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Growth and development of asparagus bean varieties about plant density

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Abstract. The growth, development, and productivity of cowpeas are influenced by soil and climatic conditions, as well as cultivation techniques, particularly the optimal stand density, which requires scientific validation for the conditions of the Right-Bank Forest-Steppe of Ukraine. This research aimed to study the characteristics of growth and development of Vigna about stand density, to optimise the productivity of different varieties. Research methods included field experiments to study cultivation techniques and statistical analysis to evaluate the reliability of the results. The study, conducted between 2014 and 2016, examined the effect of standing density on two cowpea varieties (U-Cha-Kontou and Kafedralna) using four planting schemes (70×10 cm, 70×25 cm, 70×40 cm, 70×50 cm). It was found that standing density significantly affects the growth, development, phenology, and productivity of Vigna. Field germination rates ranged from 80.0% to 85.1% across the variants studied. It was noted that an increase in the sowing rate reduced the field germination of the varieties' seeds. Differences in plant survival rates during the growing season were observed among the varieties. Extreme values of this indicator ranged from 83.6% to 87.8% for the U-Cha-Kontou variety, and from 87.7% to 91.0% for the Kafedralna variety. At a standing density of 29,000-36,000 plants per hectare, the onset of flowering

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in both varieties occurred later (24-27 June). Furthermore, the phases of flowering onset and fruit ripening were observed 2-3 days earlier than the control and the period from emergence to flowering lasted 46-51 days. The U-Cha-Kontou and Kafedralna varieties reached biological maturity on 27 and 22 August, respectively, at a standing density of 29,000-36,000 plants per hectare. The precocious plants were found in denser sowings of 143,000 plants per hectare, where the varieties' growing season lasted 135-141 days. The research findings could be valuable for practical use by vegetable growers, breeders, and specialists interested in vegetable cultivation, storage, and processing

Keywords: sowing schemes; field germination; plant survival rate; growth and development phases; technical maturity; beans

Introduction

The growth and development of cowpeas, as well as other vegetable crops, depend on soil and climatic conditions, which influence the crops' responses. At the same time, the duration of phenological phases and plant productivity are determined not only by soil and climate conditions but also by cultivation techniques. Key technological measures that contribute to optimal plant growth and development, and improved yields, include the selection of an appropriate sowing rate and plant spacing. These factors help create favourable conditions for cultivating asparagus beans.

H. Ishikawa *et al.* (2022) investigated that for leguminous crops such as *Vigna* and soybeans, planting density is particularly important, as once the seedlings emerge, the plants begin to compete with each other. Therefore, to achieve maximum yield, planting density needs to be regulated. D. Gustiningsih *et al.* (2023) described that sowing one seed per planting hole reduces competition between plants, allowing them to grow faster than when sowing more seeds.

Moreover, J.A. Adigun *et al.* (2020) noted that one approach to improving the competitiveness of crops against weeds is to reduce the row spacing. Narrower row spacing suppresses weed germination and growth, giving the crop a competitive advantage primarily through quicker canopy closure. *Vigna* typically develops full canopy cover around six weeks after emergence, allowing them to compete with weeds until maturity.

According to M. Monteiro *et al.* (2017), the larger the plant population, the lower the siliquae productivity per plant. This is attributed to high inter- and intra-plant competition at higher population densities, which leads to flower abortion and a reduction in the number of lateral branches. M.J. Cardoso *et al.* (2018) concluded that the number of siliquae per plant responds linearly to increasing plant density, indicating that for each additional plant per square metre, the number of siliquae per plant decreased by 0.213 for upright varieties, 0.166 for semi-erect varieties, and 0.378 for semi-prostrate varieties.

In the study by T. Nevhulaudzi *et al.* (2020), it was noted that plants in the flowering/early anthesis stage exposed to elevated temperatures (35°C) exhibited the greatest reduction in biomass (47% in fresh weight and 63% in dry weight) compared to plants exposed to the same temperature at other growth stages (42% and 29% in the pre-flowering phase and 1% and 0% in the post-flowering phase). According to H. Bergamaschi & J. Bergonci (2017), increased temperatures are associated with accelerated growth and phenology. As a result, when plants encounter stressful growing conditions, they alter their metabolic processes to ensure optimal growth and development. The rate at which these processes occur is influenced by the plant's stress response, which leads to increased respiration.

L.M. Nderi (2020) determined that for agricultural producers aiming to maximise the

biomass yield of *Vigna*, it is advisable to follow a sowing scheme of 60x20 cm. To achieve maximum grain yield of *Vigna* in Kilifi County, the KVU 27-1 variety is recommended with a 40x20 cm sowing scheme. In the conditions of southeastern Brazil, R.P. Soratto *et al.* (2020) concluded that the highest seed yield of *Vigna* was achieved at a stand density ranging from 216,630 to 290,537 plants per hectare (8-24% higher than the lowest density of 100,000 plants/ha). According to K. Giridhar *et al.* (2020), a sowing scheme of 20x30 cm (166,666 plants/ha) can be selected for growing *Vigna* in the sandy loam soils of Gajapati District, Odisha, as it produced higher grain yields compared to the 10×30 cm (333,333 plants/ha) and 15x30 cm (222,222 plants/ha) schemes.

E.B. Kouam *et al.* (2018) found that the adaptation of varieties can vary significantly across different environments. Breeders aim to develop varieties capable of withstanding adverse environmental conditions by regulating their developmental processes to achieve high yields with improved quality characteristics.

There is a lack of scientifically grounded research on the optimal plant density for asparagus beans. This highlights the need to investigate this issue further and establish a rational plant spacing for the crop. By optimising sowing density, favourable conditions will be created for the progression of all growth and development phases of *Vigna* plants, which will influence the formation of high fruit yields.

The aim was to study the growth and development characteristics of *Vigna* about standing density to optimise the productivity of the varieties.

Materials and Methods

Field studies were conducted from 2014 to 2016 at the collection plots of the educational laboratory "Fruit and Vegetable Garden" at the National University of Life and Environmental Sciences of Ukraine. The soils in the research area are dark grey, medium podzolized, and light loamy, with a slightly acidic soil reaction. The humus horizon has a depth of 24-28 cm. The soil was characterised by a low humus content (1.5-2.2%), average levels of hydrolysed nitrogen (26-38 mg/kg), available phosphorus (43-61 mg/kg), and potassium (28-34 mg/kg). In the years studied, the sum of effective air temperatures (>10°C) during the growing period of the *Vigna* varieties averaged 938-1,114°C, while the total rainfall ranged from 125 to 136 mm.

The study was a two-factor design. The factors examined were: Factor A – the varieties of bush asparagus bean, Kafedralna (Ukraine) and U-Cha-Kontou (China) (control); Factor B – plant density of 143,000 plants/ha (70×10 cm); 57,000 plants/ha (control) (70×25 cm); 36,000 plants/ha (70×40 cm); and 29,000 plants/ha (70×50 cm). The control was established as the 70×25 cm scheme (57,000 plants/ha) with the Chinese variety U-Cha-Kontou, which was obtained from the National Centre for Plant Genetic Resources of Ukraine. Preliminary data indicated that this particular variety stood out among all the original materials of bush-type *Vigna* (Bobos *et al.*, 2023a).

Additionally, an important aspect was establishing the relationship between growth conditions and yield indicators, which allowed for the identification of optimal agronomic parameters for cultivating *Vigna* in the temperate climate of Ukraine. The influence of meteorological conditions on plant development was considered, particularly temperature regimes and precipitation levels, both of which had a significant impact on yield formation. Phenological observations included recording the dates of germination, flowering, and pod maturation, enabling an assessment of the varieties' adaptive capabilities to specific climatic conditions. A separate analysis of pests that most actively affected yield reduction was conducted, leading to the development of recommendations for a pest and disease management system for *Vigna* crops.

The study consisted of three replicates. The total area for observation was 75 m^2, with an individual plot size of 5 m^2. Data were collected from 30 plants, with 10 plants from each replicate (Bondarenko & Yakovenko, 2001). Seeds

of the varieties were sown on 27 April 2014, 27 April 2015, and 27 April 2016 simultaneously. Care for the plants included regular tillage, weed control, and protection against diseases and pests. The experiments involved phenological observations, biometric measurements of the plants, yield assessments, biochemical analyses, and entomological and phytopathological inspections for damage to the crops caused by pests and plant diseases (Bobos *et al.*, 2023b). Harvesting of beans at technical maturity was carried out weekly on all experimental variants. Harvesting of beans at biological maturity was conducted between 20 and 29 September, during which the number, weight, length of pods, and the number of seeds per pod were recorded.

To determine the impact of sowing density on yield, a comparative analysis was conducted using statistical methods, which included the calculation of mean values, variance analysis, and hypothesis testing. Special attention was given to the study of biochemical indicators, such as the protein and carbohydrate content in the seeds, which are important criteria for assessing crop quality. Analysis of variance (ANOVA) was performed using MS Excel with the XLSTAT add-in. Significant differences were considered valid at $\alpha = 0.95$ (Rao, 2018). During the research, adherence to the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) was ensured.

Results and Discussion

During the research, it was established that in the initial phases, the growth and development of the plants occurred simultaneously, regardless of density. The difference in the timing of phenological phases was 1-3 days, which fell within the experimental error margin. A critical factor for obtaining high yields of vegetable crops, including the asparagus bean, is the emergence of uniform seedlings. The field germination of plants was not influenced by plant density in the studied varieties and averaged around 84% (Fig. 1).

