentration of roots is found, facilitates their assimilation by plants and intensive accumulation than in the case of free movement of heavy metals to deeper soil layers.

Classification of Remediation Methods and Their Impact on Xenobiotics

The clean-up of soil contaminated by military operations is a relevant and significant issue for Ukraine. Plants can accumulate xenobiotics in their biomass, which are chemical compounds present in the environment but not part of the normal biological metabolism of the soil ecosystem. Accumulated xenobiotics are metabolised by the plant and absorbed on its surface. That is why phytoremediation can be a relevant and promising method of remediating chemically contaminated and degraded soils in Ukraine. As an actively developing area of soil remediation, phytoremediation combines a considerable number of methods based on the following processes (Table 5):

Table 5. *Methods of phytoremediation*

Phytostabilisation	This process involves the immobilisation of organic and inorganic pollutants in the soil. Plants adsorb these pollutants with their roots or soil particles and deposit them in the root zone. After that, xenobiotics turn into insoluble, inactive forms that stay in the soil complex. This prevents them from moving in soil, water, or air. Phytostabilisation also reduces erosion, agricultural and chemical leaching, contributing to the restoration of ecosystems and biodiversity.
Phytoextraction	This method is used for the absorption of xenobiotics by the root system of plants. Plants absorb pollutants along with nutrients and then transfer them to their aboveground parts. At the end of the growing season, the plants are mowed and processed accordingly. This helps cleanse the soil of the effects of heavy metal and radionuclide contamination.
Phytostimulation	This process increases microbial metabolism in the plant rhizosphere. Microorganisms living near the roots of plants actively decompose pollutants, contributing to the purification process. Phytostimulation can include the use of microbial cultures or special fertilisers that support the development of the necessary beneficial bacterial and fungal cultures in the soil. Furthermore, certain plants can produce substances that stimulate the growth of microorganisms or reduce the toxicity of xenobiotics.
Rhizofiltration	Rhizofiltration is one of the phytoremediation methods that uses plants to clean the contaminated soil environment. In this process, the root system of plants participates in the process of cleansing from xenobiotics. As a result of rhizofiltration, pollutants are removed from the soil, or the latter acquire less toxic forms. This process is effective in removing a variety of xenobiotics, including petroleum products, heavy metals, and other organic and inorganic substances.
Phytovolatilisation	Phytovolatilisation is an effective method of soil phytoremediation that uses plants to clean the contaminated soil environment. In this process, plants are used to extract and transform xenobiotics by binding them and volatilising them into the air. The process of phytolatilisation involves phytovolatilisers – plants that can absorb organic substances through the root system and release them in the form of evaporation through leaves or stems (foliar). They are further decomposed by atmospheric processes to less toxic compounds. Phytovolatilisation is an effective method of cleaning soils from xenobiotic contaminants such as petroleum products, organochlorine compounds, and chemical residues. Phytovolatilisation removes pollutants from the soil and converts them into less toxic forms, which considerably improves the quality of the soil environment. However, this process can be more time-consuming than other herbal remedies and require a long time to achieve noticeable results.

Table 5. *Continued*

	Phytodegradation is an important process in soil phytoremediation, which aims to clean contaminated soil environments from toxic compounds using plants. Phytodegradation uses enzymes and other plant mechanisms to break down pollutants into less toxic or harmless compounds.
Phytodegradation	The process of phytodegradation involves various biochemical reactions, such as hydrolysis, oxidation, enzymatic action of dehydrogenase, etc. These reactions are produced by different parts of the plant, such as roots, stems, leaves, and root system microorganisms. Phytodegradation allows toxic pollutants to be degraded into less toxic or even harmless components that are absorbed by plants or removed from the soil. This process is an effective method of soil treatment, using natural decomposition mechanisms to reduce the need for chemicals or artificial processes.

Source: developed by the author of this study based on data from S. Rock *et al*. (2000)

According to the US Environmental Protection Agency's "Introduction to Phytoremediation" report, phytoremediation is a technology that uses the ability of plants to degrade, retain (immobilise) and remove contaminants in soil (Rock *et al.*, 2000). M.N.V. Prasad, a professor at the School of Science, University of Hyderabad, India, has calculated that the cost of cleaning soil contaminated with heavy metals, radionuclides, oil, or pesticides using plants that use only solar energy is only 5% of the cost of other remediation methods. This makes phytoremediation a more environmentally sound and cost-effective method of soil decontamination compared to physical, chemical, and technical methods, even if the time available to achieve the ultimate goal is limited. Phytoremediation processes are based on the ability of plants to accumulate, decompose, stabilise, transform, and volatilise pollutants from various natural environments such as soil and water (Tsytsiura *et al.*, 2022). Notably, plants also have defence mechanisms that regulate the absorption of pollutants. There are several mechanisms to control the supply of ions. They mainly accumulate in the reproductive organs and roots. The study of the movement of pollutants in plants showed that at the first stages of the elements' intake from soils, most of them accumulate in plant roots. It is assumed that the delay occurs at the periphery of the roots. Therewith, with the intensive intake of toxic ions from the soil, the defence mechanisms of the root system cannot fully protect the vegetative mass from pollution, which ultimately leads to the deposition of pollutants in the aerial parts of plants.

The chemical composition of plants depends on the composition of the soil in which they grow. As plants selectively absorb the necessary elements according to their physiological and biochemical needs, the chemical composition of plants does not repeat the chemical composition of the soil. The mechanisms of plant resistance to excess heavy metals are diverse: some plants can manifest tolerance to heavy metals and accumulate high concentrations, while others, by maximising the use of barrier properties, reduce the amount of their intake and translocation. The level of heavy metal accumulation by plants is influenced by their genetic and species characteristics.

The development of phytoremediation methods for soils contaminated as a result of military and anthropogenic impacts used in crop production is of particular importance. This is because xenobiotics present in contaminated soil can move through the soil profile and accumulate in the organs of agricultural plants, including those used for human or animal consumption. The development of scientific methods and approaches to decontamination using phytoremediation of such soils is truly relevant.

Algorithm of Remediation Actions for Agricultural Land

In Ukraine, there is a need to develop cost-effective and environmentally efficient technologies for phytoremediation of agricultural land

contaminated by military and anthropogenic factors. The use of phytoremediation technologies will not only reduce the level of environmental pollution by xenobiotics, but also, most importantly, return the restored agricultural land to land use, as heavy metals can transfer from the soil to plants and then to food. The very fact that heavy metals get into food makes it impossible to use land for crop and livestock production, considering the danger to both humans and animals. For instance, the Commission Regulation (EC) No. 1881/2006 (2006) sets maximum levels of certain contaminants in food. The restriction in the regulation also applies to heavy metals.

In terms of the agricultural lands of Ukraine affected by military operations, it is proposed to use a generalised algorithm aimed at soil restoration using phytoremediation as one of the possible methods. Simplified algorithm of actions for agricultural land damaged by explosions, burning of military equipment and ingress of fuels and lubricants into the soil:

1. demining of designated areas;
2. satellite monitoring of areas with the creation of a soil pollution map;
3. soil sampling in and around the explosive impact zone;
4. laboratory analysis for heavy metals, toxins, and other pollutants;
5. analysis of further land use and agricultural opportunities;
6. mechanical cleaning of contaminated areas from debris, sources of pollution, and remnants of hostilities;
7. Mechanical restoration of soil cover in areas damaged by explosions;
8. development of a phytoremediation plan and determination of the best phytoremediant;
9. step-by-step monitoring of phytoremediation results through soil sampling and analysis;
10. decision-making on returning the restored areas to agricultural production.

Thus, the stages of soil cleanup on land affected by military operations include the identification and assessment of the degree of contamination, mechanical removal of hazardous material residues, selection of a phytoremediant, monitoring and evaluation of the results with adjustment of the method, if necessary, and the final assessment of the degree of readiness of the soil to return to agricultural production. Notably, herbal mediation is a lengthy process that requires investment to intensify, and therefore economic substantiation to ensure the best possible result is a significant component.

Conclusions

Phytoremediation is a vital and promising area for restoring soil quality and preserving the environment. The ability of soils to restore their functional characteristics that have been lost as a result of military and anthropogenic stress depends on their type, the impact of military and anthropogenic factors, and the landscape conditions of the territory. An important mechanism for intensifying soil restoration is the combined impact of soil quality restoration technologies through the introduction of phytoremediation methods and techniques. Considering the landscape and zoning of agricultural land contaminated by military operations, phytoremediation offers a flexible approach to choosing a phytoremediant, which allows for the most suitable approach. In addition, phytoremediation can be combined with conventional soil remediation methods, enhancing their effectiveness.

The military-anthropogenic load on the soil leads to a series of physical, mechanical, and chemical interventions in the soil cover system. These interventions destroy the functions of the soil ecosystem and its structure, which leads to a deterioration in its quality and functional properties. Destruction of vegetation, damage to soil cover, chemical pollution, and insufficient natural moisture are typical consequences of military operations. This considerably impoverishes the biodiversity, which affects species and populations, and the loss of biodiversity changes the function and structure of landscapes. The dynamic nature of the military-anthropogenic load and a wide

range of factors affecting the ecosystem require a scientific approach to investigating the problem, and therefore the development of standardised action algorithms that will help improve the efficiency of decontamination of contaminated soils. The prospect of further research, in addition to algorithmisation of decontamination processes, may be to investigate the dynamics of the impact of military-anthropogenic load on the ecosystem and to create more flexible mechanisms for eliminating pollution using artificial intelligence and neural network tools. Considering the initial data, which will accommodate the factors of contamination, its degree, type or combination of types, soil type, and other natural conditions, as well as the desired result, the use of artificial intelligence will allow quickly creating a contamination mapping, decontamination forecast, determining the most suitable remediation agent and action algorithm. The synergy of this approach with technologies, such as remote monitoring using unmanned systems, would allow, apart from regular monitoring of pollution zones, to create maps of areas where herbal remedies are used, track the dynamics of their growth, condition, etc. The availability of a wide range of phytoremediation crops and a fairly typical set of xenobiotics of military-anthropogenic origin allows creating systematic and standardised algorithms for soil remediation, which helps to increase the efficiency of soil restoration.

Acknowledgements

None.

Conflict of Interest

The author of this study declares no conflict of interest.

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Фіторемедіація ґрунтів, забруднених внаслідок військово-техногенного навантаження

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Анотація. Військові конфлікти та техногенні аварії спричиняють значне забруднення ґрунтів важкими металами, нафтовими продуктами, пестицидами та іншими токсичними речовинами. Метою даної статті було висвітлення факторів впливу воєнно-техногенного навантаження на ґрунти та аналіз наявних методик щодо їх ремедіації. Узагальннено існуючі та перспективні методики фіторемедіації з оцінкою їх впливу на забруднення ґрунтів хімічними речовинами, які є типовими забруднювачами під час військових конфліктів. В результаті проведеного дослідження було підсумовано, класифіковано та порівняно групи забруднювачів, які є найбільш поширеними під час воєнних дій; проаналізовано вплив забруднювачів на родючий шар ґрунту та їх рухомість; проведено аналіз наявних методів ремедіації. Було встановлено, що наявні технології ремедіації ґрунтів, які можуть бути застосовані як окремо так і в комбінації, надають необхідний інструментарій для вирішення проблеми хімічного забруднення ґрунтів внаслідок попадання в них токсичних продуктів – похідних вибухових речовин та важких металів. Враховано ступінь економічної доцільності, що відповідно дозволило припустити, що саме фіторемедіація ґрунту може бути найбільш економічно доцільною за певних умов. Це відкриває широкі можливосі щодо наступних досліджень, де застосування синергії екології, економіки та агробіології надасть змогу розробити механізми оптимізації методів фіторемедіації ґрунтів з врахуванням їх типу, профілю та цільовому призначенню. Запропоновано алгоритм дій щодо ремедіації ґрунтів внаслідок військово-техногенного навантаження, який включає в себе пов'язаний комплекс супутніх дій з зонування, розмінування, оцінки та повернення земель у промислове використання. Результати дослідження можна застосувати при очищенні промислових територій, що зазнали забруднення під час виробничих процесів або аварій

Ключові слова: ремедіація ґрунту; фіторемедіанти; техногенний вплив; деградація ґрунтів; хімічне забруднення ґрунтів; енергоємні речовини; пропеленти

Received 15.03.2024 Revised 05.06.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 629.331, 629.017

DOI: 10.31548/dopovidi/3.2024.85

Ensuring the reliability of filtration systems for transport and processing machines by redundancy

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Abstract. The relevance of this study is subordinated to the existing global trend of applying the scientific paradigm of redundancy of individual systems of transport and technological machines. This approach ensures the uninterrupted technological process of crop production following the regulatory reliability indicators. The purpose of this study was to identify failures of subsystems and elements of transport and technological machines depending on the operating time and to ensure reliability by redundancy. The study covered the methodological approaches to the formation of reliability of transport and technological machines. The study analysed the areas of ensuring the reliability of transport and technological machines on the example of machinery and equipment for animal husbandry. Methodical approaches to ensuring the indicators of reliability and maintainability during the operation of a self-propelled mixer were covered. A systematic approach to the self-propelled mixer as a complex transport and technological machine was developed. The principal subsystems that define a self-propelled mixer as a complex transport and technological system were identified. During the study, two groups of failures were identified, which lead to the loss of performance of the research objects. The features of using information and structural redundancy to improve the reliability of filtration systems of self-propelled mixers were presented. The technical condition of the engine air filter should be checked and cleaned after 50 hours, while the cartridge should be replaced after 1000 hours of operation. The functioning of the cabin filtration subsystem is ensured by a condenser, evaporator, desiccant filter, air filter, which should be checked and cleaned every 500 hours, while spare parts should be available in stock for replacement after one year of use. The formed criteria for assessing the technical condition of air filtration systems of a self-propelled mixer will provide a higher level of reliability and expand the list of their parameters.

Suggested Citation:
Novitskyi, Yu. (2024). Ensuring the reliability of filtration systems for transport and processing machines by redundancy. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 85-95. doi: 10.31548/dopovidi/3.2024.85.

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The methodology presented in this study allows increasing the reliability and maintainability of self-propelled mixers, to provide a methodical approach to the formation of reliability of engine air filtration and operator's cabin air filtration subsystems

Keywords: criterion; self-propelled mixer; backup elements; engine air filter; cabin air filter

Introduction

As the use of transport and processing machines increases, so does their intensity of operation, which increases the risk of failures and malfunctions. This can lead to considerable financial losses, reduced productivity and quality of work performed. Modern machines, albeit with high reliability, require additional measures to ensure their trouble-free operation, especially after the warranty period has expired. Redundancy of filtration systems helps to increase the reliability and extend the service life of equipment, which is critical for the stable functioning of the agricultural sector. Improving maintenance systems, as well as developing innovative methodologies and mathematical models for predicting and preventing failures, are necessary steps to ensure the reliability and efficiency of transport and processing machines in modern environment. The current strategy for the development of Ukraine's agro-industrial complex envisages the purchase of a significant amount of foreign equipment, including transport and technological machinery. The issues of evaluating and ensuring the reliability of these machines point to the importance of conducting research to identify the parts and components that limit their performance.

A.V. Novitskyi *et al*. (2021; 2023) noted that a set of measures to ensure a suitable level of reliability of new transport and technological machines, supported by branded service, in difficult operating conditions is insufficient, and failures of elements, components, assemblies, and systems continue to occur. The practice of using the presented research objects indicates that the statistics of failures during their operation is only accumulating, and service maintenance, in most cases, is focused on performing technological maintenance operations rather than repairing individual mechanisms, restoring parts, and working bodies.

As I. Revenko *et al*. (2023) notes, self-propelled and mobile mixers are among the means for preparing and distributing feed in livestock production. Therewith, they are multi-operational transport and technological systems "Human-Machine-Environment", the reliability of which depends on the components "machine", "human operator", and "environment".

Notably, the analysis of literature sources and the practice of using mobile and self-propelled mixers shows that the "machine" component is still understudied, especially from the standpoint of ensuring operability. S. Morrone *et al*. (2022) note that one of the conditions for the highly productive development of the livestock industry can be the effective use of technical service of machinery and equipment for the preparation and distribution of feed on demand. Therewith, considering the short duration and stress of their use, there is a need to monitor the indicators of maintainability.

The component "machine" has been studied in some foreign and Ukrainian scientific studies, but only from the standpoint of functioning and ensuring design and technological characteristics (Sheichenko *et al.*, 2024). Specifically, S. Postelga (2021) described methodological approaches and presented comprehensive results of a study of the efficiency of using the Siloking SelfLine 4.0 Premium 2215 self-propelled mixer-dispenser. According to the results of testing

of the main parameters and tests of Siloking SelfLine 4.0 Premium 2215, the uniformity of mixing (94.3%) and uniformity of feed distribution (95.5%) were confirmed, considering the possible types of feed. However, there are limited materials in scientific sources that present studies of the reliability properties of mixers.

M. Pristavka *et al.* (2022) discussed the advantages and features of using graphical dependencies, compared to other conventional diagrams, to assess the quality of oil purification filter elements. The researchers concluded that an adequate and accurate implementation of real-time graphs can be useful in significantly reducing costs and time while ensuring the quality of filter elements. T. Pati *et al.* (2021) states that the quality of any engineering product can be described and evaluated based on research into the following components: product specifications; reliability; performance; and compliance with standards.

J. Katsitadze *et al.* (2021) reflected the results of assessing the operational reliability of walk-behind tractors, which represent a significant group of transport and technological machines used in agricultural production. The methodology for calculating the reliability of motorblocks and the formation of the key areas for ensuring their reliability is worthy of attention. When operating certain types of equipment, including transport and processing machines, a single machine is used that can perform a series of technological operations as a single process. According to I.M. Kuzmich *et al.* (2021), multi-operating machines are characterised by an increase in overall size, performance, and complexity, which makes the loss of their operability during technological operations particularly critical. Therefore, the reliability analysis of transport and technological machines becomes necessary to establish the causes of system failure, identify subsystems, and elements to ensure their reliability.

M. I. Chornovil (2010) described redundancy methods that can be used in design, production, and operation, and this method is one of the most effective methods of improving the reliability of technical systems, although it is costly. To ensure the reliability of machinery and equipment as technical systems, V. Kozlovskyi & B. Zalevskyi (2023) use the following types of redundancy: structural; functional; time; information; parametric; load.

The purpose of this study was to identify failures of subsystems and elements of transport and technological machines depending on the operating time and to ensure reliability by redundancy

Materials and Methods

The study was conducted in 2023–2024 at modal agricultural enterprises in Kyiv and Cherkasy oblasts, where SPW INTENSE 2 CS self-propelled mixers were operated. The SPW INTENSE 2 CS self-propelled mixer is a KUHN (France) feed preparation and distribution machine for different groups of cattle, a transport and technological machine that was operated in livestock enterprises according to the operator's manual (Operator's manual…, 2020). During operation, SPW INTENSE 2 CS was influenced by a series of objective and subjective factors that necessitated the adjustment of the manufacturer's recommendations for assessing the technical condition, replacing the working bodies and filtration elements.

The components of the object of study that formed the reliable operation of SPW INTENSE 2 CS transport and processing machines included the engine air filtration and operator cabin filtration subsystems. The engine air was filtered by an air filter. The operator's cabin was filtered by a condenser, evaporator, filter dryer, and air filter.

The SPW INTENSE 2 CS self-propelled mixer is equipped with a milling loader for self-loading. The milling mechanism ensures the integrity of the feed monolith and reduces the percentage of spoilage due to secondary fermentation. The diagram of the SPW INTENSE 2 CS self-propelled mixer is presented in Figure 1.

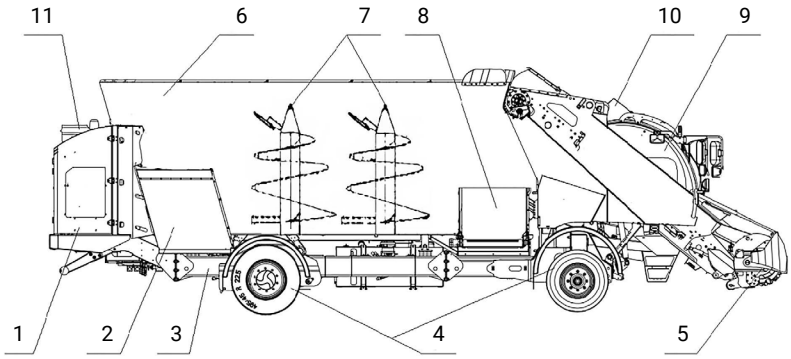


Figure 1. *Self-propelled mixer SPW INTENSE 2 CS*

Note: 1 – engine, 2 – discharge chute, 3 – frame, 4 – running subsystem, 5 – loading milling mechanism, 6 – hopper, 7 – mixing augers, 8 – discharge conveyor, 9 – operator's cabin, 10 – cabin air filtration subsystem, 11 – engine air filtration subsystem

Source: developed by the author of this study based on the Operator's manual (2020)

The test mode of the self-propelled mixer was set to operational. A plan was adopted to test the SPW INTENSE 2 CS self-propelled feed mixer for reliability [*NMT*]. The plan envisaged a certain number of test objects *N*, which, in case of failure, were restored *M*, and the research was terminated when the corresponding operating time *T* was reached (Chornovil, 2010).

The use of the presented self-propelled mixer (Fig. 1) in a livestock farm and interaction with feed components of different quality, degree of contamination and dusting, negatively affect the operational reliability of transport and technological machines and lead to failures. All failures recorded during operation were divided into two characteristic groups, depending on the mechanisms that lost their efficiency. The first group of failures was formed by the working bodies and parts of the mechanisms for loading feed ingredients, grinding and mixing, and unloading the feed mixture. The service life of these mechanisms depends on the influence of objective and subjective factors, while the frequency of replacement depends on the permissible and limit parameters, criteria for the limit state of the working bodies.

The second group of failures was made up of mechanisms whose maintenance intervals are determined by the planned preventive maintenance and repair system, which is formed by the manufacturer in the operator's manual (Operator's manual..., 2020). Such parts and elements include components of the filtration systems of SPW INTENSE 2 CS mixers.

The parameters and reliability characteristics of transport and technological machines were ensured based on an integrated approach, the essence of which is to ensure the operability of self-propelled mixers, considering the interconnection of reliability, maintainability, and operational and technical characteristics using the redundancy methodology. Below, the study presents the possibility of using information and structural redundancy of self-propelled mixers. Information redundancy in ensuring the reliability of research objects involves the use of additional information beyond that required for the efficient use and performance of production tasks. Structural redundancy involves the use of an excessive number of elements that are not part of the structure of the research object. The implementation of a structural redundancy method to increase the reliability of the filtration subsystems of a self-propelled mixer is ensured by the use of backup elements to the main one.

Results and Discussion

The process of feed distribution by self-propelled mixers and feed dispensers is less sensitive to technical malfunctions, however, the practice of use shows that during operation, failures of the mechanisms for loading feed, grinding and mixing, and unloading feed mixtures occur. Despite a series of these disadvantages, only self-propelled mixers and feed dispensers can be used to mechanically distribute feed mixtures at exercise grounds and summer camps. The practice of using self-propelled mixers has established that, as a result of the intensity of operating conditions and considerable contamination of feed storage and transportation areas, animal housing, there is a need to adjust the information on the frequency of replacement and substantiate the required number of backup elements of air filtration subsystems to ensure single and complex reliability indicators. The maintenance intervals for the filtering subsystems of the SPW INTENSE 2 CS mixer units, presented in Table 1, are considered.

Table 1. *Maintenance intervals for the filtering subsystems of the SPW INTENSE 2 CS mixer units with morphological symbols*

Morphological symbol / list of maintenance works	Frequency of maintenance					
	50 hours	100 hours	500 hours	1000 hours	2000 hours	2 years
a. Cleaning						
➤ a1. Air filter for a diesel engine.	+	–	–	–	–	–
➤ a2. Air filter for the cabin	+	–	–	–	–	–
➤ a3. Evaporator and condenser of an air conditioning system.	–	–	+	–	–	–
b. Replace						
➤ b1. Diesel engine air filter cartridges.	–	–	–	+	–	–
➤ b2. Dehumidifying filter for the air conditioning system.	–	–	–	–	+	+
➤ b3. Air filter for the cabin	–	–	–	–	+	+

Source: developed by the author of this study

The study analysed the filtration subsystems of SPW INTENSE 2 CS, which influence the formation of reliability of the machine and operator components and include: cabin filtration; engine filtration. The study considered the components of the subsystem for filtering the cabin and maintaining comfortable working conditions for the human operator. The main components that ensure the reliable operation of this subsystem are as follows: condenser; evaporator; filter dryer; air filter. The engine filtering subsystem of the self-propelled mixer includes such filters as air; fuel; oil purification; engine oil evaporation.

The functionality of the morphological symbols (Table 1) allows presenting a collapsed matrix model of the morphological description of the maintenance intervals of the filtering subsystems of the SPW INTENSE 2 CS mixer unit:

$$M_I = \begin{vmatrix} a.1 \\ a.2 \\ a.3 \end{vmatrix} + \begin{vmatrix} b.1 \\ b.2 \\ b.3 \end{vmatrix}, \quad (1)$$

where M_I is the level I functionality of the main objectives of the synthesis of the maintenance frequency system for the filtering subsystems of the mixer units. Considering the functionality according to expression (1), its general form can be obtained as follows:

$$M_I = |M_a| \cap |M_b|, \quad (2)$$

where M_a is the level II functionality of the main objectives of the synthesis of technological

operations to clean in the maintenance frequency system for the filtering subsystems of the mixer units; M_b is the level II functionality of the main objectives of the synthesis of technological operations to replace in the maintenance frequency system of the filtering subsystems of the mixer units.

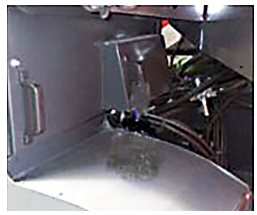
Considering the standards (Table 1) for conducting technological operations of replacement in the system of periodicity of maintenance of the filtering subsystems of the mixer units, according to expression (2), we can obtain the norm of combinations of divided hierarchical groups in the amount of 49. Thus, it is 49 partial technical solutions that can be analysed at alternative levels. This alternative will meet the regulatory reliability of a complex technical system.

In performing the functions of the SPW INTENSE 2 CS transport and processing machine, events occur in its elements, some of which lead to a decrease in the reliability of the objects under study. Another group of events includes those failures that lead to a negative impact on the functioning of the human-operator component. Of particular interest is not only the assessment of the reliability of the object of study and the frequency of maintenance, but also the assessment of maintainability, i.e., the time that the operator of a transport and technological machine must spend to restore its performance. Not all manuals for self-propelled mixers contain information on maintainability, including the average time to repair. This is especially true for the subsystems and mechanisms that ensure the functioning of the main systems of the feed preparation and distribution equipment. Such subsystems and mechanisms include the components of filtering subsystems. Let us analyse the criteria for assessing the technical condition of the filter subsystems of a self-propelled mixer. The individual filter subsystems are equipped with sensors that indicate when the filter is dirty. The results of the analysis of the technical condition assessment criteria for engine air filters and cabin filters are presented in Table 2.

Table 2. *Analysis of the criteria for assessing the technical condition of the filter systems of the SPW INTENSE 2 CS self-propelled mixer*

Name of the filter elements	Display of filter elements in the user manual	Criteria for assessing the technical condition
	Cabin air filter	
Capacitor		If dirty, the air conditioning system may shut down. Periodic inspection of the technical condition
Evaporator		Periodic check of the evaporator's technical condition
Dehumidifier filter		Periodic check of the evaporator's technical condition

Table 2. *Continued*

Air filter		Periodic check of the evaporator's technical condition
Engine air filter		
Diesel engine air filter element		Engine air filter element pressure sensor

Source: developed by the author of this study

Based on the presented analysis of the SPW INTENSE 2 CS mixer as a component of the transport and technological system "Human-Machine-Environment", it can be argued that ensuring the operability of the filtering subsystems of the self-propelled mixer can be achieved through scientific and methodological redundancy approaches. To better investigate the state of the issue, let us formulate appropriate recommendations that reflect the filtering elements, indicate the sequence of research of these events, the possibility of occurrence and prevention of failures through redundancy. The technical condition of the engine air filter should be checked and cleaned after 50 hours, while the cartridge should be replaced after 1000 hours of operation. Control of the functioning of the cab filtration subsystem and cleaning of components should be carried out after 500 hours, while the spare parts should be planned in the reserve and replaced after 1 year of use, or 2000 hours. The analysis of the presented results suggests that most authors in recent years have conducted research on transport and technological machines towards improving design and technological parameters and increasing the efficiency of their use.

Comparing the findings obtained in this study and the approach to ensuring the reliability of transport and technological machines with other studies, the following can be noted: the issue of improving the reliability of the research objects presented herein was not considered with regard to the study of filtering systems for engines, units, and subsystems that ensure the functioning of machine-tractor units (Abed *et al.*, 2022), combine harvesters (Najafi *et al.*, 2015), and feed preparation equipment (Revenko *et al.*, 2023).