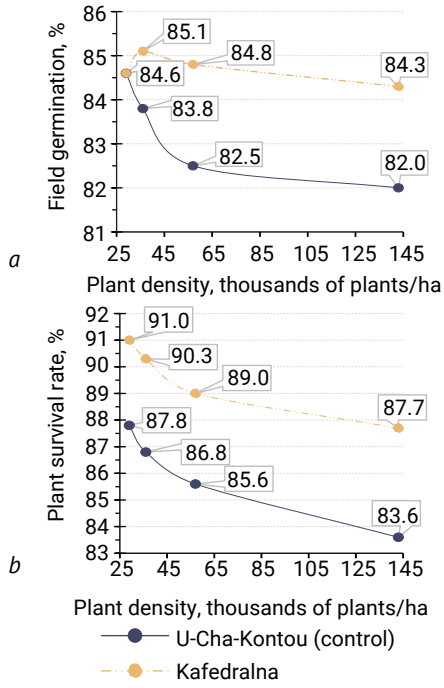

Figure 1. *The impact of plant density on field germination (a) and plant survival rate (b) of cowpeas (average for 2014-2016)*

Source: compiled by the authors

A decrease in field germination for the varieties Kafedralna and U-Cha-Kontou was noted with an increase in sowing rate. Observations of the crops during the growing season revealed that optimal conditions for the growth and development of asparagus beans were found in sparsely sown areas with a plant density of 29,000 plants per hectare. This indicates favourable conditions for the formation of robust plants. At the same time, the percentage of plant survival in the varieties varied depending on plant density. The extremes of the survival rate in U-Cha-Kontou ranged from 83.6% to 87.8%, with a variation range of 4.2%, while for Kafedralna, it ranged from 91.0% to 87.7% (with a variation range of 3.3%). The lower variation in the survival rate of the Kafedralna variety suggests its superior adaptive traits to specific growing conditions. Variability in plant survival during the growing season increased in denser sown areas. Consequently, plants from

the varieties at a density of 143,000 plants per hectare exhibited lower survival rates, with U-Cha-Kontou at 83.6% and Kafedralna at 87.7%.

The research established that plant density influenced the precocity of the crop varieties. When seeds were sown on 30 April, the growing period of the varieties was reduced by six days in denser plantings (143,000 plants/ha) compared to sparse plantings (29,000 plants/ha). A characteristic feature of the asparagus beans is the formation of flowers with long, cream-coloured peduncles (Fig. 2). Flowering depends on plant density. Later flowering was observed in varieties grown in sparsely sown areas with plant densities of 29,000-36,000 plants/ha, occurring between 24-27 June. At the same time, increased planting density accelerated the earliness of the varieties. For example, with higher plant densities, the phases of flowering onset and pod ripening occurred 2-3 days earlier compared to the control. The biological maturity of the beans was influenced by plant density. The onset of biological maturity in the beans was observed earlier in thinned stands. At plant densities of 29,000 and 36,000 plants/ha, the biological maturity of U-Cha-Kontou and Kafedralna varieties began on 27 August and 22 August, respectively, which was 2-5 days later than the control. The prolonged flowering and fruiting periods allowed for multiple harvests throughout the growing season. The duration of the interphase periods varied between cultivars and depended on plant density (Fig. 3). The duration of the period from germination to the beginning of flowering was 46-51 days for both varieties, regardless of plant density. The Kafedralna variety was more precocious in all plant spacing treatments. However, at the lowest plant density (29,000 plants/ha), the duration of this period was shortest, at 44 days, which was 11 days less compared to the U-Cha-Kontou variety.

Figure 2. *Fruit formation of the Kafedralna variety*

Source: authors' photo

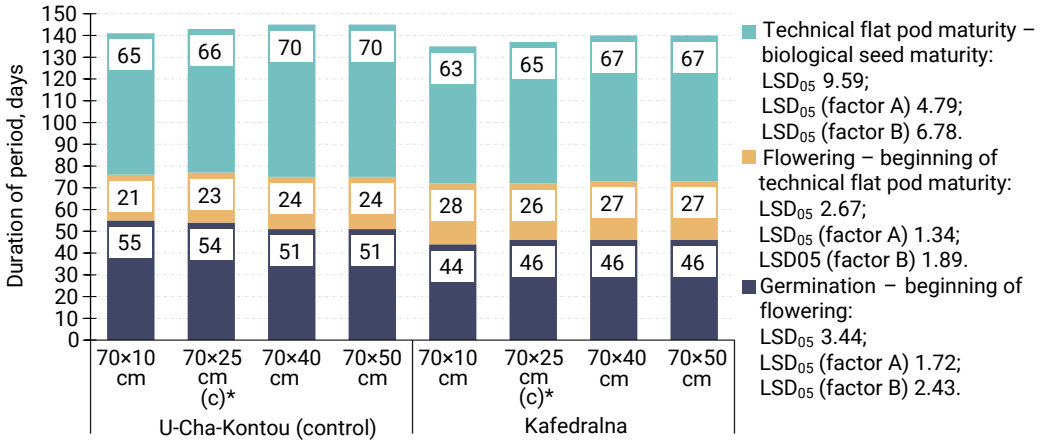

Figure 3. *Influence of plant density on the duration of phenological phases in bush Vigna varieties, days (average for 2014-2016)*

Note: (c)* – control

Source: compiled by the authors

Different plant densities within the crop stand create varied growing conditions, influencing the duration of the growing period. The period from mass germination to the beginning of technical maturity decreased with increasing plant density. This trend was consistent for both the U-Cha-Kontou and Kafedralna varieties, with a growing period lasting 72-76 days. The period from full germination to the onset of technical flat pod maturity was longer in varieties grown at lower densities (29-36 thousand plants/ha), 78 days for U-Cha-Kontou and 73 days for Kafedralna. Increasing plant density shortened the duration from flowering to technical flat pod maturity, a trend linked to high temperatures in July-August, which accelerated the progression of all growth and development phases.

The period from full germination to the onset of biological maturity was influenced by plant density, with a shorter duration observed under the planting scheme of 70×10 cm and a density of 143,000 plants/ha for the Kafedralna variety (135 days). This was attributed to the higher plant density accelerating the onset of all growth and development phases of asparagus bean plants due to the faster warming of the soil surface. Additionally, the Kafedralna variety demonstrated to be more precocious, with all phenological phases progressing more quickly.

The maturation of beans on the plant occurs unevenly, necessitating multiple harvests of the flat pods. A lower plant density of 29-36,000 plants/ha contributed to an extended fruiting period for the beans. Additionally, a longer period from emergence to the biological maturity of the beans was observed in the more sparsely planted U-Cha-Kontou variety, which took 145 days, 4 days longer than the control.

Increased planting density also influenced the length of the growing season for the asparagus bean varieties, reducing it to 135-141 days, which is 2-3 days shorter than the control variant. In contrast, the growing season for the more sparsely planted varieties extended to 140-145 days. At a plant density of 29-36,000 plants/ha, both the technical and biological maturity stages occurred simultaneously in the varieties. For example, these stages for the U-Cha-Kontou variety were 78 and 145 days, respectively, while for the Kafedralna variety, they were 73 and 140 days.

The duration of the interphase periods in asparagus bean varieties was influenced by plant density. The growing conditions in the fields with varying plant densities affected the length of the growing season for the varieties. Increased plant density resulted in a shorter period from germination to technical maturity. A similar pattern was observed in the progression of all growth and development phases in the asparagus bean varieties. The U-Cha-Kontou and Kafedralna varieties exhibited more precociously in denser plantings (143,000 plants/ha), with a shorter growing season of 135-141 days.

The stem length of the U-Cha-Kontou variety varied between 26.5 and 32.9 cm, depending on the planting scheme (Table 1). The greatest stem length was observed with the planting scheme of 70×10 cm at a density of 143,000 plants/ha, while the shortest stem length was recorded with the 70×50 cm scheme at a density of 29,000 plants/ha. On average, over the study years, the Kafedralna variety had a shorter stem length compared to U-Cha-Kontou, ranging from 25.6 to 31.7 cm. The Kafedralna variety also exhibited a clear trend of increased stem length with higher plant densities.

Table 1. *Characteristics of morphological traits of cowpeas under different planting schemes (average for 2014-2016)*

Experimental variants (factor B)	Plant density, thousand plants/ha	Stem length, cm	Number of shoots, pcs	Pod length, cm
U-Cha-Kontou (control)(factor A)				
70 × 10	143	32.9	4.3	26.2

Table 1. *Continued*

Experimental variants (factor B)	Plant density, thousand plants/ha	Stem length, cm	Number of shoots, pcs	Pod length, cm
U-Cha-Kontou (control)(factor A)				
70 × 25 (control)	57	32.2	5.4	24.2
70 × 40	36	27.5	6.5	23.4
70 × 50	29	26.5	6.8	22.7
Kafedralna				
70 × 10	143	31.7	4.6	26.5
70 × 25 (control)	57	30.3	6.1	24.8
70 × 40	36	27.4	7.5	24.3
70 × 50	29	25.6	7.9	23.4
LSD_{05}		1.04	0.18	0.85
factor A		0.52	0.09	0.43
factor B		0.74	0.12	0.60

Source: compiled by the authors

Sparser planting promoted the formation of more shoots on the cowpea plants. For instance, under the planting scheme of 70 × 50 cm with a density of 29,000 plants/ha, the number of shoots was the highest: 6.8 for the U-Cha-Kontou variety and 7.9 for the Kafedralna variety. Similar to stem length, pod length showed a direct correlation with plant density. As the plant density increased from 29,000 to 143,000 plants/ha, pod length increased from 23.4 to 26.5 cm for the Kafedralna variety and from 22.7 to 26.2 cm for the U-Cha-Kontou variety.

Plant density is regulated to achieve maximum yield, as plants compete with one another after germination (Bastos *et al.*, 2020). For the growth and development of leguminous crops such as *Vigna*, seeding density plays a crucial role. According to S.D. Oliveira *et al.* (2015), a larger population of plants results in lower siliquae productivity per plant. This phenomenon can be attributed to high inter- and intra-plant competition at elevated population densities, which leads to flower abortion and a reduction in the number of lateral branches. These findings are consistent with the research conducted by E. François *et al.* (2017), who assert that a spacing of 40 × 40 cm between plants enhances light accessibility, thereby improving photosynthetic processes. Conversely, at higher plant densities, the duration of the growing season is reduced, with leaves predominantly forming lower on the plant, resulting in decreased yield.