Some scientists have conducted research into the design and improvement of filtration elements in the car cabin. X. Dong *et al.* (2021) presented practical approaches to fan selection, filter and housing design, parts manufacturing, filtration unit assembly, and recommendations for the operation process. Thanks to the use of an engineered filter air purifier, the cabin air purifier can remove harmful substances such as formaldehyde. This is only part of a long-term programme to use air purifiers that can also be used for other transport and processing machines. However, this study does not contain recommendations for improving the functioning of the condenser and evaporator.

M. Gailis & V. Pirs (2011) evaluated the existing frequency of replacement of the Renault engine air filter and determined the impact of this operation on some vehicle performance indicators. The experience of use, operating costs,

and the factual condition of the vehicle are linked to a scientifically substantiated maintenance and repair system. The authors of the study note that the engine air filter replacement intervals declared by Renault range within 30–120 thsd km, depending on the model and type of engine. However, based on the results of testing the car on dusty roads, it is recommended to reduce the replacement interval by half. The authors of the presented study also point out the need to reduce the frequency of monitoring and cleaning the engine air filter when using a self-propelled mixer in dusty conditions, and to replace it based on the results of diagnostics or according to the criteria of the limit state.

T. Dziubak & G. Boruta (2021) highlighted the theoretical and experimental studies of the air filter of the engine of caterpillar vehicles. The paper presents a study of the influence of mineral dust in the air sucked through the filtration system on the accelerated wear of engine parts. According to the researchers, the study of regression models of engine air filters functioning for individual vehicles is of significant scientific and practical significance, as it allows to move from a planned preventive strategy for the use of air filters operated on special vehicles in conditions of variable dustiness to strategies according to their factual technical condition.

Along with the presented scientific findings, there are a series of studies in the technical literature that experimentally and numerically investigate the effect of air filter design on various parameters, on the efficiency and performance of the vehicle engine. T. Dziubak & G. Boruta (2021) and D. Thomas *et al.* (2021) describe the influence of the following parameters of filter elements on the performance of engines of mobile power vehicles: pleat height; pleat spacing; pleat shape; average filter thickness; air velocity on constant fuel consumption; dust load.

S. Anchal *et al.* (2022) obtained analogous results, since the reliability of filter systems of transport and technological machines in the dominant component depends on the reserved machine. Such studies have resulted in the formation of a multifunctional reliability capability, which forms a single continuous process. As the size and complexity of the filter systems of transport and processing machines continue to grow, the consequences of failures of these systems are expected to become more complex and critical. Since, according to F. Tian *et al.* (2020), the analysis of filter systems of transport and technological machines is necessary to identify weaknesses in these systems and monitor components with low reliability for a given operational performance.

The findings obtained allow correlating them with those previously presented in R. Majdan *et al.* (2017). Specifically, there is a similarity in the three circuits of the mobile energy filtration system in the production cycle of crop production. Thus, it is possible to develop universal filtration systems for agricultural machinery.

The task of ensuring the appropriate level of reliability arises at all stages of the life cycle of self-propelled mixers, which necessitates a comprehensive analysis, selection, substantiation of evaluation methods and ensuring the reliability and maintainability of systems.

Conclusions

Based on the findings of the study, a comprehensive methodology was developed to ensure the operational reliability of transport and technological machines. Specifically, a detailed system analysis of the SPW INTENSE 2 CS self-propelled mixer was performed, based on which practical recommendations were formulated for maintenance and increased reliability by redundancy of critical subsystems, such as engine and air filtration in the operator's cabin.

One of the key aspects of ensuring the high reliability and ergonomics of the SPW INTENSE 2 CS is regular maintenance, including inspection of the technical condition, prompt replacement of the filter elements and provision of a reserve. According to the developed recommendations, the engine air filter cartridge needs to be reserved and replaced every 1000 hours of operation. Cabin air filtration

elements must be replaced every 2000 hours of operation. This helps to avoid unforeseen malfunctions and extend the life of the equipment.

Particular attention is also paid to the maintenance of the filtration systems of the pneumatic systems of the power plant unit and the operator's seat. To maintain their reliability, regular checks should be carried out at 50-hour intervals. An essential element is also the maintenance of air conditioning systems every 2 years, which ensures comfortable working conditions for the operator and long-term uninterrupted operation of the equipment.

The developed methodology can be adapted to other transport and technological machines used in various industries, such as agriculture, transport, construction, and industry. This will help to create more efficient, reliable, and durable transport and technological complexes that will ensure a prominent level of productivity and safety in various technological operations. The implementation of this methodology will considerably reduce maintenance and repair costs and increase the efficiency of vehicle and technology use, which will ultimately have a positive impact on the economic performance of enterprises.

A promising task for further research is to synthesise innovative implementations of Smart technologies for the reliability of filtration systems of transport and technological machines with redundancy in the Agriculture 4.0 concept.

Acknowledgements

The author of this study would like to express his gratitude to the Centre for Collective Use of Scientific Equipment for the Latest Agricultural Technologies 'Agroindustrial Complex, Forestry, Gardening and Veterinary Medicine', which operates at the National University of Life and Environmental Sciences of Ukraine.

Conflict of Interest

The author of this study declares no conflict of interest.

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Реалізація надійності систем фільтрації транспортно-технологічних машин резервуванням

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Анотація. Актуальність дослідження підпорядковано існуючому світовому тренду застосування наукової парадагми резервування окремих систем транспортно-технологічних машин. Такий підхід забезпечує беззупинковий технологічний процес виробництва сільськогосподарських культур із дотримання нормативних показників надійності. Метою дослідження є виявлення відмов підсистем та елементів транспортно-технологічних машин в залежності від часу експлуатації та забезпечення надійності резервуванням. В статті розкрито методологічні підходи до формування надійності транспортно-технологічних машин. Проаналізовано напрямки забезпечення показників надійності транспортно-технологічних машин на прикладі машин та обладнання для тваринництва. Розкрито методичні підходи до забезпечення показників безвідмовності та ремонтопридатності в процесі експлуатації самохідного змішувача. Сформовано системний підхід до самохідного змішувача як складної транспортно-технологічної машини. Встановлені основні підсистеми, які визначають самохідний змішувач як складну транспортно-технологічну систему. Під час проведення досліджень визначені дві групи відмов, які призводять до втрати працездатності об'єктів досліджень. Представлено особливості використання інформаційного та структурного резервування для підвищення надійності систем фільтрації самохідних змішувачів. Контроль технічного стану повітряного фільтра двигуна та його очищення слід проводити через 50 годин, а мати в комплекті резервних елементів картридж через 1000 годин експлуатації. Функціонуванні підсистеми фільтрації кабіни забезпечують конденсатор, випарник, фільтр осушувач, повітряний фільтр, контролювати технічний стан яких та очищати слід через 500 годин, а передбачити наявність в резерві запасних частин для заміни через рік використання. Сформовані критерії оцінки технічного стану фільтрувальних систем повітря самохідного змішувача забезпечать більш вищий рівень надійності, розширить перелік їх параметрів. Наведена в статті методологія дає можливість підвищити показники безвідмовності та ремонтопридатності самохідних змішувачів, забезпечити методичний підхід до формування надійності підсистем фільтрації повітря двигуна та фільтрації повітря кабіни оператора

Ключові слова: критерій; самохідний змішувач; резервні елементи; фільтр повітряний двигуна; фільтр повітряний кабіни

Received 30.01.2024 Revised 29.04.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 632.7, 633.11

DOI: 10.31548/dopovidi/3.2024.96

Neuron network prediction of damage of *E. integriceps* bug on winter wheat in Ukraine

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Abstract. Protecting wheat from pests directly affects the country's food security. Therefore, the purpose of this study was to create predictive models for estimating the harmfulness of *E. integriceps* by years. The harmfulness of *E. integriceps* was considered depending on the following indicators: pest abundance, environmental index (Wolf number) and hydrothermal moisture coefficient (HTC).

Suggested Citation:
Dolia, M., Lysenko, V., Lendiel, T., Nakonechna, K., & Humeniuk, L. (2024). Neuron network prediction of damage of *E. integriceps* bug on winter wheat in Ukraine. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 96-105. doi: 10.31548/dopovidi/3.2024.96.

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The study proved the existence of mathematical uncertainty of information flows in relation to the specified pest, and therefore the mathematics of artificial neural networks with the structure of "multilayer perceptron" was used for forecasting. The results of the study of the harmfulness of *E. integriceps* to winter wheat in Ukraine were presented, including a forecast of the phytosanitary state of agrocenoses of Ukraine and recommendations for assessing the distribution of harmfulness of *E. integriceps* by years of observation (1996-2023) for the Odesa Oblast. It was noted that this distribution corresponds to a normal law with a mathematical expectation of 25%, which is confirmed by the results of observations for other regions of the Steppe zone. The relationship between the number of *E. integriceps*, Wolf number, and the accumulated integrated temperature and humidity characteristics of the environment was analysed. It was found that the harmfulness of *E. integriceps* is characterised by a fading periodic component with a period of 10-12 years. This result suggests the impact of the current year's *E. integriceps* damage on the next year in 10-12 years. According to the forecasting results, the dependence of the harmfulness of *E.integriceps* on its number and the Wolf number was presented. Therewith, the accumulated integrated temperature and humidity characteristics of the environment were considered. The obtained findings are recommended for consideration in the organisation of planned technological operations for the protection of cereal grain crops

Keywords: plant protection; artificial neural networks; multilayer perceptron; Wolf number; mathematical expectation

Introduction

With modern crop production technologies, the imperfect forecasting and control of harmful bugs spread substantially contributes to annual significant grain losses due to pests. During pest outbreaks, these losses can be severe, often leading to a marked deterioration in grain quality and, in extreme cases, to complete harvest failure. Improving forecasting accuracy and implementing effective control measures are essential to mitigate these risks and ensure sustainable agricultural production.

Therefore, in the study by I. Rogovskii *et al.* (2024), without a substantiated forecast of phytophage reproduction and protection measures, even with a high agronomic background, the yield of low-quality winter wheat grain is formed within 2-4 t/ha, and with prompt and adequate protection – within 9-10 t/ha. At the same time, according to I.L. Rogovskii (2021), every third and sometimes second hectare of arable land should be accompanied by a comprehensive assessment and modelling of the patterns of development, reproduction, and spread of economically dominant types of pests. B. Motie *et al.* (2023) believe that the rapid identification of pest concentration points and assessment of infestation levels in fields can be useful for production management and reducing the use of chemical sprays. At the same time, the study proposed the use of software computing and image processing approaches to identify areas infested with sunn pests based on the use of aerial photographs in the near-infrared and visible ranges. However, the study did not predict the number of pests to synthesise a crop management strategy.

M. Mehrabadi *et al.* (2012) presented *Eurygaster integriceps Put.* (*Hemiptera*: *Scutelleridae*), which was a major pest of wheat in the Middle East and some other regions, causing serious qualitative and quantitative damage. However, this study also did not offer an opportunity to predict the harmfulness of this pest in crop production. S. Gürsoy *et al.* (2012) proposed to plant different plant varieties in the specified area to

reduce the number of pests. P.A. Edde (2021) also presented integrated approaches to pest management in crop production, however, for the accuracy of the forecast of each individual method, it is necessary to use the principles of mathematical modelling.

V. Sakhnenko & D. Sakhnenko (2018) presented long-term data on the dynamics of the number of harmful bugs (*Eurygaster integriceps Put.*) in the Mykolaiv Oblast. The influence of winter wheat predecessors and sowing dates on the number of pests in the Southern Steppe of Ukraine was presented. The researchers presented their findings on the effectiveness of modern insecticides against pests on winter wheat crops. P. Lykhovyd (2023) presented the results of a mathematical study of the 40-year dynamics of the number of *E. integriceps* in the south of Ukraine, as well as statistics on the number of bugs that can be used to predict the development of the specified pest.

The purpose of this study was to develop predictive models for assessing the harmfulness of the *E. integriceps* on winter wheat.

Materials and Methods

Data Sources and Variables:

The primary data sources included long-term forecasts of the phytosanitary state of agrocenoses in Ukraine, along with recommendations for plant protection (Map of solar insolation of Ukraine, n.d.; Phytosanitary status of agricultural plants, 2024). The study focused on Odesa Oblast from 1996 to 2023, using electronic resources to obtain the most recent data (Map of solar insolation of Ukraine, n.d.; Phytosanitary status of agricultural plants, 2024).

Key variables influencing the harmfulness of the *E. integriceps* were identified as follows:

1. Population Size (K): The number of *E. integriceps* bugs present in the region, which directly affected the extent of crop damage.

2. Solar Radiation Intensity: This was quantified using the Wolf number (W), a numerical indicator of solar activity correlated with the number of sunspots observed. Solar radiation affected various biological processes and environmental conditions.

3. Temperature-Humidity Characteristics (HTC): Integrated temperature and humidity measurementsthat accounted for cumulative environmental conditions influencing the life cycle and behaviour of the *E. integriceps* bug.

Methodological Approach:

- Analysis of historical data. Historical data on the distribution of harmfulness of the *E. integriceps* bug was analysed to identify trends and patterns. This involved examining records of harmfulness and correlating them with environmental and biological factors (Suárez-Varela *et al.*, 2022; Tam *et al.*, 2022).
- Statistical analysis. The harmfulness of the *E. integriceps* bug (S) was assessed using statistical methods to determine its distribution.
- Predictive modelling. Based on the identified factors (K, W, and HTC), predictive models were created to estimate future harmfulness levels. These models incorporated historical patterns and current environmental data to forecast potential outbreaks and assess the impact on wheat crops.
- Graphical representation. The findings were visually represented through graphs and charts to illustrate the distribution patterns and forecast models. This visual representation offered insight into the trends and helped to make data-driven decisions for pest management and crop protection.
- Correlation analysis. Methods of correlation analysis, including constructing autocorrelation functions, were used to assess the impact of each variable on the dynamics of pest numbers for subsequent years. This approach helped in understanding the temporal relationships and dependencies between different factors.
- Mathematical model selection. The normal law of harmfulness distribution by years provided a basis for analysing the possibilities of using mathematical models of different content and choosing the best option (Suárez-Varela *et al.*, 2022; Tam *et al.*, 2022). Specifically, the following formula was used:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad (1)$$

where σ is the standard deviation; μ is the mathematical expectation.

➤ Neural network tools. Neural network tools were employed to assess the forecast of pest harmfulness, considering long-term statistics. These advanced techniques enabled the modelling of complex, non-linear relationships between variables, and improved the accuracy of harmfulness predictions.

The research methodology ensured a comprehensive understanding of the factors affecting the harmfulness of the *E. integriceps* bug and provided a robust framework for predicting and mitigating its impact on wheat production.

Results and Discussion

The results of the analysis on the distribution of the number of pests are presented in the form of a normal distribution in Figure 1. The distribution presented in Figure 1 suggests that it corresponds to the normal law with a mathematical expectation of 25%, which is confirmed by the results of observations for other regions of the Steppe zone.

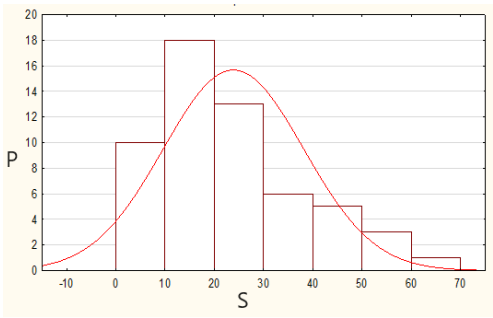

Figure 1. *Normal distribution of the harmfulness of the E. integriceps bug*

Note: *abscissa axis – harmfulness (S), %; ordinate axis – probability (P), %*

Source: developed by the authors of this study based on Map of solar insolation of Ukraine (n.d.), Phytosanitary status of agricultural plants (2024)

To choose a mathematical modelling method, it is necessary to analyse the relationship between harmfulness and the factors mentioned above. The study showed a relationship between harmfulness and K number, where the result is presented in Figure 2a. Figure 2b shows the relationship between virulence and Wolf number W, while Figure 2c shows the relationship between virulence and HTC. According to M. Mehrabadi *et al.* (2014) and J. Motie *et al.* (2023), results from the analysis suggested the presence of significant uncertainty, as the linear correlations are low, and the coefficient of determination suggests that the linear mathematical model is inadequate. This was partially confirmed by other researchers – B.R. Critchley *et al.* (1998), H. Dizlek & M.S. Özer (2024). B.R. Critchley *et al.* (1998) revealed the statistics of pest outbreaks and noted the absence of a clear strategy for controlling pest populations. H. Dizlek & M.S. Özer (2024) showed the consequences of damage to the wheat kernel caused by the pest, which affects the yield.

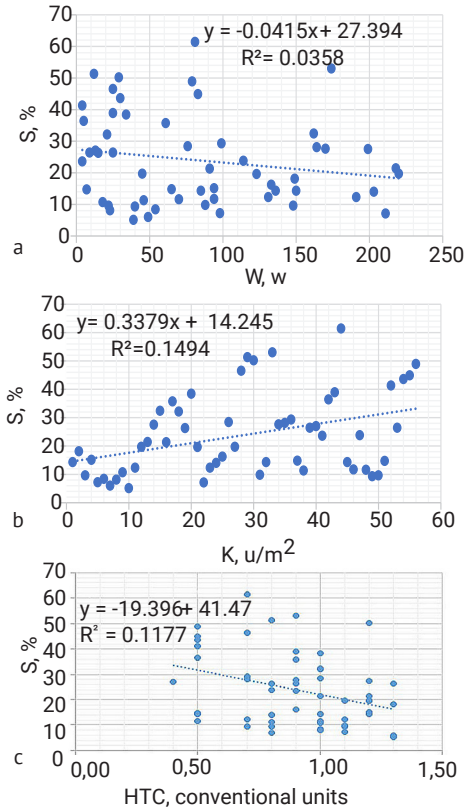

Figure 2. *Dependence of the harmfulness of the bug-harmful shell on key variables*

Note: a – Wolf number, b – Population Size, c – HTC

Source: developed by the authors of this study based on Map of solar insolation of Ukraine (n.d.), Phytosanitary status of agricultural plants (2024)

Interesting conclusions can be drawn by constructing the autocorrelation function of the harmfulness of the *E. integriceps* bug (shift of the ordinate by years with a discreteness increasing from 0 by 1 year – Fig. 3).

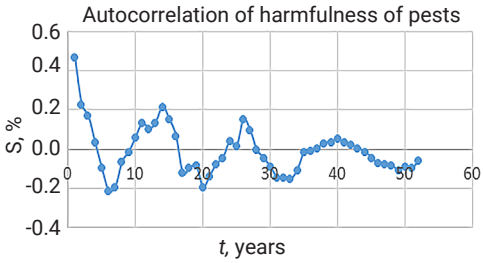

Figure 3. *The autocorrelation function of the harmfulness of the E. integriceps bug (shift of the ordinate by years)*

Source: developed by the authors of this study based on Map of solar insolation of Ukraine (n.d.), Phytosanitary status of agricultural plants (2024)

The autocorrelation function was constructed from sample data as follows (Tam *et al.*, 2022):

$$R_{xx}(\tau) = \frac{1}{N-\tau-1}\sum_{i=1}^{N-\tau}(x_i - M_x)(x_{i+\tau} - M_x), \quad (2)$$

where *N* is the data sample; τ is the shift between ordinates; M_x is the mathematical expectation of harmfulness as a random variable x.

The autocorrelation function is characterised by a decreasing periodic component with a period of 10-12 years. This suggests the influence of the harmfulness of the current year's sunn pest on the next one in 10-12 years. This circumstance should be considered when planning measures to protect grain crops, paying attention to the factors of influence and their periodicity in nature (Wolf number, abundance, HTC).

A special place among the factors affecting the harmfulness of the sunn pest is its number. In this case, it is necessary to build and analyse the autocorrelation function of the number of *E. integriceps* bugs with a shift along the ordinate axis by year, increasing from zero with a discreteness of 1 year (Fig. 4). The complex form of the autocorrelation function indicates a significant influence of the first current year on the next 10-12 years later, and then the influence "fades". Perhaps the reason is also inaccuracy in measurements based on the results of observations.

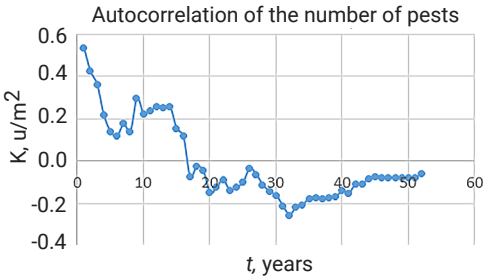

Figure 4. *Autocorrelation function of the number of sunn pest bugs (with a shift of ordinates by years with a discreteness of 1 year)*

Source: developed by the authors of this study based on Map of solar insolation of Ukraine (n.d.), Phytosanitary status of agricultural plants (2024)

As already mentioned, predicting the harmfulness of the *E. integriceps* bug is the main goal of this study. Since uncertainty is involved, it is advisable to achieve this goal by using artificial neural networks. The experience of using an artificial neural network with the structure of a "multilayer perceptron" (Lysenko *et al.*, 2022) allows recommending it to achieve this goal (Fig. 5).

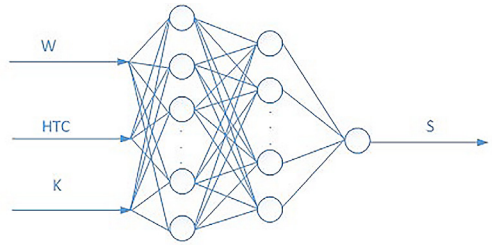

Figure 5*. Structure of the artificial neural network "multilayer perceptron"*

Source: developed by the authors of this study

For multilayer networks, the output of the previous layer is the input of the next one (Zaiets *et al.*, 2019):

$$y^{m+1} = f^{m+1}(w^{m+1} y^m + b^{m+1}), m = 0,1,\ldots,M-1, \quad (3)$$

where M is the number of network layers; y is the input vector, w is the weight matrix, b is the shift vector, f is the activation function; m is the layer number.

For this type of neural networks, the fastest descent algorithm for calculating the root mean square error with the learning rate α has the following form (Tregub *et al.*, 2020, Tam *et al.*, 2022):

$$w_{ij}^{m}(k+1) = w_{ij}^{m}(k) - \alpha \frac{\overline{\partial F}}{\partial w_{ij}^{m}};$$
$$b_{i}^{m}(k+1) = b_{i}^{m}(k) - \alpha \frac{\overline{\partial F}}{\partial b_{i}^{m}}, \quad (4)$$

where i, j are the elements of the matrix of input values; x_{ik} and x_{jk} are the k^{th} elements of the vectors x_i and x_j, respectively; F is the sensitivity value of the network function. The results of predicting the harmfulness of the *E. integriceps* bug are presented in Figures 6, 7. The analysis of the results of observations and analytical materials in Figure 8 points to a complex form of influence of the Wolf number on harmfulness. This is especially pronounced when this factor is within 120-220 and 20-100. The minimum harmfulness is achieved at a Wolf number of 140 and 60. It is advisable to use this information to minimise the use of insecticides used in modern crop protection technologies.

HTC has a relatively uniform effect on the harmfulness of *E. integriceps* bug compared to the Wolf number in Figure 8. Therefore, it is the number of pests that should be considered, which largely determines the final damage.

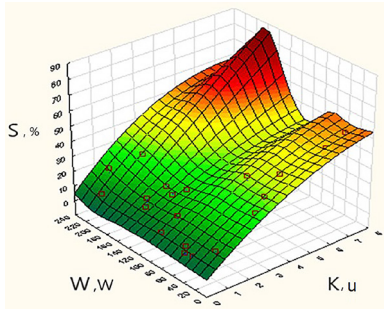

Figure 6. *Dependence of E. integriceps bug damage on its number and Wolf number*
Note: K is the number of *E. integriceps* bugs, W is the Wolf number, S is the damage, %
Source: developed by the authors of this study

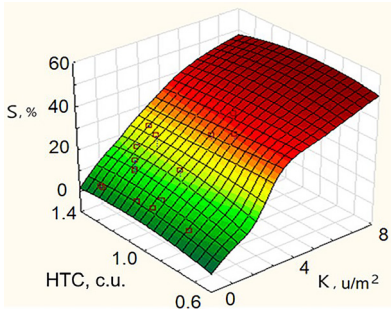

Figure 7. *Dependence of E. integriceps bug damage on its number and HTC*
Source: developed by the authors of this study

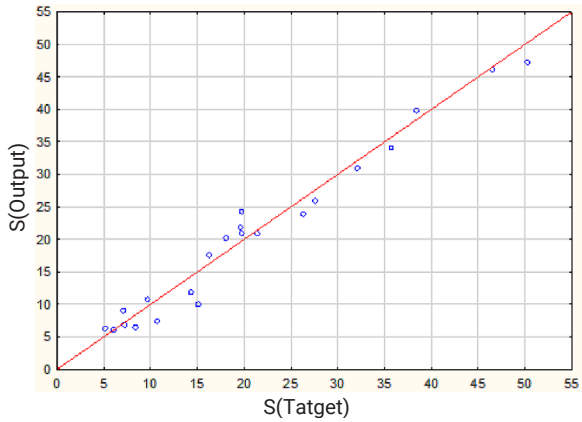

Figure 8. *Comparison of the result of the neural network (Output) with observation data (Target)*
Source: developed by the authors of this study

It is important to decide on the results of forecasting harmfulness by comparing them with observational data, as presented in Figure 10. The analysis of the materials in this figure suggests that the accuracy is sufficiently high: only for certain years, the error does not exceed 20%. According to practicing agronomists, this result creates all the conditions for high-quality preparatory work on planning the control of the *E. integriceps* in the year following the current one.

K. Sabanci *et al.* (2022) presented findings on detection of pest-damaged wheat grains using deep learning. Using the created image acquisition mechanism, healthy and uniform wheat grains were displayed. Scientists performed image pre-processing applied to the raw images, and then performed data augmentation. The augmented image data was provided as input for two different deep learning architectures. Therewith, a comparison was made according to the accuracy of the operation of these two architectures.

However, the cited studies do not indicate the possibility of using modern tools regarding the possibility of forecasting the harmfulness of pests. It is proposed to use the neural network tool to implement harmfulness prediction. For the application of the mentioned approach, a clear multi-year sample is necessary, which will allow achieving a high accuracy of the forecast. S. Khaki & L. Wang (2019) showed yield prediction using deep neural networks. In this study, the results also illustrated that environmental factors had a significant effect on yield. However, the scientists performed neural network prediction based on defined training data, which included three sets: crop genotype, yield indicators, and environment (weather and soil). The impact of pests on plant development was not fully demonstrated. In the study, the scientists implemented a neural network with sufficient accuracy. Machine learning techniques were used to predict yield, including multivariate regression, decision trees, association rule analysis, and artificial neural networks. G. Aubakirova *et al.* (2022) presented the application of an artificial neural network for forecasting the yield of wheat. In the study, scientists considered a series of factors affecting the development of wheat and its harvest in the territory of Kazakhstan. However, the researchers used a sample of data only for 2008-2022. The influence of pests as one of the factors on productivity was presented, and therefore the question of determining the forecasting of the number of pests arises.

Conclusions

According to the results of observations, it was shown that the principal factors influencing the harmfulness of the *E. integriceps* bug are its quantity, Wolf number, and HTC. Since the declared factors of influence on the harmfulness of the *E. integriceps* bug are characterised by small values of the coefficient of determination, which indicates the inadequacy of the linear model, and small values of linear correlation coefficients, it can be concluded that such dependencies are uncertain. Since the regression equation does not allow for a high-precision forecast under conditions of uncertainty, it is recommended to use artificial neural networks. An artificial neural network with a "multi-layer perceptron" structure creates conditions for predicting the harmfulness of a sunn pest bug with sufficient accuracy for preparatory work.

To save resources planned for controlling the number of *E. integriceps* bugs and their damage, it is advisable to consider not only the projected number of pests, but also factors such as the Wolf number and HTC. The analysis of the results of observations and analytical materials indicates a complex form of influence of the Wolf number on the harmfulness of the *E. integriceps* bug. This is especially pronounced for indicators of the specified factor within 120-220 and 20-100. Therewith, the minimum harmfulness is achieved for the Wolf number of 140 and 60. It is advisable to use the specified information to minimise the use of insecticides. The presented findings of the analysis of long-term observations create the conditions for an early forecast of grain yield assessment, which will enable early planning and organisational preparation for the next stage in grain production.

Acknowledgements

None.

Conflict of Interest

None.