The current study established that the duration of interphase periods in asparagus bean varieties was dependent on plant density. An increase in plant density affected the reduction in the duration of the period from germination to the onset of technical maturity. These results corroborate the findings of N.S. Tehulie *et al.* (2021). At the same time, research by T. Nleya *et al.* (2020) conducted on soybeans indicates that a high seeding rate delays flowering and decreases the number of shoots per plant. R.F. Chen *et al.* (2015) determined that the number of seeds sown in a single planting hole directly influences the stand density of plants. This factor is critical for the formation of the optimal feeding area for each plant, which, in turn, affects their development, productivity, and resilience to stress conditions. Excessively dense planting can lead to competition for resources such as light, water, and nutrients, adversely impacting yield.

On the other hand, insufficient density may lead to ineffective resource utilisation and a reduction in overall field productivity. Plant density is regulated not only by the sowing scheme but also by the number of seeds sown per planting hole. N.G. Yalombe *et al.* (2018) assert that sowing one seed per planting hole promotes optimal plant growth and development, thereby increasing yield. Similar claims have been reported by Y.J. Gnamien *et al.* (2023). The lowest plant density of 62,500 plants per hectare (40 cm x 40 cm) with one plant per planting hole resulted in a higher yield compared to the treatment of 250,000 plants per hectare (20 cm × 20 cm) with two plants per planting hole. At the same time, these findings contradict the results of U.S. Yannick *et al.* (2014). The authors state that *Vigna* yield is higher when three seeds are sown per planting hole, which can be attributed to the differing spacing between plants.

Extreme temperatures also influence the growth rates of plants throughout their life cycle. Research conducted by J.L. Hatfield & J.H. Prueger (2015) and D. Schmidt *et al.* (2017) indicates that the reproductive development stage is the most sensitive to extreme temperatures across all plant species. In different regions, sowing density may vary. F.O. Oroka (2017) demonstrated that for *Vigna* varieties with differing morphological structures, it is essential to select varying plant densities to ensure a high yield of pods at technical maturity. Sowing density affects not only yield but also the precocity of varieties, as confirmed by observations in this study. The varieties U-Cha-Kontou and Kafedralna exhibited more precocious in densely sown fields (143,000 plants per hectare) with a shorter growing period of 135-141 days.

D.A. Animasaun *et al.* (2015) and O.A. Osipitan (2017) asserted that the introduction of varieties from other countries and their evaluation for the selection of superior strains is a crucial step in breeding new, desirable plant varieties. Variations among parental genotypes and crossings reflect genetic diversity and the potential for selection. According to the findings of H.E. Zaki & K.S. Radwan (2022), crosses involving the genotypes "Al" and "Com1" enhanced the performance of other varieties, namely "Col", "D331", and "Cr7". The crossings Cr7 x Com1 and D331 x Al were identified as the most promising breeding programmes focused on *Vigna*.

The results of the study indicated that the biological characteristics of the variety, alongside ecological and agronomic factors, influence the dynamics of formation and the intensity of all assimilatory processes in the plant. These factors determine the rate of growth and development, the intensity of photosynthesis, and ultimately the yield. The duration of phenological phases in the growth and development of asparagus bean plants was found to depend on planting density. Increased plant density affected the reduction in the duration from the onset of mass germination to technical maturity throughout the entire growing period of the studied asparagus bean varieties. The shortest plant height and pod length for the cowpeas occurred at a density of 29,000 plants per hectare, while these measurements increased with higher densities. Sparse planting positively influenced the number of shoots produced by the plants.

Conclusions

The planting schemes influenced the precocity of the species. Nevertheless, the varieties of cowpea were characterised as precocious regardless of the planting scheme, which is attributed to the bushy growth form of the stems in these varieties. However, when sowing seeds on 30 April, the growing period for asparagus bean varieties was reduced by six days in dense plantings (143,000 plants per hectare) compared to the lowest plant density (29,000 plants per hectare). The duration of the period from germination to the onset of flowering in the varieties ranged from 46 to 51 days, regardless of plant density. The Kafedralna variety was the most precocious across all planting configurations, with the shortest duration of 44 days observed at the lower plant density (29,000 plants per hectare).

An increase in plant density was associated with a reduction in the duration of the period from the onset of mass germination to technical maturity. This trend was evident for both the U-Cha-Kontou and Kafedralna varieties, which exhibited a growing period of 72 to 76 days. In contrast, the period from full germination to the onset of technical maturity for the varieties was longer under sparse plantings (29,000 to 36,000 plants per hectare), with durations of 78 days for U-Cha-Kontou and 73 days for Kafedralna. Furthermore, an increase in plant density shortened the duration from flowering to the attainment of technical maturity. The U-Cha-Kontou and Kafedralna varieties were more precocious in dense plantings (143,000 plants per hectare), exhibiting a shorter growing period of 135 to 141 days. This pattern is linked to the high temperatures experienced in July and August, which accelerated the progression of all phases of plant growth and development. The Kafedralna variety has proven to be adaptive to growing conditions characterised by a short duration of phenological phases of growth and development. It can be utilised by producers for the harvest of flat pods and in breeding programmes aimed at developing precocious varieties of asparagus beans. However, the promotion of less common legumes in the market is hindered by consumer unfamiliarity with these crops. Therefore, a subsequent priority for research will be to establish mechanisms for their popularisation and subsequent integration into dietary practices.

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Conflict of Interest

None.

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Ріст і розвиток сортів вігни спаржевої залежно від густоти рослин

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Анотація. Ріст, розвиток і продуктивність вігни овочевої залежать від ґрунтово-кліматичних умов та технології вирощування, зокрема, від оптимальної густоти стояння, яка потребує наукового обґрунтування в умовах Правобережного Лісостепу України. Мета досліджень полягала у вивченні особливостей росту та розвитку вігни в залежності від густоти стояння для оптимізації продуктивності сортів. Методи дослідження: польові – для вивчення елементів технології вирощування; статистичні – для оцінки достовірності отриманих результатів. У дослідженні, проведеному в 2014-2016 роках, вивчали вплив густоти стояння на два сорти вігни овочевої («У-тя-Контоу», «Кафедральна») за чотирма схемами вирощування (70×10 см, 70×25 см, 70×40 см, 70×50 см). З'ясувалося, що густота стояння значно впливає на ріст, розвиток, фенологію та продуктивність вігни. Польова схожість коливалась від 80,0 % до 85,1 % у мажах досліджуваних варіантів. Відмічено, що збільшення норми висіву зменшувало польову схожість насіння сортів. Серед сортів спостерігалися відмінності за відсотком збереження рослин протягом вегетаційного періоду. Екстремальні значення цього показника коливалися від 83,6 % до 87,8 % у сорту «У-Тя-Контоу», а у сорту «Кафедральна» – від 87,7 % до 91,0 %. За густоти стояння рослин 29-36 тис. рослин/га початок цвітіння у сортів спостерігався пізніше (24-27.06). Крім того, фази початку цвітіння й дозрівання плодів спостерігався раніше на 2-3 дні порівняно з контролем. Період від початку сходів до цвітіння тривав 46-51 днів. У сортів «У-тя-Контоу» та «Кафедральна» біологічна стиглість спостерігалася 27 та 22 серпня, відповідно, з густотою рослин 29-36 тис. рослин/га. Найбільш скоростиглими виявилися рослини у загущених посівах – 143 тис. шт./га, де тривалість вегетаційного періоду сортів становила 135-141 день. Результати досліджень можуть бути цінними для практичного використання овочівниками, селекціонерами, спеціалістами, що цікавляться питаннями вирощування, зберігання та переробки овочів

Ключові слова: схеми сівби; польова схожість; ступінь виживання рослин; фази росту та розвитку; технічна стиглість; боби

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Development of a simulation model of grain delivery in global supply chains

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Abstract. The main export shipments of grain to Ukraine are carried out through commercial seaports of the Black Sea, while the complex and multiphase transportation process creates delays and leads to additional costs at the points of connection of various types of transport. The purpose of the study was the process of transporting grain cargo for export through commercial seaports. Ukraine is a developed agricultural country that produces a significant share of the world's grain volume, most of which is exported. The optimisation simulation model of multimodal grain cargo transportation developed in the study, in contrast to the existing ones, is a multiphase process with many initial parameters, subsystems, and technological elements that adequately reflect all components of the technological

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process of organising transportation by road, rail, and sea, and helps to optimise these processes. The model consisted of several transport and technological subsystems, each of which corresponded to the process of grain transportation by road, rail, or water. The minimum total duration of cargo transportation from the place of origin to the moment of sending grain cargo for export by sea was chosen as the optimal criterion. To establish the minimum required number of replications and the minimum required model time, a series of experiments were performed, where the key and systematic modelling measurement parameter is the total time of grain delivery by land, from the point of origin to the sea trade terminal. As a result of modelling, the optimal number of rolling stock of different types of transport and the transportation time for each phase of the process were determined. Logistics operators of the agro-industrial sector can apply the model to improve grain delivery routes and schemes, evaluate and improve technological parameters, and minimise transportation time and costs

Keywords: agent-based simulation model; Java SE (Oracle); AnyLogic University Researcher; technological process; minimising delivery time; optimising business process

Introduction

According to official statistics, the Ukrainian agricultural industry, even during the period of large-scale military aggression by the russian federation and the blocking of transport corridors, remains an important player in the world market. A particular problem is the constant blocking of commercial seaports and shipping routes in the Black Sea. According to optimistic data from a number of institutions (the US Department of Agriculture, the Ministry of Agrarian Policy and Food of Ukraine, etc.), Ukraine's exports of grains, legumes, oilseeds and their primary processing products will reach approximately 50-70 million tonnes per year in 2028-2030 (U.S. Department of Agriculture, n.d; Ministry of Agrarian Policy and Food of Ukraine, 2024). This forecast should be highlighted not only in terms of increasing production volumes, but also increasing the carrying capacity of the national transport system within global supply chains. Therefore, the search for new methods of organising grain supplies within such global chains remains relevant.