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Нейромережеве прогнозування шкідливості клопа-шкідливої черепашки на пшениці озимій в Україні

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Анотація. Захист пшениці від її шкідників безпосередньо впливає на продовольчу безпеку країни. Тому метою досліджень було створення за роками прогнозних моделей для оцінок шкідливості клопа-шкідливої черепашки. Шкідливість клопа-шкідливої черепашки розглядали в залежності від наступних показників: чисельність шкідника, показник природнього середовища (число Волфа) та гідротермічного коефіцієнту зволоження (ГТК). Доведено, що стосовно зазначеного шкідника існує математична невизначеність інформаційних потоків, а тома для прогнозування використовувалась математика штучних нейронних мереж із структурою «багатошаровий перцептрон». Наведено результати дослідження шкідливості клопа-шкідливої черепашки для пшениці озимої в Україні матеріалів, що включає прогноз фітосанітарного стану агроценозів України та рекомендації з оцінки розподілу шкідливості клопа-шкідливої черепашки за роками спостереження (1996-2023 роки) для Одеської області. Зазначено, що цей розподіл відповідає нормальному закону із математичним очікуванням 25 %, що підтверджується результатами спостережень для інших регіонів Степової Зони. Виконано аналіз зв'язку між чисельністю клопа-шкідливої черепашки, числом Вольфа та накопиченої інтегрованої температурно-вологістної характеристики навколишнього середовища. Визначено, що шкідливість клопа-шкідливої черепашки характеризується затухаючою періодичною складовою із періодом 10-12 років. Наведений результат свідчить про вплив шкідливості клопа-шкідливої черепашки поточного року на наступний через 10-12 років. За результатами прогнозування наведено залежності шкідливості клопа-шкідливості черепашки від її чисельності та числа Вольфа. При цьому враховувалась накопичена інтегрована температурно-вологістна характеристика навколишнього середовища. Отримані результати досліджень рекомендуються до врахування для організації проведення планових технологічних операцій захисту зернових колосових культур

Ключові слова: захист рослин; штучні нейронні мережі; багатошаровий перцептрон; число Вольфа; математичне очікування

Received 14.03.2024 Revised 10.05.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 330.332

DOI: 10.31548/dopovidi/3.2024.106

Evaluation of the effectiveness of implementing measures to preserve natural resources in the context of sustainable development

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Abstract. Performance evaluation helps to identify the most effective approaches to conserving natural resources, which helps to optimise costs and increase the efficiency of using financial and material resources. The purpose of this study was to assess the effectiveness of implementing

Suggested Citation:
Khryk, V., Mazepa, V., Sytnyk, O., Levandovska, S., & Kimeichuk, I. (2024). Evaluation of the effectiveness of implementing measures to preserve natural resources in the context of sustainable development. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 106-118. doi: 10.31548/dopovidi/3.2024.106.

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measures to preserve natural resources in the context of sustainable development. The study employed the evaluation and sustainable development methods for a comprehensive assessment of the effectiveness of measures to preserve natural resources, considering economic, environmental, and social aspects. The research findings show that sustainable development is a critical concept for the modern world, as it ensures a balanced combination of economic growth, social well-being, and environmental sustainability. The performance measurement framework emphasises the significance of integrating different management systems, such as the balanced scorecard, value-based management principles, and integrated risk management (IRM). This integration enables effective risk management at all stages of project implementation, which provides a strategic focus on improving business performance and contributes to a greater probability of achieving sustainable development goals. The results of the study showed that a systematic approach to planning natural resource conservation measures is key to success. It includes eliminating differences in planning systems, detailing results through balanced scorecard projections, continuous monitoring of processes, and active staff involvement, which helps reduce agency conflicts. The results of the study can be used by environmental protection institutions to plan and implement effective measures to preserve natural resources, which will help achieve environmental goals at minimal cost

Keywords: natural resources; project; economic assessment; environmental sustainability; social impact; environmental goals

Introduction

In modern world, the issue of preserving natural resources is becoming increasingly important due to population growth, urbanisation, and industrialisation. The depletion of natural resources, climate change, and ecosystem degradation threaten the economic well-being and quality of life of future generations. In this context, the concept of sustainable development, which envisages a balanced combination of economic growth, social well-being, and environmental protection, is becoming central to the policies of many countries. Effective management and conservation of natural resources are key components of sustainable development. Implementation of measures aimed at the rational use of resources requires a thorough economic analysis to assess their impact and benefits. That is why the investigation of the cost-effectiveness of such measures is relevant. Evaluating the effectiveness of the measures taken to preserve natural resources is a key element in ensuring their long-term impact. However, despite a significant amount of research in this area, there are still gaps in understanding which approaches and tools are most effective in concrete economic, social, and environmental contexts. At the same time, most studies focus on the development of individual measures without due attention to their comprehensive assessment and integration into overall sustainable development strategies. Further research should focus on developing integrated assessment methods that factor in all these components and on investigating the long-term effects of conservation measures.

Assessment of the effectiveness of measures to preserve natural resources includes an analysis of the costs and benefits associated with the implementation of such measures. Studies conducted by I.A. Vasylenko *et al.* (2019) show that the rational use of resources and the introduction of energy efficient technologies can considerably reduce production and operating costs. S.M. Smyrnova *et al.* (2020) emphasised the significance of considering ecosystem services when assessing economic efficiency.

Significant attention of scientists, politicians, and the public is focused on the development

and implementation of measures to preserve natural resources in the context of sustainable development. According to S.I. Boguslavska (2021), the basis for assessing the effectiveness of such measures is the concept of sustainable development, which combines economic, social, and environmental aspects. According to this concept, measures aimed at preserving natural resources should not only prevent ecosystem degradation, but also contribute to economic growth and social well-being.

According to R. Korchovyi (2023), the introduction of economic instruments such as pollution taxes, payments for ecosystem services, subsidies for environmentally friendly technologies, and the creation of an emissions allowance market play an important role in ensuring the effectiveness of measures to preserve natural resources. The use of these tools helps to increase the motivation of enterprises to operate in an environmentally responsible manner and reduce their environmental impact.

N. Avanesova *et al.* (2021) also considered that the role of evaluating the effectiveness of implemented measures is important. The methodologies developed for this assessment include cost-benefit, product life cycle, and environmental indicators to determine the extent to which environmental and resource-saving goals are being met. Among these methods, the approach based on the Balanced Scorecard (BSC), which allows considering both financial and non-financial factors, stands out.

There are several approaches in the scientific literature to assessing the cost-effectiveness of natural resource conservation measures. According to V.V. Makedon & O.G. Mykhaylenko (2022), traditional methods include cost-benefit analysis, which allows assessing the economic feasibility of projects. Other approaches considered by O. Khokhulyak (2023) include life cycle assessment, which assesses environmental and economic impacts throughout the life cycle of a product or service. Social aspects of sustainable development include equity, access to basic services, human rights, and social cohesion. A.A. Ivashura (2022) found that environmental aspects focus on conserving biodiversity, maintaining ecosystem services, and reducing pollution. M.A. Khvesyk & V.K. Holyan (2006) showed that measures to preserve natural resources can considerably improve the quality of life of the population and contribute to social stability. The literature review suggests that assessing the economic efficiency of natural resource conservation measures is a complex and multifaceted process that includes economic, social, and environmental aspects.

The purpose of this study was to analyse and identify the most effective approaches to implementing measures that promote the conservation of natural resources, considering the principles of sustainable development.

Objectives of the study:

- to investigate the methodologies for assessing the economic efficiency of measures to preserve natural resources;
- to propose an assessment of the economic efficiency of concrete measures to preserve natural resources;
- to analyse the impact of natural resource conservation measures on sustainable development.

Materials and Methods

The economic valuation method was used to determine the economic efficiency of implementing measures to preserve natural resources. Different scenarios for implementing measures to preserve natural resources were considered to determine the most effective one. Specifically, the economic feasibility of such measures was assessed through the lens of their impact on profitability, payback, and reduction of resource costs. The study considered both direct economic benefits and indirect effects, such as reduced environmental burden, improved quality of life, and enhanced ecosystem services. The method of analytical synthesis helped to systematise and interpret the results of studies conducted in different conditions and using distinct approaches. Data collected from scientific sources of C. Wang & G. Dong (2019),

A. Ivashura (2022), R. Korchovyi (2023), D. Bukreeva *et al.* (2023) were systematised to create a holistic picture of the cost-effectiveness of natural resource conservation measures. This is how the methodological issues of implementing green technologies are presented in the study.

The analysis method was employed to assess the effectiveness of measures to preserve natural resources. This method involved a cost-benefit analysis to determine the economic feasibility of the measures implemented, specifically their impact on cost reduction, revenue growth or improvement of the economic performance of enterprises or regions. The analysis also included market research, examination of structural changes in the economy, assessment of the value of ecosystem services and opportunities for their monetisation, which helped to identify the effectiveness of measures in terms of both short-term and long-term economic results. This approach has provided a more accurate and informed understanding of the financial implications of implementing environmentally friendly measures. The analysis also included market research, examination of structural changes in the economy, assessment of the value of ecosystem services and opportunities for their monetisation, which helped to identify the effectiveness of measures in terms of both short-term and long-term economic results.

The method of scientific synthesis was used to systematise and analyse the available data obtained from various studies, expert assessments, and empirical research related to natural resource conservation and sustainable development. This method helped to summarise scientific approaches, experience of implementing measures in different countries and regions, as well as to identify best practices and key success factors. Based on the synthesis, recommendations were developed for the implementation of measures adapted to concrete conditions, factoring in the environmental, social, and economic features.

To assess environmental performance, the study used quantitative indicators of greenhouse gas emissions reduction, water and air pollution reduction, and biodiversity conservation. The study included collecting data from environmental monitoring systems and analysing the results of the implementation of measures at the enterprises. Specifically, the results of the implementation of drip irrigation systems, renewable energy sources, and waste recycling in various sectors of the economy were investigated.

An essential element of the study was the systematisation of measures to preserve natural resources based on Ukrainian and foreign practices. This included an analysis of existing waste management systems, energy efficiency technologies, renewable energy sources, and agricultural irrigation systems. The study was conducted with due regard to the specifics of each sector of the economy and the possibility of scaling the results to the national level.

The application of these scientific methods in the study helped to comprehensively assess the effectiveness of measures to preserve natural resources, considering all key aspects of sustainable development.

Results and Discussion

Sustainable development is a concept that emerged as a response to the global environmental and socio-economic challenges facing humanity in the second half of the 20th century. Comparing the findings with the studies of other researchers helps to identify general trends and specific approaches to assessing the effectiveness of measures to preserve natural resources in the context of sustainable development. Raising environmental awareness among the population and encouraging environmentally responsible behaviour. Sustainable development and economic efficiency are interrelated concepts that reinforce each other. Implementation of the principles of sustainable development can contribute to economic efficiency through the following mechanisms (Andryeyeva *et al.*, 2019):

1) rational use of resources and implementation of energy-efficient and energy-saving

technologies can significantly reduce production and operation costs;

2) sustainable development stimulates the development of innovative technologies that can increase the productivity and competitiveness of the economy;

3) ensuring social justice and improving the quality of life contribute to social stability, which is an important factor for economic growth;

4) support of ecosystems and preservation of natural resources ensures long-term sustainability of economic development, preventing resource depletion and adverse environmental impacts.

The interconnection between these concepts helps to create the conditions for a balanced and harmonious development that meets the needs of present and future generations. In the context of modern environmental challenges, the conservation of natural resources is becoming an integral part of sustainable development strategies, and it is the economic benefits of implementing measures to conserve natural resources that can be assessed by a series of defining criteria, namely: the introduction of energy efficient technologies and renewable energy sources can reduce energy and fuel costs, e.g., the use of solar panels can substantially reduce electricity costs for businesses and households; optimisation of waste management and recycling reduces disposal costs and helps to create new sources of income from the sale of secondary materials; water conservation measures, such as drip irrigation systems, can increase agricultural productivity and reduce water supply costs (Zhylins'ka, 2017). Enterprises that implement conservation measures can avoid fines for environmental violations and reduce the cost of compensation measures, and such an assessment of the costs of implementing conservation measures is a critical aspect of determining their cost-effectiveness. Such costs may include initial investments in equipment procurement and installation, development of innovative technologies, and staff training. For example, the installation of solar panels requires a significant initial investment, but these costs can be offset by electricity savings in the long run (Makedon & Makovets'ka, 2023). Operational costs include the cost of maintaining and operating new systems and technologies, such as drip irrigation systems, which may require additional costs but will ensure more efficient use of water. Administrative costs for project management, monitoring, and reporting, which may include the costs of developing natural resource management strategies and policies. Some measures may require government support or funding from international organisations, which should also be considered in the overall cost estimate.

The performance assessment framework developed based on the analysis of experience in implementing measures to preserve natural resources in the context of sustainable development and involving the use of a management system focused on economic performance criteria and taking into account the balanced scorecard tools is presented in Figure 1.

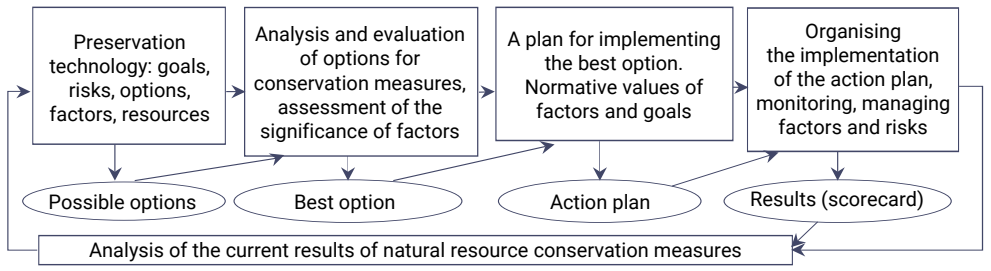

Figure 1. *The structure of the process of assessing the economic efficiency of natural resource conservation measures*

Source: developed by the authors of this study

A key element in planning measures for the conservation of natural resources is a system for evaluating options and substantiating intermediate results. The specific features of planning measures to preserve natural resources of enterprises are as follows:

- eliminating differences in planning systems and organising the implementation of plans;
- the need to highlight the results of the initiated measures in the context of the projections of the balanced scorecard;
- in monitoring the process of measures to preserve the natural resources of the divisions by a set of indicators;
- in carrying out a set of activities to involve staff in the natural resource conservation and reduction of agency conflicts.

It is necessary to discuss the need for measures to preserve the natural resources of the risk management system in a balanced scorecard. However, to manage the processes of natural resource conservation, we propose an integrated system that combines the conceptual foundations of three currently progressive systems. Therewith, in terms of the principles of risk management, they focus on the integrated risk management system (IRM), which is still in its infancy but is already effectively used by a series of Ukrainian and foreign industrial enterprises. The conservation of natural resources is based on the Balanced Scorecard (BSC), Value Based Management (VBM), and the concept of an integrated risk management system (IRM). The analysis shows a series of common aspects for all three management systems: strategic orientation of all integrated systems, their focus on increasing business efficiency; the concept of risk management should be considered as a way to manage risks that act as value management factors.

Therewith, value management factors become risk factors at the same time, and the system makes provision for risk analysis of initiatives to use the factors, namely:

- use of indicators (early indicators) that characterise the goals and results of individual projections of the balanced scorecard, identify risks in the risk management system and can be intermediate indicators in the management system for the cost of implementing measures to preserve natural resources;
- an integrated approach where the entire value chain is analysed with a focus on the relationship between business processes and results, and risks are considered not only as hazards but also as hidden opportunities to improve efficiency.

Therefore, the integrated management system for natural resources conservation efficiency is represented by the diagram presented in Figure 2.

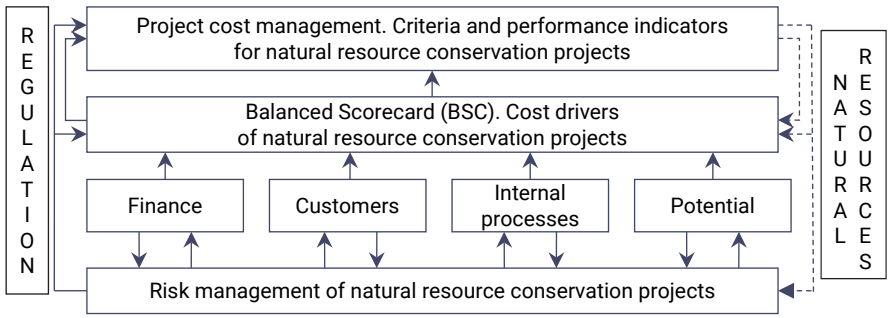

Figure 2. *Integrated system for managing the economic efficiency of natural resource conservation projects*

Source: developed by the authors of this study

In this system, performance management of natural resource conservation projects is, firstly, an element of all BSC projects, and secondly, an independent element of managing the cost of such projects. The identification and structuring of risks in natural resource conservation projects using an integrated management system should follow the logic of the balanced scorecard and the sequence of the integrated measure itself (Villanueva & Blanco, 2019). The economic efficiency of implementing natural resource conservation projects considered as investment projects is proposed to be defined as a ratio:

$$\xi = NAV \ / \ [P_B + PV(E)], \qquad (1)$$

where $PV(E)$ is the capitalisation of business integration costs. This approach is substantiated by the fact that the denominator (1) includes all capitalised costs of natural resource conservation projects. The economic implementation of such projects is more efficient if $\xi > WACC$ of the project being implemented.

To formalise the problem of managing the efficiency and effectiveness of natural resource conservation projects, let us introduce the concepts of ideal (index 0), estimated (index 1) and actual values of enterprises at time t (index 2). The ideal value of the cost of the project for the conservation of natural resources A in year t($BPV_{A0}(t)$) is determined by two conditions: compliance with the real market situation (the real state of the environment) and the ideal (best within the available possibilities) reaction of the economic environment. $BPV_{A2}(t)$ is the factual value of the cost of natural resource conservation projects "A" in year t, which corresponds to the real market situation and the factual level of management decisions of the customers of such projects. Other elements of the incremental value of natural resource conservation projects have an analogous interpretation (Avanesova *et al*., 2021).

The difference $NAV_1 - NAV_2 = \Delta NAV_{1/2}$ is an error in the efficiency assessment associated with miscalculations in the assessment of the current value of natural resource conservation projects and deviations of the forecast (estimated) values of cash flows and risks from the factual ones ($\Delta NAV_{1/2} <> 0$). The difference $NAV_0 - NAV_2 = \Delta NAV_{0/2}$ is the loss of effect caused by the imperfection of the investment project management process ($\Delta NAV_{0/2} <= 0$). $NAV_0 - NAV_1 = \Delta NAV_{0/1}$ – deviation of the estimated value of the effect of the association's natural resources conservation projects from the ideal value due to errors in cash flow estimates and risks caused by uncertainty in the market situation and the quality of calculations:

$$\Delta NAV_{0/1} = \Delta NAV_{1/2} + \Delta NAV_{0/2}. \qquad (2)$$

The ideal estimate of the economic effect of implementing measures to preserve natural resources under this approach would be equal to:

$$NAV_0 = NAV_1 + \Delta NAV_{1/2} + \Delta NAV_{0/2}. \qquad (3)$$

Since $\Delta NAV_{0/1} <> 0$, (1) can be considered as a transition from a point estimate of the effect to an estimate with confidence intervals. Therefore, the analysis of the economic efficiency of concrete measures to preserve natural resources requires careful consideration of both the economic benefits and costs of their implementation. Implementation of such measures can lead to significant economic benefits, cost savings, and improved environmental sustainability, but requires detailed planning and evaluation to maximise results.

Implementation of measures to preserve natural resources has a comprehensive impact on sustainable development, covering economic, environmental, and social aspects. Measures aimed at preserving natural resources can have a considerable economic impact. Renewable energy sources, such as solar panels and wind turbines, reduce dependence on fossil fuels and create new jobs in the green energy sector. This leads to economic growth and the development of new sectors of the economy (Bhunia *et al*., 2021).

The environmental benefits of natural resource conservation include reduced environmental

pollution, biodiversity conservation, and improved ecosystems. The social benefits of natural resource conservation include improved quality of life, new jobs, and increased social cohesion. The long-term effects of conservation measures can be significant and multifaceted, and include sustained economic growth, environmental sustainability, and social progress (Hurochkina & Sokur, 2021). Implementing sustainable practices in production and consumption can ensure long-term economic stability. Investments in renewable energy, energy-efficient technologies, and waste recycling contribute to the development of new sectors of the economy and reduce the risks associated with the depletion of conventional resources, enabling the economy to adapt to changes and ensure sustainable growth.

Long-term environmental sustainability is ensured by preserving natural resources and maintaining ecosystem services. Measures aimed at reducing pollution, conserving biodiversity, and using resources rationally help maintain the natural balance and ensure a healthy environment for future generations, which reduces the risks of environmental disasters and ensures ecosystem resilience (Hablovskyi *et al.*, 2023). Based on the substantiations provided, a summary Table 1 is presented.

Table 1. *Integrated impact of natural resource conservation measures on sustainable development*

Category	Examples of measures	Effects	Advantages	Long-term effects
Economic results	Energy efficient technologies, renewable energy sources	Reduced energy costs, economic growth	Increased competitiveness, new jobs	Stable economic growth
Environmental results	Transition to renewable energy sources, waste management	Reducing pollution, preserving biodiversity	Reducing environmental risks, improving ecosystems	Ecosystem resilience
Social results	Improvement of the energy efficiency of residential buildings, creation of jobs	Improvement of the quality of life, creation of jobs	Reduction of energy costs for households, social cohesion	Social progress
Long-term economic effects	Investments in renewable energy and waste recycling	Economic stability, development of new economic sectors	Reduction of the risks of resource depletion, sustainable growth	Stable economic growth
Long-term environmental effects	Conservation of natural resources, support for ecosystem services	Environmental sustainability, support of the natural balance	Reduction of the risk of environmental disasters, healthy environment	Ecosystem resilience
Long-term social impacts	Investments in the green econ omy, educational programmes on environmental responsibility	Improvement of the quality of life, development of human capital	New employment opportunities, reduction of social inequality	Social progress

Source: developed by the authors of this study based on B. Hablovskyi *et al.* (2023)

Considering this, the following measures can be taken to preserve natural resources:

1. The use of resource-saving technologies in manufacturing, agriculture, and construction can

considerably reduce the consumption of water, energy, and raw materials. These aspects include the use of recycling methods, recycling of materials, use of energy-efficient equipment, and optimisation of production processes to reduce resource waste.

2. Implementation of sustainable consumption and production policies. Encouraging more responsible consumption through educational programmes, information campaigns, and eco-labelling initiatives. Encouraging manufacturers to reduce their negative impact on the environment by introducing environmentally friendly technologies and production processes.

3. Promotion of the use of renewable energy sources. Development and support of solar, wind, geothermal, and biomass projects that will help reduce the consumption of non-renewable natural resources such as coal, oil, and gas, as well as greenhouse gas emissions.

4. Creation of economic incentives for resource conservation. Introduction of a system of financial and tax incentives that encourage businesses and citizens to use natural resources rationally. This could include subsidies for the introduction of environmentally friendly technologies, tax breaks for businesses that reduce their environmental impact, and fines for violations of environmental regulations.

5. Development of science-based strategies for the conservation of natural resources. Investigation of local ecosystems, monitoring of the state of natural resources and developing adapted strategies that consider local characteristics, environmental risks, and socio-economic conditions, including the implementation of programmes to preserve water resources, protect forests, and other natural ecosystems.

Therefore, the conducted study is intended to provide a comprehensive analysis of the effectiveness of natural resource conservation measures, which will facilitate the adoption of informed decisions in the field of sustainable development, which will not only reduce the negative impact on the environment, but also provide economic benefits, promote social well-being, and long-term sustainability of the economy. The impact of natural resource conservation measures on sustainable development is multifaceted and complex.

The findings of the present study confirm the significance of preserving natural resources as a key aspect of sustainable development that meets modern global environmental and socioeconomic challenges. The principles of natural resource conservation, such as rational use, support for ecosystem resilience, pollution prevention, and biodiversity protection, are key components of sustainable development strategies. At the same time, the results of the present study confirm that these measures not only ensure environmental sustainability, but also have a significant economic impact.

N.Yu. Lazorenko-Hevel' (2014) emphasised the importance of rational use of natural resources, including efficient and careful use of resources, minimisation of waste, and introduction of technologies that reduce adverse environmental impact. These principles are in line with the findings of the present study, which also emphasises the significance of cost-effectiveness of such approaches. There is a similar focus on rational use and waste minimisation. The difference is that the cited study focuses more on technological aspects, while the present study covers a wider range of economic instruments and strategies. N. Andryeyeva *et al.* (2019) focused on the relationship between sustainable development and economic efficiency, emphasising the importance of energy efficiency, innovation, and social stability. The present study confirms these findings and extends them by adding the need to integrate management systems (BSC, VBM, IRM) to increase the effectiveness of natural resource conservation measures. There is a common recognition of the role of economic instruments in ensuring sustainable development, while the difference is the broader scope of management approaches in the present study.

Researchers L.P. Ishchuk *et al.* (2018) identified the environmental benefits of implementing measures such as the use of renewable energy

sources and optimisation of waste management systems. This approach is consistent with the presented findings on the economic benefits of energy efficiency technologies. O. Zhylins'ka (2017) focused more on specific waste management measures, while the present study covers more comprehensive approaches, including the integration of different management systems. B. Scholtens (2017) considered economic instruments, such as pollution taxes and emission allowance markets, as key to effective natural resource conservation policies. The present study also emphasised the significance of economic instruments, but additionally considered their integration with management systems (IRM, VBM, BSC), which makes our approach more comprehensive. There is a common understanding of the need for economic stimulus, but the present study suggests a more integrated approach to its application. V.V. Makedon & O.G. Mykhaylenko (2022) addressed the importance of using a balanced scorecard (BSC) to assess the effectiveness of environmental measures. The present study supports this idea and extends it by integrating the principles of value-based management (VBM) and integrated risk management (IRM). The common thread is the recognition of the importance of BSC, while the present study adds more tools for integrated management.

Authors C. Wang & G. Dong (2019) focused on climate change adaptation as a key element of sustainable development, which requires effective management of natural resources. The current study highlighted the significance of these measures to ensure long-term economic sustainability, but also added economic aspects such as cost optimisation and productivity gains. The common thread is the recognition of the importance of resource management, while the present study focuses more on cost-effectiveness. B. Hablovskyi *et al.* (2023) pointed out the need for an integrated approach to the conservation of natural resources, including social, environmental, and economic aspects. The present study also emphasised the importance of this approach but added concrete recommendations on the use of different management systems and economic instruments. There is a common recognition of the significance of a comprehensive approach, while the present study proposes more concrete methods for its implementation.

In particular, it was found that the rational use of resources and the introduction of energy-efficient technologies can significantly reduce production costs and increase economic efficiency, and such findings are consistent with previous studies that highlight the economic benefits of introducing green technologies, such as the use of renewable energy sources and optimised waste management systems. This approach not only reduces energy costs but also creates new sources of income, which confirms the relationship between sustainable development and economic efficiency. The effectiveness of implementing natural resource conservation measures largely depends on the ability to integrate various management systems, such as the Balanced Scorecard (BSC), Value Based Management (VBM), and Integrated Risk Management (IRM). The study showed that these systems have common features, including a strategic focus on increasing business efficiency and managing risks that affect the cost of resource-saving projects.

At the same time, it is important to consider that the implementation of measures to preserve natural resources may face a series of challenges, including the need for sizeable initial investment and operating costs for innovative technologies and equipment. In this context, it is important to assess not only the economic benefits, but also the potential costs, including administrative and operational costs, to ensure maximum efficiency and long-term sustainability of measures.

Conclusions

The study investigated the basic principles of sustainable development, which focus on the conservation of natural resources, specifically their rational use, maintaining the ability of ecosystems to recover, preventing environmental pollution,

and protecting biodiversity. It was found that the implementation of these principles is key to achieving sustainable development and economic efficiency. Approaches to assessing the economic efficiency of measures to preserve natural resources were developed. The study suggested using the balanced scorecard (BSC), value-based management (VBM) principles, and the concept of an integrated risk management system (IRM) to improve the efficiency of natural resource management and achieve the goals of sustainable development.

The economic benefits of implementing measures to conserve natural resources, such as energy-efficient technologies, optimised waste management and water conservation, were assessed. It was found that these measures help to reduce production costs, increase productivity, ensure social stability, and long-term sustainability of economic development. An integrated system for managing the cost-effectiveness of natural resource conservation projects was developed, which considers the relationship between business processes, results, and risks. The study presented a system that combines elements of BSC, VBM, and IRM and allows achieving sustainable goals more efficiently through optimised use of investments and risk management.

The study substantiated the need for an integrated approach to the implementation of measures to preserve natural resources, including the use of scientifically sound strategies, integration of local communities into the decision-making process, development of the "green" economy, and strengthening of the regulatory framework. This approach ensures a balanced development of economic, social, and environmental components of sustainable development. It was proved that long-term environmental sustainability directly depends on the implementation of measures to preserve natural resources and maintain ecosystem services. The measures considered, aimed at reducing pollution, preserving biodiversity, and rational use of resources, play a key role in maintaining the natural balance and ensuring a healthy environment for future generations. It was found that the introduction of resource-saving technologies in various sectors of the economy can considerably reduce the consumption of water, energy, and raw materials, which is critical for reducing environmental risks and increasing the resilience of ecosystems. Furthermore, implementing sustainable consumption and production policies, encouraging responsible consumption, and incentivising producers to adopt environmentally friendly technologies are crucial steps towards achieving social progress and economic stability. Thus, an integrated approach to the conservation of natural resources helps to ensure long-term sustainability of ecosystems, economic development, and improvement of the quality of life, which will help to prevent environmental disasters and ensure sustainable development at all levels.