The problem of cargo transportation in global supply chains is becoming a particularly relevant issue for grain-producing regions and countries. In their study, C. de Faria *et al.* (2024) investigate the reduction of the negative impact of the Brazilian transport system on the environment. The main problem, according to researchers, is the insufficiently efficient planning of complex, multi-element supply chains for export cargo and the low level of use of railway electric transport, which leads to excessive CO_2 emissions. The result of the study is the developed standard technological models for organising grain routes. However, the researchers do not provide forecast data on ensuring the carrying capacity of these shipments.

Other researchers, representatives of Canada E. Sharifi *et al.* (2024) point to the problems of the supply chains of grain exports from Canada, which are mostly associated with severe climatic conditions – long winters – which make most ports unable to operate fully throughout the year, and the significant length of railway routes, most of which are non-electrified, which creates a negative impact on the environment. The researchers proposed a multi-criteria optimisation model based on the Torabi and Hasini fuzzy programming method and minimax rules, aimed at improving the sustainability and efficiency of intermodal supply chains in the context of modern challenges to the Canadian transport system:

the COVID-19 pandemic, increased demand for transportation due to the military aggression of the Russian Federation against Ukraine. However, the paper does not address the issues of increasing throughput in conditions of uncertainty.

V. Matsiuk *et al.* (2023) present the results of experiments with a developed simulation model of the global grain supply chain using a multimodal route. In addition to the standard optimisation criterion – average transportation time – studies were conducted to assess the fault tolerance of transport technologies. As a result, the range of fluctuations in cargo flows is established, at which the transport system provides the necessary level of fault tolerance. However, the model is implemented only for the land part of the supply chain, which does not cover the entire transportation route.

Improving the efficiency of grain transportation is no less relevant for the countries receiving grain crops. This is especially true in regions that lack fresh water for agricultural production. A. Adenle *et al.* (2019) determine the key role of transport in the rapid delivery of mineral fertilisers, machinery, and workers to the places of sowing, harvesting, etc. The problem is that most regions of Africa have a significant shortage of fresh water. Because of this, the regions of agricultural production are constantly changing, which requires significant mobility of production capacities. The paper by V. Aulin *et al.* (2024) presents mathematical models of the functioning of the transport system under conditions of uncertainty. However, the models are quite abstract, which allows obtaining only an approximate assessment of the effectiveness of decision-making.

It is transportation in the global economy that is becoming a direct link between smart technologies of agricultural production, as noted by O. Zagurskiy *et al.* (2024), thereby increasing the overall economic effect by reducing the logistics component in the final cost of products. S. Garg *et al.* (2023) indicate that transportation is the production process of the processing and agricultural industries. Therefore, according to P. Yablonskyi *et al.* (2024), elements of precision farming and global positioning should also apply to transport processes, in particular, docking, loading, and unloading points. I. Rogovskii *et al.* (2024) assess the possibility of implementing precision farming principles in the functioning of transport systems. However, the study does not provide models for making effective decisions.

The purpose of the study was to develop a simulation model of the grain delivery process in global supply chains, which, unlike the existing ones, would allow considering the variability of technological processes and the interaction of road, rail, and water transport on the network. To achieve this goal, the following tasks were completed:

1) an optimisation mathematical (simulation) model of a transport and technological grain delivery line has been developed with substantiation of the optimisation criterion;

2) a set of optimal parameters of the transport and technological grain delivery line in global supply chains has been experimentally established.

Materials and Methods

Optimisation (mathematical) model

The total time of cargo delivery was considered as a system indicator of the functioning of the transport and technological line, since it considers the presence of goods at all stages of transportation – from waiting for rolling stock and free infrastructure, to the time of accumulation to the norm of mass when loading into transport units. Grain delivery in the most productive and rational way, such as multimodal – with the participation of road, rail, and water (sea) transport, is considered.

Then the time of delivery of the cargo from the primary point of accumulation to loading into the sea vessel will be:

$$\overline{t_{del.stnd}} = \overline{t_{del.auto}} + \overline{t_{del.rail}} + \overline{t_{del.ship}}, \quad (1)$$

where $\overline{t_{del.stnd}}$ – average, standard, cargo delivery time, hours; $\overline{t_{del.auto}}$ – average, standard, time of cargo delivery by motor vehicle, hours; $\overline{t_{del.rail}}$ – average, standard, time of cargo delivery by train, hours; $\overline{t_{del.ship}}$ – average, standard, time of cargo delivery by sea, hours.

The organisation of delivery by road was the delivery of grain from the primary points of accumulation and storage of grain to the elevator where the grain route is loaded and served by rail. This process was difficult from the standpoint of the variability of road routes, since it has many points of departure, and, accordingly, many grain delivery routes. The average value of grain delivery time by road largely depended on the characteristics of the entire set of delivery routes in the region of attraction to the point of loading the grain route, the required fleet of vehicles and their cargo capacity, and the time of loading and unloading the vehicle. Then the average value of the duration of grain delivery by road can be represented in implicit terms as a function of the time of accumulation of cargo mass to the loading rate ($f_{accum.auto.}$) and transportation time ($f_{transp.auto.}$):

$$\overline{t_{del.auto}} = f_{accum.auto}(\lambda_{cargo}; N_{v.a.}) + \\ + f_{transp.auto.}(\{M_{a.i} : M_{a.I}\}; N_a; N_{v.a.}; t_{load.a.}; t_{unload.a.}), \quad (2)$$

where λ_{cargo} – intensity of cargo arrival at the storage point before loading into the truck, tonnes/day; $N_{v.a.}$ – average technical load rate of a truck, tonnes; $\{M_{a.i} : M_{a.I}\}$ – a set of parameters that characterise grain delivery routes by road in the region where a railway grain route is created; N_a – required fleet of trucks, units; $t_{load.a.}$ – standard time of loading the car with grain, hours; $t_{unload.a.}$ – standard vehicle unloading time, hours.

The organisation of delivery by rail is the creation of grain shipping routes as those that can technologically provide the shortest delivery time by rail. This process was complicated by the specific features of railway transport regarding the need for allocated capacity, the need for rolling stock and locomotives. The average value of grain delivery time by rail routes in most cases depends on the intensity of cargo receipts for loading wagons, the duration of technological operations at marshalling depots, the time when the train is located at transit technical stations when changing locomotives, and the time for cargo operations at loading and unloading points. The average value of the duration of grain delivery by rail can be represented as the product of the functions of the time of cargo accumulation to the rate of loading into the railway route ($f_{accum.rail.}$) and the time of transportation by grain route ($f_{transp.rail.}$):

$$\overline{t_{del.rail}} = f_{accum.rail}(\lambda_{cargo.rail}; N_{rail.rout.}) + \\ + f_{transp.rail.}\begin{pmatrix}\{M_{rail.i}: M_{rail.I}\}; N_{d.c.rail}; N_{car}; N_{locom}; \\ N_{v.car.}; t_{load.rail.}; t_{unload.rail.}; t_{add.t.rail.}\end{pmatrix}, \quad (3)$$

where $\lambda_{cargo.\ rail}$ – intensity of cargo arrival at the point of accumulation by road before loading into the railway route, tonnes/day; $N_{rail.rout.}$ – technological rate of loading of the railway route, tonnes; $\{M_{rail.i} : M_{rail.I}\}$ – set of parameters that characterise the routes of grain delivery by rail to the commercial seaport; where $N_{d.c.rail}$ – required dedicated capacity for organising ring railway routes, pairs of trains; N_{car} – required fleet of freight cars-grain carriers, units; N_{locom} – required fleet of locomotives for organising grain routes, units; $N_{v.a.}$ – average technical loading rate of a grain carrier car, tonnes; $t_{load.rail.}$ – standard time for loading a railway route with grain, hours; $t_{unload.rail.}$ – standard unloading time of the railway route, hours; $t_{add.t.rail.}$ – additional time for organising the route at the marshalling depots and destination, hours.

For the marine transport subsystem, the key was the process of forming the cargo mass for loading into the ship and the process of servicing ships in commercial seaports. Therefore, the key time was the accumulation of cargo mass to the norm of loading into the bulk carrier and the time of servicing the ship before departure. The very process of following a ship to the destination port is quite linear and largely depends on technological aspects. So the average time of finding the cargo mass in a commercial seaport is the product of two functions – the time of accumulation of cargo to the rate of loading into a sea ship ($f_{accum.sea.}()$) and the time of servicing the ship in the port when loading grain and sending it on a voyage ($f_{transp.sea.}()$):

$$\overline{t_{del.tot.}} = f_{accum.sea.}(\lambda_{cargo.port.}; N_{ship}) + \\ + f_{transp.sea.}\begin{pmatrix}\{M_{port.i}: M_{port.I}\}; N_{sea.port}; N_{ship};\\ t_{load.sea.}; t_{add.t.sea.}\end{pmatrix}, \quad (4)$$

where $\lambda_{cargo.port.}$ – intensity of cargo arrival at the storage point by rail before loading into a sea vessel, tonnes/day; N_{ship} – technological rate of loading of a ship, tonnes; $\{M_{port.i} : M_{port.I}\}$ – set of parameters that characterise grain delivery routes by rail to commercial seaports of cargo destination; $N_{sea.port}$ required dedicated processing capacity in the commercial seaport for servicing ships, vessels/day; $t_{load.sea.}$ – standard loading time of the ship with grain, hours; $t_{add.t.sea.}$ – additional time for servicing the ship in the port, h. Total grain delivery time from production points to destination port:

$$t_{del.stnd} = f_{accum.auto.}(\lambda_{cargo}; N_{v.a.}) + f_{transp.auto.}(\{M_{a.i} : M_{a.I}\}; N_a; N_{v.a.}; t_{load.a.}; t_{unload.a.}) + \\ + f_{accum.train.}(\lambda_{cargo.train.}; N_{train.route.}) + \\ + f_{trans.train}\begin{pmatrix}\{M_{train.i}: M_{train.I}\}; N_{d.c.rail}; N_{car}; N_{locom};\\ N_{v.car.}; t_{load.rail.}; t_{unload.rail.}; t_{add.t.rail.}\end{pmatrix} + \\ + f_{accum.sea.}(\lambda_{cargo.port.}; N_{ship}) + \\ f_{transp.sea.}\begin{pmatrix}\{M_{port.i}: M_{port.I}\}; N_{sea.port}; N_{ship};\\ t_{load.sea.}; t_{add.t.sea.}\end{pmatrix}, \quad (5)$$

and the optimisation task is to minimise this time:

$$t_{del.stnd} \rightarrow min,$$

under restrictions, in accordance with the recommendations proposed by V. Matsiuk *et al.* (2023) and M. Namazov *et al.* (2023):

$$\begin{cases} N_{d.c.rail} \le N_{avail.d.c.route}, \\ N_{sea.port} \le N_{sea.port.grain.} \\ \xi_{p1} \le p(N_a) \le \xi_{b.v.1}, \\ \xi_{p2} \le p(N_{car}) \le \xi_{b.v.2}, \\ \xi_{p3} \le p(N_{locom}) \le \xi_{b.v.3}, \\ \xi_{p4} \le p(N_{ship}) \le \xi_{b.v.4}, \\ \{N_a, N_{car}, N_{locom}, N_{ship}\} = total; \end{cases} \quad (6)$$

where $p(N_a)$, $p(N_{auto})$, $p(N_{train})$, $p(N_{ship})$ – the actual level of use of the fleet of vehicles, respectively, the fleet of motor vehicles, railway cars, ships; ξ_{p1}, ξ_{p2}, ξ_{p3}, ξ_{p4} – lower limit of optimal use of the fleet of vehicles, respectively, the fleet of motor vehicles, railway cars and locomotives, ships; $\xi_{b.v.1}$, $\xi_{b.v.2}$, $\xi_{b.v.3}$, $\xi_{b.v.4}$ – upper limit of optimal use of the fleet of vehicles, respectively, motor vehicles, railway cars and locomotives, ships.

All functions of the optimisation model are presented implicitly, which makes their practical implementation difficult. The most appropriate and convenient way to implement this model was computer simulation.

The model was implemented on the example of grain production in the Poltava Oblast in 2021 and its further transportation for export. The main costs of time and speed of vehicles

were determined following standard norms. All demand flows and demand service intensity were the simplest and therefore subject to exponential distribution and Poisson distribution. An experiment was considered for a traffic volume of 883,560 tonnes per year.

Results and Discussion

Development of a simulation model

The simulation model of the grain delivery process in a mixed road-rail-water connection is a complex, multiphase process with many initial parameters, subsystems, and technological elements.

Modelling of the transport and technological line for grain delivery is the interaction of many transport and technological subsystems of road, rail, and sea transport. Each transport subsystem includes subsystems:

- accumulation and formation of cargo mass required to the vehicle loading rate;
- loading and operations to prepare the vehicle for the flight;
- movement of the corresponding transport unit to its destination or connection with another mode of transport.

Thus, the process of functioning of the transport subsystem can be represented as a typical algorithm (Fig. 1). Block 1 corresponds to the process of cargo arrival at the point of accumulation (temporary storage) at the point of origin or production of grain. Blocks 2 and 3 simulate the cycle of checking the sufficiency of cargo to the norm of loading into the vehicle. Block 4 defines the predefined process of finding a free transport unit and cargo means. This process can also be presented as complex, but standard and driven by a cycle of monitoring the changing situation. This block is the most important in terms of time delays due to inconsistent actions regarding the receipt of cargo, preparation of vehicles for the flight, and the creation of a sufficient number of cargo devices. Block 5 is also a predetermined process of moving a vehicle to its destination or connecting to another mode of transport is predefined, since most of them depend only on the length of the route and the average (route) speed of movement.

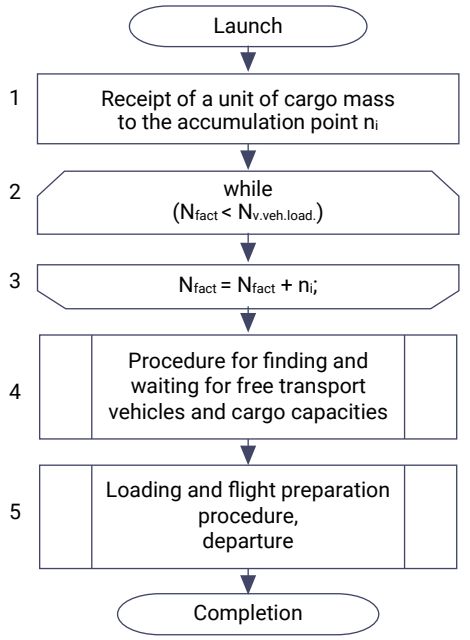

Figure 1. *Algorithm of functioning of the transport subsystem of grain delivery*

Note: n_i – amount of cargo arriving at the point of cargo formation for shipment; N_{fac} – actual volume of cargo available for loading into the vehicle; $N_{v.veh.load.}$ – technical loading standard for a vehicle

Source: compiled by the authors

The next step was to develop a simulation model of the grain delivery process: by road to railway loading stations; by rail grain routes to the port of destination, ship handling in the port, and departure. It is this part of the process that is more inherent in the functioning of Ukrainian transport in terms of ensuring sustainable grain exports in global supply chains. In accordance with the agent-based principle, the following agents are formed (Table 1).

Table 1. *Specification of simulation model agents*

Agent name	Agent function
Automotive line	Modelling of the process of receipt and accumulation of cargo up to the normal weight of loading into a truck. Modelling of the process of managing an existing fleet of trucks. Modelling of the waiting process for free cargo devices and loading points. Modelling of truck traffic in a full cycle of cargo turnover.
Railway line	Modelling of the process of receipt and accumulation of cargo up to the standard weight of loading into a railway route. Modelling of the process of managing the existing fleet of freight cars and locomotives. Modelling of the waiting process for free cargo devices and loading points. Modelling of the movement of grain routes in the full cycle of cargo turnover.
Sea line	Modelling of the process of receipt and accumulation of cargo up to the normal weight of loading into a sea vessel (bulk carrier). Modelling of the process of managing the existing fleet of cargo vessels. Modelling of the process of waiting for free cargo capacities. Modelling of the movement of sea vessels in the full cycle of cargo turnover.
Warrant	Modelling of an information message about the process of cargo mass formation.
Truck fleet	Population of agents of the "truck" type for modelling the quality of use of the existing fleet of road transport vehicles.
Fleet of freight cars (grain carriers) and locomotives for organising grain routes	Population of agents of the "railway route" type to model the quality of use of the existing fleet of railway vehicles.
Fleet of cargo vessels (bulk carriers)	Population of agents of the "bulk carriers" type for modelling the quality of use of the existing fleet of marine vehicles.
Grain departure points	Population of agents of the "point of departure" type for modelling the routes of departure of vehicles with grain during the initial accumulation of grain.
Railway station	"Railway station" type agent for modelling the organisation of railway routes.
Seaport	"Seaport" type agent for modelling the organisation of a loaded grain vessel.

Source: compiled by the authors

The interaction of these agents allowed modelling different grain delivery scenarios, considering potential delays and resource optimisation. The model helped to analyse the efficiency of each stage of transportation and identify critical points that can reduce the overall performance of supply chains.

Configuring the Main agent

The agent which ensures the interaction of all other agents with each other is the Main agent. This procedure is determined by the standard project development procedure in the Java SE development environment (Oracle, USA). The main element of the Main agent is the space marking element – GIS map, which allows developing the processes of agent movement along the labels of existing railway, road, and sea transport maps. In addition, the Main agent includes all key parameters of the transport and technological line in the form of hyperlinks of the Parameters type:

- truckNumber_Polt – accepted number of vehicles involved in the transportation process, units;
- truckCapacity – accepted technical standard for vehicle loading (cargo capacity), tonnes;

➤ truckSpeed – average (route) speed of trucks, km/h;

➤ railNumber – accepted number of railway routes (railway cars with locomotives), units;

➤ railCapacity – accepted technical standard for loading (net tonnes) of a railway route, tonnes;

➤ railSpeed – route speed of railway routes, km/h;

➤ shipNumber – accepted number of sea ships, units;

➤ shipCapacity – accepted net deadweight, tonnes;

➤ shipSpeed – average (route) speed of the ship, km/h.

In addition to the presentation of the model itself, agent Main displays diagrams of statistical modelling results: delivery time and the required capacity of grain transshipment points.

Setting up the population of agents "Grain departure points"

The population of "Grain departure points" agents is initial when modelling the grain delivery process and simulates the initial accumulation of grain to the size of loading into the machine. The process itself is an ordinary discrete-event process, consisting of only two elements: the source requirements generator and the end of the sink grain receipt process (Fig. 2). The requirements generator produces a simpler (exponential) flow of requirements with a set (available) average intensity λ_{grain} with the density of the probability distribution:

$$\begin{cases} \lambda_{grain} e^{-\lambda_{grain} x}, & x > 0, \\ 0, & x < 0, \end{cases} \qquad (7)$$

where λ_{grain} – average flow rate of grain requirements to the point of primary accumulation before loading into cars, tonnes/year. Each requirement generated by the source block represents one ton of grain. When a requirement for the sink element is received, an algorithm is implemented for generating an information request (Order population agent) for loading a batch of cargo ready for shipment into one truck (Fig. 3).