Further research could be aimed at developing integrated natural resource management systems that combine the concepts of risk management, value-based management, and a balanced scorecard, which would allow for more effective risk control and achievement of strategic goals of sustainable development.

Acknowledgements

None.

Conflict of Interest

None.

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Оцінка ефективності впровадження заходів зі збереження природних ресурсів у контексті сталого розвитку

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Анотація. Оцінка ефективності допомагає визначити найбільш результативні підходи до збереження природних ресурсів, що дозволяє оптимізувати витрати та підвищити ефективність використання фінансових і матеріальних ресурсів. Мета статті оцінка ефективності впровадження заходів зі збереження природних ресурсів у контексті сталого розвитку. В статті застосовано методи оцінки та сталого розвитку для комплексної оцінки ефективності заходів зі збереження природних ресурсів з урахуванням економічних, екологічних та соціальних аспектів. Результати дослідження показують, що сталий розвиток є критично важливою концепцією для сучасного світу, оскільки забезпечує збалансоване поєднання економічного зростання, соціального благополуччя та екологічної стійкості. Була структура оцінки ефективності підкреслює значення інтеграції різних систем управління, таких як збалансована система показників, принципи управління за вартістю та комплексна система управління ризиками (ERM). Завдяки цій інтеграції стає можливим ефективне управління ризиками на всіх етапах реалізації проєктів, що забезпечує стратегічний фокус на підвищення ефективності бізнесу та сприяє більшій вірогідності досягнення цілей сталого розвитку. Результати дослідження показали, що системний підхід до планування заходів зі збереження природних ресурсів є ключовим для успіху. Він включає ліквідацію відмінностей у системах планування, деталізацію результатів через проекції збалансованої системи показників, постійний моніторинг процесів та активне залучення персоналу, що сприяє зниженню агентських конфліктів. Результати дослідження можуть бути використані установами, що займаються охороною навколишнього середовища, для планування та впровадження ефективних заходів зі збереження природних ресурсів, що сприятиме досягненню екологічних цілей при мінімальних витратах

Ключові слова: природні ресурси; проєкт; економічна оцінка; екологічна стійкість; соціальний ефект; екологічні цілі

Received 11.03.2024 Revised 04.06.2024 Accepted 26.06.2024

Vol. 20, No. 4
2024

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 62-597

DOI: 10.31548/dopovidi/3.2024.119

Technical overview of the main types, designs, and materials of brake pads for mobile agricultural machinery

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Abstract. Brake pads are a critical element of any machine, as they directly affect the safety of its use. Accordingly, the quality of brake pads, their resistance, and durability are key aspects that must be considered when developing braking systems for mobile agricultural machinery. The purpose of this study was to review scientific sources related to the study of the tribological properties of brake pads, their operating modes, and friction materials included in brake linings. The main parameters affecting the efficiency of brake pads were analysed and the main criteria for selecting materials for brake pads of mobile agricultural machinery were defined, namely, wear resistance, temperature resistance, and corrosion resistance. Accordingly, the materials used in the production of brake pads for such equipment must be capable of operating under any conditions, have high thermal conductivity, help reduce the wear rate, have a stable friction coefficient, and be environmentally friendly. The study focused on an overview of the types and design of brake pads, their systematisation by various features (by purpose; by design features; by friction material composition; by the presence of wear sensors) and composition (semi-metallic, non-asbestos organic, and ceramic). The study described modern components of friction materials for brake linings and found that they are usually composites formed by hot pressing coarse powders, which include many different components: a binder (thermosetting phenolic resins, often with rubber added), structural materials (metal, carbon, glass, and/or Kevlar fibres), fillers (mica and vermiculite), and friction additives (graphite and various metal sulphides). The study also assessed the main characteristics of friction material components used in the manufacture of brake linings. The findings of this study can provide researchers and scientists with useful information on the types and design of brake pads and the main materials used in the manufacture of brake linings and be useful for further practical development of braking mechanisms

Keywords: brake system; composite materials; friction; tribological properties; friction materials

Suggested Citation:
Zagurskiy, A. (2024). Technical overview of the main types, designs, and materials of brake pads for mobile agricultural machinery. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(4), 119-130. doi: 10.31548/dopovidi/3.2024.119.

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Introduction

The braking system is a critical mechanism that ensures the safety of people and goods. It works through friction between the disc and the pad, which slows the vehicle down. The brake pads grip the disc, reducing its rotation and decelerating the vehicle. The behaviour of the friction elements is determined by the active surfaces of the pad and disc and the third bodies between them. This complex tribosystem has not yet been fully explored and studied. The correct type and material for brake pads therefore directly affects braking performance and reduces maintenance costs. It is also important to consider the environmental friendliness of materials and use modern solutions to improve the safety and environmental friendliness of mobile agricultural machinery.

Brake pads, their operating modes, and the materials they are made of continue to attract considerable research attention due to their environmental impact and performance. O.I. Nazarov *et al*. (2023) investigated the frictional properties of brake materials under different braking conditions, focusing on how these conditions affect the performance of brake pads. M.G. Faga *et al*. (2019) found that the service life of braking mechanisms directly depends on braking conditions and is the inverse of the wear of friction surfaces. L. Wei *et al*. (2019) confirmed that the materials used to make pads are a key factor in wear.

D. Carlevaris *et al*. (2023) proposed the use of rice husk as a component of friction materials, while S. Venkatesh & K. Murugapoopathiraja (2019) and W. Li *et al*. (2021) investigated the potential of rice husk ash and barite-calcite as inert filler. Their findings showed that the use of these natural ingredients not only does not impair the performance of brake pads but contributes to improved wear resistance and reduced friction material emissions.

Composite materials, as noted by F. Khan *et al*. (2024), play a key role in improving the durability of brake linings due to their ability to withstand high loads and ensure stable performance even under extreme conditions. The use of such materials reduces the risk of damage and wear to brake components, making the system more reliable and durable. This is especially important for heavy vehicles and vehicles operated at high speeds and requiring frequent braking. The high strength of the composites also reduces the need for frequent brake pad replacements, which helps to reduce maintenance costs and improve overall vehicle efficiency.

On the other hand, S. Mulani *et al*. (2022) emphasised that the use of composite materials can considerably reduce the weight of a car, which improves its handling and dynamic characteristics. Reducing vehicle weight helps to save fuel, which is an essential factor in reducing carbon dioxide emissions and increasing the environmental sustainability of road transport. The lighter brake pads also reduce the load on the suspension and braking system, which improves the overall stability of the vehicle on the road and provides a more comfortable driving experience.

S. Manoharan *et al*. (2019) further showed that the morphology of potassium titanate used in composite materials considerably affects the performance of braking systems. This component contributes to the formation of contact plateaus and transfer films on rubbing surfaces, which results in high frictional stability and wear resistance. According to the findings, potassium titanate in the form of chips demonstrates improved characteristics compared to other materials, which allows increasing the reliability of brake systems, reducing wear, and ensuring stable friction properties even under high loads. Thus, the introduction of new materials and technologies in the production of brake systems opens new opportunities to improve the efficiency and environmental safety of vehicles.

P. Ghosh *et al*. (2020) investigated the effect of the concentration of fibre components (aramid/lapinus) on friction composites. Their findings confirmed that changing the composition of the composite affects properties such as the coefficient of friction and thermal conductivity. S. Jeganmohan *et al*. (2020) studied the thermal properties of materials, including thermal

decomposition, while V.V. Kumar & S.S. Kumaran (2019) found that composites with lower fibre content have a lower wear rate, but higher fibre content increases thermal conductivity.

Therewith, the available information is usually scattered, and methodological issues are still understudied, namely definitions, systematisation, and classification of types, designs, and materials of brake pads. The purpose of this study was to review, systematise, and classify the types and design of brake pads and analyse modern materials used in the manufacture of brake linings.

The study employed systematic and qualimetric approaches, which involve the use of analysis and synthesis, formalisation, tabular and graphical interpretation of the results and contribute to the integrity of the study, with the identification of various characteristic features.

Material Requirements for Disc Brake Pads

During braking, the force acting on the pad attracts it to the disc, forming a so-called tribological contact between them (Aulin *et al.*, 2024). Tribological contact is the interaction between surfaces that are in relative motion to each other. The term combines the aspects of friction, wear, and lubrication studied in tribology, which are characterised by certain tribological properties that determine the behaviour of materials or joints in friction. The main tribological properties are presented in Table 1. These qualities are key when selecting materials for mechanisms and joints subject to friction to ensure their durability and efficiency. And, as shown in Figure 1, as a result of friction in the braking system of mobile agricultural machinery, kinetic energy is dissipated and converted into heat.

Table 1. *Basic tribological properties and their characteristics*

Properties	Characteristics
coefficient of friction	determines the sliding resistance between two surfaces
wear resistance	determines the ability of the material to resist mechanical wear
anti-friction property	determines the possibility of reducing friction between moving parts
score resistance	determines the ability of surfaces to resist scoring on contact
lubricating property	indicates the ability of a material or lubricant to reduce friction and wear
temperature resistance	determines the ability to maintain tribological properties at hot or cold temperatures
corrosion resistance	ability to resist corrosion in friction conditions

Source: compiled by the author of this study based on W. Li *et al.* (2022)

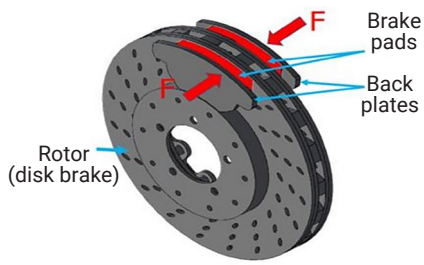

Figure 1. *Friction force between brake pads and brake disc surface*

Note: F – friction force
Source: A.P. Irawan *et al.* (2022)

The power dissipation equation proposed by R. Dante (2015) is a basic expression for any type of brake, as it introduces the concept of an external force, which is a source of counteracting the motion, into the underlying concept:

$$\frac{\delta W_d}{dt} = w(\bar{X})F_N, \quad (1)$$

where W_d is the dissipated work; t is time; $w(\bar{X})$ is the proportionality coefficient; $\bar{X}$ is a set of variables affecting the proportionality coefficient; v is velocity; F_N is the friction force created between two opposing surfaces.

The heat energy generated by power dissipation is transferred to the components in contact. Excessive thermal load can cause vibration (disc thickness changes), surface cracking, and severe wear of the contact surfaces (Fig. 2).

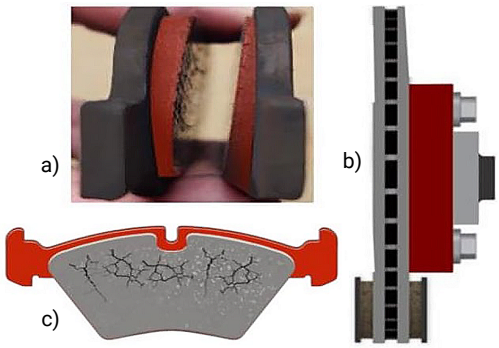

Figure 2. *Brake pad failure caused by excessive heat load*
Note: a – wear, b – change in disc thickness, c – surface cracking
Source: A.P. Irawan *et al*. (2022)

This reduces the thickness of the friction material of the pad. Reaching the limit value, the pad must be replaced. The friction material is the very obstacle that, when the brakes are applied, allows the vehicle to decelerate and stop in time. To avoid such defects, the material used in the production of brake pads must meet the following criteria:

- be operable in various operating situations (e.g., high temperature, pressure, velocity);
- have high thermal conductivity;
- help reduce the rate of wear;
- have a stable coefficient of friction;
- be environmentally sustainable.

Therefore, for the braking mechanism to function efficiently and for the pads themselves to be durable, the quality of their manufacture becomes a vital aspect to consider when selecting the right combination of materials.

Main Types and Designs of Disc Brake Pads

When considering the classification of brake pads, it can be noted that they are divided into several main types, depending on the design features and material of manufacture:

For its intended purpose:

- for ordinary road vehicles – designed for moderate use in urban and intercity conditions;
- for high-speed vehicles – designed for higher velocities and frequent braking;
- for trucks and buses – designed for heavy loads and intensive use;
- for racing cars – optimised for maximum performance under extreme braking conditions.

For design features:

- single-layer – consisting of a single layer of friction material;
- multilayer – have several layers of friction material to increase strength and efficiency;
- with additional layers – have additional layers of friction material to reduce vibrations and noise.

According to the composition of the friction material:

- semi-metallic;
- NAO – non-asbestos organic;
- ceramic.

The composition and main characteristics of brake pads by type are presented in Table 2.

Table 2. *Composition and main characteristics of brake pads by type*

Name	Composition	Advantages	Disadvantages
Semi-metallic	The composite of this friction material consists of 30–70% metal (copper or steel) and graphite. This composite is complemented by other inorganic materials and binders	➤ high thermal conductivity, which allows for efficient heat dissipation during braking; ➤ long service life; ➤ wide temperature range; ➤ good performance at hot temperatures.	➤ noisier; ➤ higher levels of brake disc wear; ➤ less environmentally friendly and generate more black dust.

Table 2. *Continued*

Name	Composition	Advantages	Disadvantages
NAO (non-asbestos organic)	The friction linings are made from a mixture of organic fibres such as glass fibre, Kevlar, aramid, carbon fibre, and high-temperature resins. The metal content in their composition does not exceed 20%.	➤ less noise and softer braking; ➤ less wear on the brake discs; ➤ more environmentally friendly as they do not contain asbestos.	➤ shorter service life than metal pads; ➤ less effective at hot temperatures; ➤ used for small passenger cars
Ceramic	The friction layer of this type consists of ceramic fibres bonded with special resins, sometimes with a small amount of non-ferrous metals	➤ long service life; ➤ stable performance even at hot temperatures; ➤ reduce the amount of brake dust.	➤ more expensive to produce and usually have a higher price; ➤ low initial coefficient of friction.

Source: compiled by the author of this study based on V.I. Mohyla & M.H. Aldokimov (2018), A. Sinha *et al*. (2020)

In terms of the availability of wear sensors:

➤ without wear sensors and without mechanical wear detectors;

➤ with mechanical wear detectors;

➤ with wear sensors: with pre-installed sensors, with seats for mounting existing sensors, with integrated sensors.

Each type of brake pad has its advantages and disadvantages, and the choice depends on the concrete operating conditions and performance requirements. A closer look at the construction of brake pads reveals that they usually comprise several layers (Fig. 3).