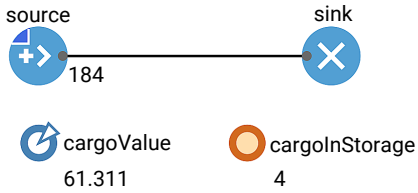

Figure 2. *Discrete-event process of agent population "Grain departure points"*

Source: compiled by the authors

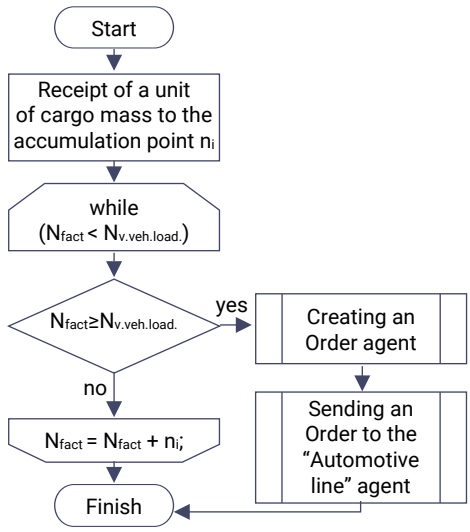

Figure 3. *Algorithm for forming a population agent Order*

Source: compiled by the authors

The algorithm shown in Figure 3 is implemented with each request received using Java code:

```
cargoInStorage++;
if (cargoInStorage >= main.truckCapacity){
Order newOrder = new Order ( this );
send ( newOrder, main.store_Poltava );
cargoInStorage -= main.truckCapacity;
}
```

Each agent of the population "Grain departure points" simulates the process independently

of the others, thus simulating the accumulation and formation of shipments for each of the grain departure points in the selected region.

Setting up agents "Automobile line", "Railway line" and "Sea line"

Agents "Automobile line", "Railway line", and "Sea line", according to their functional purpose, intended to simulate the turnover of the corresponding vehicles when organising the transportation of a batch of goods. The process of grain transportation begins with the accumulation of grain to the required loading rate in a truck (population of agents "Grain departure points"). After receiving an information message about a sufficient amount of cargo at a certain point of departure, this message is transmitted to the Enter block of the "Automobile line" agent. Next, the information message is sent to the seize element, where a free resource is captured – a vehicle from the Truck element. In the absence of a free vehicle, the requirement for grain transportation remains pending.

If there is a free car, the full cargo turnover is simulated on the route from the point of origin of the cargo mass to the point of transshipment to the railway car:

- moveTo block – simulation of empty mileage from the place of permanent deployment to the place of loading the car;
- delay block – simulates the time spent loading the car;
- moveTo block – simulation of a cargo flight of a car to the point of reloading into a car;
- delay1 block – simulates the time spent on unloading the car.

After simulating unloading, the vehicle moves to the truck block and then presents a free resource for use. Thus, this approach makes it possible to simulate a full cycle of technological operations related to a single cargo transportation.

At the same time, the delay1 (unloading) block implements an algorithm for forming the cargo mass for the possibility of loading into railway cars (Fig. 4).

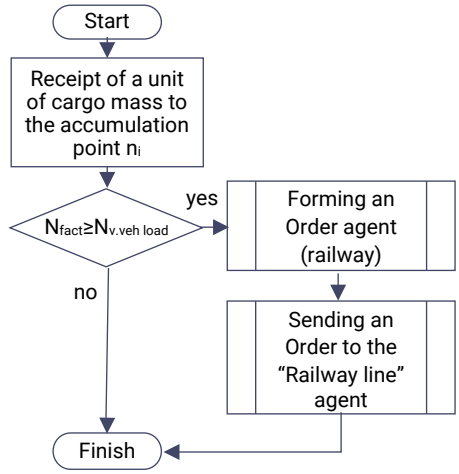

Figure 4. *Algorithm for forming a cargo mass for loading into a railway shipping route*

Source: compiled by the authors

The algorithm shown in Figure 4 is implemented using Java code:

```
"inStorage += main.truckCapacity;
if(inStorage >= main.railCapacity){
main.railLine.source.inject(1);
inStorage -= main.railCapacity;
}"
```

The end result of executing this code is that when the volume of cargo required for loading the sending route is accumulated, an information message is created in the railway line agent. The procedure for simulating the turnover of a railway departure route and servicing a sea vessel (bulk carrier) in the port is essentially similar to the agent "Automobile line". All technological operations in these agents – movement, loading, unloading, etc. – can be simulated as discrete or continuous values.

The presented approach simulates centralised management of the vehicle fleet on the cargo delivery network. This approach is especially relevant for the organisation of distribution logistics by road, where there are many points of origin of cargo and grain consolidation warehouses.

In addition, it is also advisable to apply this approach for railway transport, since there may also be several stations for creating grain routes that will act as route bases within the same transport and technological line.

Even with an extended simulation of grain exports from Ukraine, there may be a problem in using several alternative sea grain terminals in different ports at once, which will also allow simulating an extensive network.

Ensuring the reliability of modelling results

The modelling process in the developed simulation model is stochastic and is based on the model runtime. For such models, the simulation result in most cases depends on the duration of the model time and the total number of replications of experiments. This method is valid only when the simulation result, as a random variable, is subject to a normal distribution (Matsiuk *et al.*, 2023; Namazov *et al.*, 2023).

Therefore, to establish the minimum required number of replications and the minimum required model time, a series of experiments was performed, where the key and system parameter of the simulation measurement is the total time of grain delivery on land, from the point of origin of cargo to the sea trade terminal. First of all, the sample of the general set of experimental data is tested for the hypothesis of approximation by a normal law.

Thus, even with a model time of 3 months, a single replication is sufficient to provide 95% confidence (Table 2).

Simulation results

As a result of experiments for the volume of traffic in 883,560 tonnes per year, the following results were obtained:

- optimal fleet of motor vehicles: 50 units with an average load of 63%;
- optimal fleet of railway routes: five units with an average load of 57%.

Average delivery time of a batch of goods:

- by car: 6.5 hours with a standard deviation of 0.323 hours (Fig. 5a);
- by rail: 82,996 hours with a standard deviation of 7,057 hours (Fig. 5b).

Table 2. *Results of estimating the mathematical expectation and standard deviation of samples*

Duration of model time		1 month	3 months	6 months	12 months	30 months
Confidence interval	Left limit of conf. interval	91.877	91.883	91.885	91.887	91.890
	M(x)	91.891	91.891	91.891	91.891	91.891
	Right limit of conf. interval	91.906	91.900	91.898	91.896	91.893
Number of replications	Calculated value	2.47	0.87	0.50	0.22	0.11
	Limit integer value	3	1	1	1	1

Source: compiled by the authors

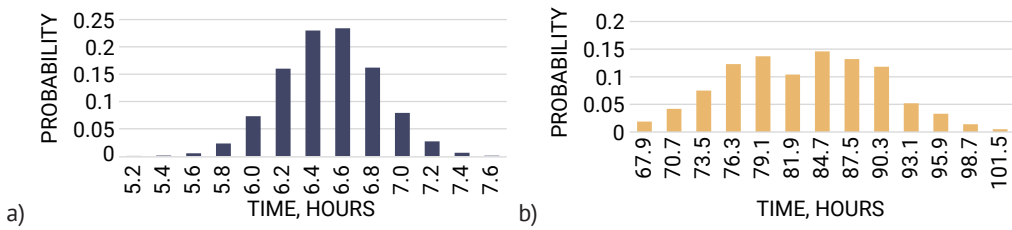

Figure 5. *Densities of the probability distribution of the time of stay of the cargo shipment*

Note: a) in the road transport subsystem; b) in the railway transport subsystem

Source: compiled by the authors

Maximum cargo volume observed in the transit grain elevator:

- at the railway station 4000 tonnes;
- there are 52,000 tonnes in the commercial seaport.

The presented simulation model optimises the total transportation time (5), (6) in a complex grain supply chain on the network of cargo flow origination. Through the use of GIS technologies, an agent-based and discrete-event approach in one common process, delivery times in road, rail, and water transport and technology systems are optimised (Fig. 2-4).

The model is implemented as interaction at docking points – grain cargo terminals – of individual technological processes of vehicle turnover on the grain cargo flow service network.

The model is developed using agent-based and discrete-based principles in the AnyLogic University Researcher simulation model development environment. Since AnyLogic University Researcher does not provide standard tools for some processes, namely managing oncoming vehicle flows, this subprocess was implemented via Java algorithms (Fig. 3, 4).

The simulation involves the interaction of ten populations of agents and individual agents with each other (Table 1). All agents can be divided into three parts:

1) rolling stock parks;

2) infrastructure facilities and communication routes;

3) informational messages about cargo shipments.

This approach, in contrast to the research by N. Shramenko & V. Shamenko (2020) allowed applying a systematic approach and evaluating the entire transportation process at once by one aggregate criterion – the average cargo delivery time, in accordance with the objective function of the optimisation model (5) and its constraints (6).

The obtained average time and the density of its distribution by transport subsystems (Fig. 5) are normal, which indicates the "naturalness" and reliability of the technological process. In contrast to the studies by V. Blazek *et al.* (2024), the developed approach allowed applying multi-criteria optimisation. The main optimisation criterion is the average delivery time. In addition, the vehicle fleets themselves have optimal use. This approach is not often implemented, as evidenced by the review by T. Pereglin & R. Stankovic (2023).

A significant number of specialists see the solution to security and efficiency issues in the use of modern information technologies. Thus, at the design stage of transport processes, N. Shramenko & V. Shamenko (2019) offer mathematical models that optimise the parameters of the entire supply chain based on the time criterion. However, the researchers do not point out the possibility of optimal loading of the vehicle fleet and do not fully use probabilistic distributions of the time of technological operations, such as loading, unloading or time in motion of the vehicle. The same situation is observed in another study, where N. Shramenko & V. Shamenko (2020) offer a simulation model of the intermodal transport supply chain. This study also uses only one criterion for finding optimal solutions.

V. Butkovsky & O. Ilina (2023) consider the problems of grain storage not only during storage, but also during transportation. Researchers limit humidity standards and optimise the volume of cargo according to the criterion of safety during transportation. However, the researchers do not focus on the specifics of delivery by different modes of transport, which complicates the decision-making process for organising specific transportation.

Many researchers continue to present transport processes as multi-channel queuing systems, but it is computer modelling of transport processes and systems that is becoming increasingly widespread. This technology opens up very great opportunities for modelling transport processes and systems. A. Gupta *et al.* (2023) prove the possibility of using a systematic approach, multi-element, multi-factorial, and multi-criteria in the study of transport processes, therefore, it

is computer modelling of multiphase and complex processes that is most appropriate when studying the problems of the presented study. A similar conclusion can be drawn from the study by M. Ďuriška *et al.* (2024), which presents a multi-factor simulation model developed using the agent-based principle. The presented models have a large abstraction, which cannot provide the proper level of reliability and adequacy.

The proposed simulation model can use the average level of CO_2 emissions over the entire complex transportation route as an optimisation criterion. In the study of this problem, M. Kumari *et al.* (2023) optimise supply chains based on the average CO_2 emissions per unit of transportation work. The researchers introduce such a concept as an integrated approach to supply chain optimisation solutions. Optimisation is carried out by developing mathematical models and conducting a series of experiments on the model sensitivity. The researchers claim significant economic effects from minimising CO_2 emissions, but do not provide specific measures of cost-effectiveness. C. de Faria *et al.* (2024) in their study cite the results of the creation of a national network of interval grain supply chains in Brazil. This situation partially coincides with the realities of the Ukrainian transport system, since road, rail, and sea transport are involved in the transportation of mass volumes of grain. The researchers cite the results of estimating the total CO_2 emission during grain transportation and propose an approach to sustainable development of the national transport system, which provides for reducing CO_2 emissions by 66.8 thousand tonnes per year. The solution is based on optimising the network of grain cargo mass accumulation points and maximising the use of electric railway transport.

In addition, an important achievement compared to other similar studies, A. Adenle *et al.* (2019) determine the importance of a systematic approach in evaluating the efficiency of any production. Using the example of agricultural business, researchers determine the key role of transport as a narrowing link in the supply of raw materials and final products. However, the paper does not provide specific decision-making tools.

During the entire modelling period, the maximum capacity of track development of railway stations should accommodate and organise one train (net weight 4,000 tonnes), the terminal capacity in a commercial seaport is 52,000 tonnes.

The model does not consider the actual degree of use of port land routes and the seasonal unevenness of grain cargo formation. In addition, the model does not implement possible failures and stops due to possible technical malfunctions of vehicles and transport infrastructure. The further development of the presented research can be the creation of automated systems in the management of the transportation process, and consideration of the above.

Conclusions

The paper formalises the process of grain delivery in global supply chains by means of an optimisation mathematical model in the form of an objective function that formalises the average time of cargo delivery in a complex, multi-phase, intermodal grain supply chain involving: a road network for the supply of grain mass and its primary accumulation at points of connection with railway transport; a railway transport network with the organisation of railway shipping routes; the maritime transport network and the accumulation of cargo at the grain terminal to the loading rate for a sea vessel. Restrictions on the model provide for an optimal level of vehicle usage. The model is presented as a multi-criteria optimisation mathematical model.

Since most of the optimisation model functions are represented in an implicit expression, the model is implemented as a computer simulation. The simulation model is developed using agent-based and discrete-event principles with developed additional functions (Java, Oracle) for managing oncoming vehicle flows. The simulation model is implemented as a set of technological processes of vehicle turnover with their

interaction at docking points – cargo terminals. This principle provided a systematic approach in estimating the average delivery time of a unit of cargo mass, ensured optimal use of the fleet of vehicles, and assessed the actual loading of planned cargo flows to the transport and warehouse infrastructure of the transport and technological line.

As a result of the implementation of the simulation model and conducting a series of experiments on the example of the grain supply chain from the Poltava Oblast (in the amount of 883,560 tonnes), optimal fleets of cars (load factor 63%), railway shipping routes (load factor 57%) were determined. The average time for grain delivery by land was 6.5 hours (by road subsystem) and 83 hours (by rail subsystem). The density of delivery time distribution within each transport and technological line is normal, which indicates the naturalness and optimality of the calculated technological parameters. A separate result of experiments is the determination of the actual volume of cargo mass simultaneously located at cargo terminals. This approach helped to establish the required capacity of grain elevators at the primary level of cargo mass formation (automobile – railway connection points) and the second level of cargo mass formation (commercial seaports).

A further area of research on the presented issues may be the substantiation and development of effective automated control systems for the grain transportation process in multimodal traffic.

Acknowledgements

None.

Conflict of Interest

None.

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Розробка імітаційної моделі доставки зернових у глобальних ланцюгах постачання

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Анотація. Основні експортні відправлення зернових в Україні здійснюються через морські торговельні порти Чорного моря, при цьому складний і багатофазний процес транспортування створює затримки та призводить до додаткових витрат у пунктах стикування різних видів транспорту. Метою дослідження був процес транспортування зернових вантажів на експорт через морські торговельні порти. Україна є розвинутою аграрною країною, що забезпечує виробництво значної частки світового обсягу зернових, більша частина яких спрямовується на експорт. Розроблена в роботі оптимізаційна імітаційна модель мультимодального перевезення зернових вантажів, на відміну від існуючих, являє собою багатофазний процес із множиною вихідних параметрів, підсистем та технологічних елементів, що адекватно відображають всі складові технологічного процесу організації перевезення автомобільним, залізничним та морським транспортом, та дає можливість оптимізувати ці процеси. Модель складалася з декількох транспортно-технологічних підсистем, кожна з яких відповідала процесу транспортування зернових автомобільним, залізничним або водним транспортом. В якості критерію оптимальності обрано мінімум загальної тривалості перевезення вантажу від місця зародження до моменту відправки зернового вантажу на експорт морським транспортом. Для встановлення мінімально-необхідної кількості реплікацій та мінімально-необхідного модельного часу, виконана серія експериментів, де ключовим та системним параметром заміру моделювання виступає загальний час доставки зерна по суходолу, від пункту зародження вантажу до морського торговельного терміналу. В результаті моделювання встановлено оптимальну кількість рухомого складу різних видів транспорту та час перевезення по кожній фазі процесу. Логістичні оператори агропромислового сектору можуть застосувати модель для вдосконалення маршрутів і схем доставки зернових, оцінки та вдосконалення технологічних параметрів, мінімізації часу та витрат на транспортування

Ключові слова: агентна імітаційна модель; Java SE (Oracle); AnyLogic University Researcher; технологічний процес; мінімізація часу доставки; оптимізація бізнес процесу

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Blood lipid profile in rats with tetracycline-induced liver damage

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Abstract. Drug-induced liver injury leads to significant morbidity and mortality due to the development of severe complications, making it a leading cause of acute liver failure in animals. Among medications with direct cytotoxic effects on liver cells, tetracycline antibiotics are notable, as improper use can induce fatty liver disease. This study aimed to examine changes in the blood lipid profile of laboratory rats with tetracycline-induced liver damage, alongside assessing the corrective potential of milk phospholipids. The lipid composition of native blood was analysed using thin-layer chromatography. The findings indicate that, in cases of artificially induced tetracycline liver damage in rats, there was a deficit in all five indicators of the native blood lipid profile, including a 30.8% reduction in total lipids, a 45.3% decrease in triacylglycerols, a 37.0% decline in phospholipids, a 46.2% drop in free fatty acids, a 23.1% decrease in free cholesterol, and a 32.0% reduction in esterified cholesterol, compared to the control. This may be attributed to diminished appetite in affected animals, insufficient lipid absorption in the digestive tract, and the inhibition of endogenous lipid synthesis in the livers of affected rats. The administration of milk phospholipids as the dietary supplement "FLP-MD" to diseased animals demonstrated a pronounced corrective effect, manifested by the restoration of quantitative parameters across all studied lipid fractions and their overall content. Oral administration of this supplement to clinically healthy rats showed no toxic impact on liver cells or the organism as a whole. Additionally, a tendency towards an increase in the absolute content of most examined blood lipid fractions was observed. Thus, this experimental study revealed

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marker changes in the quantitative parameters of the native blood of the laboratory rats, lipid profile, which may be valuable in understanding the pathogenesis of tetracycline-induced injury in mammals and testing newly developed hepatoprotective agents

Keywords: corrective therapy; milk phospholipids; fatty liver disease; thin-layer chromatography; lipid fractions

Introduction

The liver plays a crucial role in regulating lipid metabolism, and any impairment of its functions leads to significant alterations in the lipid profile, which may serve as an early marker of toxicity. Studying the blood lipid profile in cases of tetracycline-induced liver damage provides a means to assess the extent of metabolic disturbances and aids in understanding the mechanisms underlying the development of fatty liver disease. This is vital not only for the diagnosis and monitoring of liver health but also for developing therapeutic approaches aimed at preventing and treating liver failure induced by toxic drug doses.

N. Stefan *et al.* (2019) emphasised that metabolic disorders in mammals lead to fatty liver disease, triggering numerous structural and functional disturbances, which subsequently progress to fibrosis, cirrhosis, and liver cancer. As well, K. Mohammadhasani *et al.* (2024) suggested that the pathogenic mechanisms underlying fatty liver degeneration are associated with various pathological factors, including drug-induced damage, cardiovascular conditions, extrahepatic complications, and diabetes. Implementing a regimen of active physical exercise, along with hypolipidaemic agents and insulin sensitisers, is considered, as noted by S. Pouwels *et al.* (2022), to be a potential therapeutic strategy for patients with fatty liver disease. However, these treatments demonstrate limited efficacy and are often accompanied by adverse effects. Consequently, there is a pressing need to develop new therapeutic approaches that minimise toxic effects on living organisms.

F. Zhang *et al.* (2022) identified that liver metabolites of a lipid nature, such as sphingomyelin and glycerophospholipid, exert a corrective effect in cases of toxic liver injury by regulating fatty acid synthesis, correcting lipid metabolism disorders, and reducing inflammatory responses. Furthermore, it was found that structural lipids within cell membranes help maintain stability in lipid metabolism, disruptions of which can lead to the development of fatty liver disease. The authors highlighted various types of membrane lipids, including their metabolites – phospholipids, cholesterol, and sphingolipids – whose dysregulation was implicated in the onset of fatty liver disease. Through the use of new drug-based artificial models involving laboratory animals, the role of certain lipid classes in the pathogenic mechanisms underlying hepatopathology, particularly fatty liver degeneration, has been demonstrated, confirming their potential use in treating fatty liver disease. As noted by X. Gao *et al.* (2024), most conventional therapies target pathways of lipid accumulation within liver cells, as well as inflammation and hepatocyte damage, which are typically consequences of metabolic stress in the context of steatosis. This highlights that fundamental research on pharmaceutical support for patients with fatty liver disease predominantly focuses on cellular mechanisms responsible for these pathophysiological outcomes in mammals.