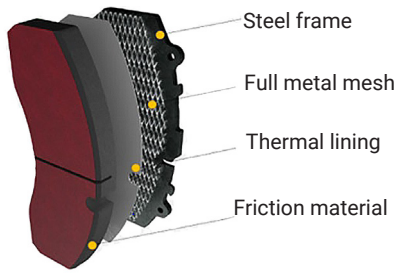

Figure 3. *Brake pad layers*
Source: developed by the author of this study

Adhesive – designed to hold the friction material to the other layers of the brake pad. This is ensured by a sub-layer placed between the friction material and the back plate. The main function of the sub-layer is to reduce vibrations caused by the contact of friction materials with the disc. Rear plate – designed to maintain the necessary rigidity in the brake pad to allow it to continue to move along the calliper guide. Some brake pads use special interference pads to minimise the amount of unnecessary noise during braking. Friction material is the main layer on the brake pads that comes into direct contact with the brake disc during braking. Friction material comprises various components, each of which is designed for specific applications (Arman *et al.*, 2018; Ige *et al.*, 2019; Kumar & Selvaraj, 2019). The combination of these components can vary depending on the performance requirements and the purpose of the material (Rogovskii, 2021). Such materials are widely used in various industries, and therefore their composition is adapted to concrete operating conditions. This approach allows achieving optimum performance that ensures the reliability and durability of products in various environments.

Main Components of Brake Lining Friction Materials

Brake lining materials are usually composites created by hot pressing coarse powders, which also contain many (usually 10-20) different components. The components of friction materials are as follows: Binders– designed to create a thermally

stable matrix (holding all other components together). Typically, they consist of thermosetting phenolic resins, often with the addition of rubber to improve the damping friction properties; Structural materials – provide mechanical strength of the pad. For these purposes, metal, mineral, and ceramic fibres, glass, and/or Kevlar fibres, and rarely various carbon fibres are used; Fillers – designed to reduce the cost and improve the processability of the lining. Various minerals such as mica and vermiculite are often used as fillers; Friction additives – help to ensure stable friction properties of the pad and control the wear rate of the friction pair (disc and pad). They contain solid lubricants (graphite and various metal sulphides) that help to stabilise the coefficient of friction, especially at hot temperatures. Abrasive particles – designed to create a more reliable friction surface by removing iron oxides and other unwanted surface films from the brake disc. The latter are usually made of aluminium oxide and silicon, which increase both the coefficient of friction and disc wear. The main components of the brake lining friction materials are described in Table 3.

Table 3. *Composition and characteristics of the main components of brake lining friction materials*

Components	Materials	Characteristics
Metal particles	Steel	➤ used to increase strength and thermal conductivity, ➤ promotes rapid dissipation of heat generated during braking.
	Copper	➤ increases thermal conductivity and wear resistance, ➤ improves braking performance at hot temperatures, ➤ its use is decreasing due to environmental restrictions.
	Brass and aluminium	➤ used to reduce pad weight and increase corrosion resistance, ➤ improve heat transfer and resistance to deformation during heating.
Organic materials	Cellulose	➤ provides good adhesion and reduces the weight of the material.
	Natural rubber and rubber compounds	➤ added to improve flexibility and reduce braking noise, ➤ contribute to increased wear resistance and durability at cold temperatures.
	Kevlar and other synthetic fibres	➤ used to increase strength and heat resistance, ➤ provide high resistance to abrasive wear.
Ceramic particles	Silicon carbide	➤ increases the wear resistance and heat resistance of the material, ➤ known for its ability to operate at hot temperatures without losing efficiency.
	Aluminium oxide	➤ increases wear resistance and helps dissipate heat, ➤ helps to reduce braking noise.
Resins	Phenolic resins	➤ used as a binder to hold all the components together, ➤ high heat resistance and strength.
	Epoxy resins	➤ used to provide additional strength and chemical resistance, ➤ improve the adhesion between different components of the material.
Fillers and modifiers	Graphite	➤ reduces friction and wear, ➤ helps to avoid squeaks and noises when braking.
	Copper powder	➤ increases thermal conductivity and wear resistance, ➤ improves overall friction characteristics.
	Metal sulphides	➤ used to reduce friction and increase wear resistance, ➤ reduce the possibility of jamming the pads.
Anti-friction additives	Anti-friction additives	➤ reduce wear and friction between the brake disc and brake pad, ➤ improve the overall efficiency and durability of the braking system.

Source: compiled by the author of this study based on D. Chan & G.W. Stachowiak (2004), R. Dante (2015), G. Gautier di Confiengo & M.G. Faga (2022)

The main purpose of using composite materials in brake linings is to achieve the optimum combination of strength, wear resistance, thermal conductivity, noise absorption, and other characteristics that are important for effective braking. Their advantages and disadvantages are presented in Table 4.

Table 4. *Advantages and disadvantages of using composite materials in brake linings*

Advantages	Disadvantages
Stable performance regardless of operating conditions	Higher cost
Less aggressive on brake discs, reducing wear	Greater sensitivity to operating conditions
Higher environmental friendliness compared to asbestos pads, which reduces the impact on the environment and human health	Need for special storage conditions
More effective braking compared to conventional materials	

Source: compiled by the author of this study based on R. Dante (2015)

Notably, current research on the components of friction materials for brake linings is largely concerned with two areas: 1) ceramic-based materials, which use high-purity inorganic compounds and ultrafine synthetic substances as raw materials, which have a high melting point and can maintain good chemical stability at hot temperatures (Li *et al.*, 2021), which allows for stable friction coefficient, good heat resistance, long service life, comfortable braking, no braking noise, etc. Such pads have an exact chemical composition, precision production technology, and excellent structure; 2) ceramic-based materials that use natural fibres that are not harmful to human health. Biomass from agricultural activities is a trendy material to produce brake pads because it is commercially acceptable and environmentally friendly. Banana peels, palm waste, aramid fibres, flax fibres (Arman *et al.*, 2018), cashew shells, coconut shells (Irawan *et al.*, 2022), rice straw, and rice husks (Carlevaris *et al.*, 2023) all contain agricultural waste that can be used as reinforcing material in polymer composites. Natural fibres have many advantages over synthetic fibres due to their low density, abundance, low cost, recyclability, biodegradability, renewability, and relatively high strength and rigidity.

Earlier studies, presented by A.A. Kashkanov *et al.* (2010), mainly focused on the interaction of the brake disc and pad, with special attention to the formation of a tribofilm on the disc surface. This study has identified critical aspects of the braking process but has hardly addressed the characteristics of the brake pad surface itself. Other researchers noted this shortcoming, specifically, M. Eriksson & S. Jacobson (2000). They stressed that the surface of the pad is still relatively unexplored, noting the need for a deeper investigation of this element of the tribosystem.

Subsequent research, such as the study by P. Balaji *et al.* (2024), aims to expand the knowledge of the brake disc and pad tribosystem, including a detailed analysis of the pad surface. V. Jankauskas & D. Kairiūnas (2021) also confirmed the significance of this aspect, focusing on the characteristics of the pad surface and its materials. M. Kchaou *et al.* (2013) indicated that pad surface properties play a crucial role in ensuring stable braking. Additionally, the materials used to make the pad substantially affect its performance, as discussed in T. Singh *et al.* (2016).

U.V. Saindane *et al.* (2020) discussed the prospects for the use of new friction materials for brake pads, focusing on improving their wear resistance, stability of friction characteristics, and environmental safety. Scientists propose the use of alternative materials that can replace conventional metal or asbestos components, which are still widely used but have a series of disadvantages, including negative impacts on health and the environment. According to their research, new composite materials, which can include organic

and inorganic components, such as fibres, nanoparticles, ceramics, help to improve braking efficiency and reduce wear, as well as reduce emissions of harmful particles during operation.

In terms of environmental impact, A.P. Irawan *et al*. (2022) raised the issue of the environmental impacts of brake pad wear. N.M. Kharytonova & V.O. Khrutba (2021) developed a classification of micro-pollutants contained in waters near motorways, where a considerable proportion of pollution comprises polymeric components from brake pads. This highlights the significance of investigating the environmental impact of brake materials.

Special attention is paid to improving brake pad materials. D. Aleksendrić & P. Carlone (2015) propose innovative solutions for the design and manufacture of composite materials that can improve the efficiency and reliability of braking systems. According to K.L. Sundarkrishnaa (2015), composite materials not only improve the performance of brake pads, but also reduce brake dust and noise during braking, which is a compelling argument in favour of their use.

Another area of research is the impact of nanomaterials. K.H. Cho *et al*. (2008) investigated how nanoparticles of various materials can improve the performance of brake pads. The researchers highlighted the potential of nanoparticles in composite materials to improve their friction properties. M. Baklouti *et al*. (2015) analysed the effect of various ingredients in friction material compositions, which also contributed to the efficiency of the braking process.

Thus, research in this area is expanding the understanding of the mechanisms of interaction between brake discs and pads, specifically their surface characteristics and the impact of the latest materials, which opens opportunities for improving the design and efficiency of braking systems.

Using agricultural waste in brake linings can reduce environmental pollution and health risks. However, the use of agricultural waste or natural fibre in the manufacture of brake linings considerably affects the wear rate, friction coefficient, and durability.

Conclusions

A critical review of scientific sources related to the study of the tribological properties of brake pads, their operating modes, friction materials that make up brake linings and emissions of harmful particles into the environment during braking showed certain methodological gaps in this area of research, namely, a lack of definitions, systematisation of information, and a lack of classification of types, designs of pads and materials for the manufacture of brake linings.

To overcome the identified shortcomings, the study systematised and classified the types and design of brake pads and analysed the key characteristics of the main materials used in the manufacture of brake linings for mobile agricultural machinery. It was found that the main criteria for selecting materials for brake pads are wear resistance, temperature resistance, and corrosion resistance. Accordingly, the materials used to produce brake pads must be able to perform under different conditions, have high thermal conductivity, help reduce the wear rate, have a stable coefficient of friction, and be environmentally friendly.

In this study, all brake pads were divided into four types depending on the requirements of particular brakes and vehicles: by purpose; by design features; by friction material composition; and by wear sensors. Each type of brake pad has its advantages and disadvantages, and the choice depends on the concrete operating conditions and performance requirements. By composition, brake pads are classified into semi-metallic, non-asbestos organic, and ceramic

As for modern components of friction materials for brake linings, they were divided into six main groups: metal particles (steel, copper, brass); organic materials (cellulose, natural rubber, rubber compounds, Kevlar, and other synthetic fibres); ceramic particles (silicon carbide, aluminium oxide); resins (phenolic and epoxy); and fillers.

Further research will be related to the development, testing, and application of new components of brake lining friction materials and, accordingly, the expansion of the classification

of types of brake pads and brake lining friction materials.

Acknowledgements

The author of this study would like to express gratitude to the Centre for Collective Use of Scientific Equipment for the Latest Agricultural Technologies "Agroindustrial Complex, Forestry, Gardening and Veterinary Medicine", which operates at the National University of Life and Environmental Sciences of Ukraine.

Conflict of Interest

None.

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Технічний огляд основних типів, конструкцій та матеріалів гальмівних колодок мобільної сільськогосподарської техніки

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Анотація. Гальмівні колодки є критично важливим елементом будь-якої техніки, оскільки вони безпосередньо впливають на безпеку її використання. Відповідно якість гальмівних колодок, їх стійкість та довговічність є ключовими аспектами які обов'язково потрібно враховувати при розробці гальмівних систем мобільної сільськогосподарської техніки. Метою роботи було здійснити огляд наукових джерел пов'язаних з дослідженнями трибологічних властивостей гальмівних колодок, режимів їх функціонування та фрикційних матеріалів, які входять до складу гальмівних накладок. Проаналізовано основні параметри, що впливають на ефективність гальмівних колодок та визначено головні критерії щодо вибору матеріалів для гальмівних колодок мобільної сільськогосподарської техніки, а саме: зносостійкість, температурна стійкість та корозійна стійкість. Відповідно матеріали що застосовуються при виробництві гальмівних колодок для такої техніки мають бути працездатним за будь яких умов, мати високу теплопровідність, сприяти зниженню швидкості зносу, мати стабільний коефіцієнт тертя та бути екологічно стійким. Основну увагу в дослідженні приділено огляду типів та конструкції гальмівних колодок, їх систематизації за різними ознаками (за призначенням; за конструктивними особливостями; за складом фрикційного матеріалу; за наявністю датчиків зносу) та складом (напівметалеві, органічно-безасбестові та керамічні). Проведено опис сучасних компонентів фрикційних матеріалів гальмівних накладок у якому визначено, що вони зазвичай являють собою композитиви утворені шляхом гарячого пресування грубих порошків, що включають багато різних компонентів: сполучну речовину (термореактивні фенольні смоли, часто з додаванням каучуку), конструкційні матеріали (металеві, вуглецеві, скляні та/або кевларові волокна), наповнювачі (слюда та вермікуліт), фрикційні добавки (графіт та різні сульфіди металів). Також в роботі дано оцінку основним характеристикам компонентів фрикційних матеріалів, що застосовуються при виготовлені гальмівних накладок. Результати цього дослідження можуть надати дослідникам і вченим корисну інформацію щодо типів та конструкції гальмівних колодок та основних матеріалів, що застосовуються при виготовлені гальмівних накладок і бути корисними для подальших практичних розробок гальмівних механізмів

Ключові слова: гальмівна система; композитні матеріали; тертя; трибологічні властивості; фрикційні матеріали

НАУКОВІ ДОПОВІДІ НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ БІОРЕСУРСІВ І ПРИРОДОКОРИСТУВАННЯ УКРАЇНИ

Науковий журнал

Том 20, № 4. 2024

Заснований у 2005 р. Виходить 6 разів на рік

Оригінал-макет видання виготовлено у відділі науково-технічної інформації
Національного університету біоресурсів
і природокористування України

Відповідальний редактор:
Г. Івченко

Редагування англомовних текстів:
С. Воровський, К. Касьянов

Комп'ютерна верстка:
К. Пилипенко

Адреса видавництва:
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SCIENTIFIC REPORTS OF THE NATIONAL UNIVERSITY OF LIFE AND ENVIRONMENTAL SCIENCES OF UKRAINE

Scientific Journal

Volume 20, No. 4. 2024

Founded in 2005. Published 6 times a year

The original layout of the publication is made in the Department of Scientific and Technical Information of National University of Life and Environmental Sciences of Ukraine

Managing Editor:
H. Ivchenko

Editing English-Language Texts:
S. Vorovsky, K. Kasianov

Desktop Publishing:
K. Pylypenko

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