T. Harayama & N. Riezman (2018) found that a primary disturbance in the development of fatty liver disease is the dysregulation of lipid metabolism, leading to intense deposition of cholesterol and fatty acids within hepatocytes, a phenomenon known as hepatic lipotoxicity. Lipid-based substances play a central role in maintaining numerous cellular functions and are considered essential structural components

of biomembranes. The researchers highlighted key lipid classes found in the cell membranes of eukaryotes: phospholipids, sterol lipids, sphingolipids, and cholesterol. In animals, phospholipid molecules contain one hydrophilic group and two hydrophobic acyl chains, with ceramides acting as primary precursors in sphingolipid formation, while cholesterol possesses a steroid backbone and serves as an important sterol component of cell membranes. H. Duan *et al.* (2024) noted that carbohydrates form complex compounds with proteins and lipids, resulting in glycoproteins and glycolipids, respectively. Membrane lipids are also critical in maintaining lipid homeostasis, energy storage, cell signalling, and providing a supportive environment for protein function. Additionally, L.Y. Swindale *et al.* (2023) emphasised the unique structural and functional characteristics of biomembranes, stemming from their distinct lipid organisation. Further research is needed to clarify the responses of various structural lipids during the progression of pathological processes, including fatty liver disease.

V.A. Gryshchenko *et al.* (2019) indicated that the liver plays a central role in lipid metabolism within mammalian organisms. Alongside hepatocytes, the primary functional cells, other liver cells, including hepatic stellate cells, cholangiocytes, and Kupffer cells, also contribute to maintaining homeostasis in animals, especially under conditions of liver pathology. These cells all eventually sustain damage due to fatty infiltration and lipotoxicity in the liver. Numerous experimental and clinical studies have shown that fatty liver degeneration arises in response to alterations in the intracellular lipid composition of the liver. Additionally, most studies, including those in pharmacology and genetics, underscore the importance of triacylglycerol accumulation as a key factor in the development of fatty liver disease. Given the complexity of its pathogenesis, the accumulation of triacylglycerols alone is insufficient for the development of this hepatopathy. Therefore, the authors highlighted the need for a novel research approach in lipid studies to determine the roles of specific lipid classes, including cholesterol, phospholipids, and sphingolipids, in the progression of fatty liver disease. For example, research by M. Jiang *et al.* (2019) demonstrates that obesity affects ceramide levels in the liver parenchyma, resulting in insulin resistance, steatosis, and hepatocyte necrosis.

The study by J.N. van der Veen *et al.* (2017) indicated that phosphatidylcholine (PC) and phosphatidylethanolamine (PE) are among the most prevalent phospholipids in mammalian cells, primarily localised within membrane structures. The stability of the cell plasma membrane is maintained by preserving the balance between PC and PE. Consequently, any disturbance in membrane composition increases the susceptibility of hepatocyte plasma membranes to various pathological damages, including toxic lipid radicals, activators, and immune messengers, which can lead to inflammation, fatty liver disease, and cell necrosis. As noted by R.G. Joergensen (2022), substantial evidence supports the critical role of phospholipids in preventing and potentially reversing fatty liver disease. Thus, phospholipid-based therapies with hepatoprotective and reparative properties have become increasingly relevant in treating fatty liver degeneration, showing high efficacy in clinical applications. The aim of this study was, therefore, to assess the effect of milk phospholipids on the lipid composition of native blood in rats while simultaneously artificially inducing fatty liver disease using tetracycline hydrochloride as a provoking factor.

Materials and Methods

Laboratory studies were conducted in 2023 using the scientific facilities of the Faculty of Veterinary Medicine at the National University of Life and Environmental Sciences of Ukraine (Kyiv) and the Educational and Scientific Institute of High Technologies at Taras Shevchenko National University (Kyiv). The experimental work was carried out at the vivarium of the Educational and Scientific Institute of High Technologies at Taras Shevchenko National University (Kyiv), which is equipped with plumbing, drainage, ventilation, and air

conditioning. Regular cleaning with disinfectants was performed in the vivarium. Laboratory rats were housed in cages with wood shavings as bedding, which were replaced every two days.

Laboratory white rats weighing 200-250 g were used for the experiment. Consequently, four groups were formed (three experimental groups and one control group), each consisting of eight individuals. Each group of animals was housed in separate cages with free access to water and food. Prior to the commencement of the experiment, the animals were quarantined, during which their clinical condition was monitored. Throughout the experiment, observations were made regarding the amount of water consumed, appetite, and changes in body weight among the animals in all groups. The experimental studies were conducted over a period of nine days.

The conduct of scientific research involving laboratory animals adhered to the European Convention for the Protection of Vertebrate Animals Used for Research and Other Scientific Purposes (1986) and Law of Ukraine No. 3447-IV (2006). All planned procedures on the laboratory rats were performed following the ARRIVE guidelines and the fundamental principles of Council Directive 2010/63/EU (2010).

In the two experimental groups of rats ("Self-rehabilitation" and "Correction"), hepatosis was experimentally modelled using the antibacterial agent tetracycline hydrochloride, administered orally at a dose of 250 mg/kg of body weight as a solution once daily for 7 days (Gryshchenko *et al*., 2019). Notably, the rats in the first experimental group ("Self-rehabilitation") did not receive any treatment, whereas the laboratory animals in the second experimental group ("Correction") were given a 1% solution of milk phospholipids in the form of liposomes (the dietary supplement (DS) "FLP-MD") at a dosage of 13.5 mg/kg of body weight for 9 days. The third experimental group ("Healthy animals + DS "FLP-MD") consisted of clinically healthy rats that were administered the DS "FLP-MD" at the same dosage for 9 days. The control group comprised intact rats that were provided with an equivalent volume of distilled water. Each group included 8 animals.

On the 10th day, blood samples were obtained from rats in all groups for subsequent analysis of their lipid composition. Blood sampling was conducted under ether anaesthesia from the abdominal aorta. The lipid profile of the native blood was determined using thin-layer chromatography according to the methodology (Kostenko *et al*., 2001).

Lipid extraction from the plasma was performed using a one-phase system of organic solvents in the following ratio: chloroform:acetone:ethanol (7:2:1). The amount of extracting solvent was taken in a ratio of 20:1 to the sample. In a test tube, 1 mL of the specified solvent was added to the crushed chromatographic paper containing the blood samples, which was then left for 15 minutes in a shuttle apparatus. The resulting liquid was collected into a beaker, and an additional 0.5 cm^3 of the extracting liquid was added twice, with a 5-minute interval, in the shuttle apparatus. The obtained extract, containing the blood lipids, was subjected to analysis after the solvent had been evaporated.

The chromatographic separation of total lipids from native blood was conducted on thin-layer plates "Silufol" (15×15 cm), which were pre-activated in a thermostat at 110°C for one hour. During this time, filter paper was placed in the chromatographic chamber to enhance saturation, and a mixture of solvents – hexane:diethyl ether:acetic acid (7:23:1) – was added. The dry lipid residue was dissolved in chloroform:benzene:acetone mixture (1:2:1) in volumes ranging from 20 to 100 µL and then applied to the premarked chromatogram.

Over a period of 10-15 minutes, the blood lipids were separated on the plate into fractions: cholesterol esters, free cholesterol, triacylglycerols, free fatty acids, and phospholipids. The solvent was removed from the chromatogram in a fume hood. Subsequently, the chromatogram was stained with a 10% solution of phosphomolybdic acid in ethanol using a glass laboratory sprayer.

To visualise the lipid fractions, the stained chromatogram was placed in a thermostat set to 110°C. The quantitative assessment of blood lipids was performed using a densitometer model DO-1M (Ukraine).

Statistical analysis of the experimental data was conducted using the computer programme Statistica 5.0 (StatSoft Inc., USA), taking into account the Student's t-test under normal distribution of results. Differences were considered statistically significant at $P < 0.05$.

Results and Discussion

The chromatographic analysis of the lipid spectrum in the native blood samples from laboratory rats undergoing artificially induced tetracycline-induced hepatosis (first experimental group, "Self-rehabilitation") revealed that their qualitative composition included five lipid fractions: phospholipids, free fatty acids, free cholesterol, esterified cholesterol, and triacylglycerols. The total content of these fractions corresponded to the parameter for total lipids (Table 1).

Table 1. *Lipid spectrum of native blood in experimental rats (M ± m, n = 8, mg%)*

Parameter	Group "Control"	First experimental group "Self-rehabilitation"
Total lipids	639.43 ± 49.56	402.56 ± 31.80*
Phospholipids	374.21 ± 29.12	221.43 ± 20.94*
Free fatty acids	41.42 ± 2.61	22.30 ± 1.84*
Free cholesterol	96.11 ± 7.32	73.88 ± 3.21*
Esterified cholesterol	99.34 ± 8.13	67.54 ± 4.64*
Triacylglycerols	26.35 ± 2.38	14.41 ± 1.17*

Note: * – P<0.05 compared to the control group
Source: developed by the authors

During the development of tetracycline-induced hepatosis (first experimental group, "Self-rehabilitation"), a significant decrease in the total lipid content was observed in the native blood of affected rats, with a reduction of 37.0% compared to intact animals (control group) (Table 1). This trend may be attributed to a decreased appetite in the affected animals due to the overall intoxication resulting from the toxic effects of tetracycline hydrochloride. Additionally, it could be related to disorders in the absorption of dietary lipids in the intestine caused by the onset of cholestasis, which is characteristic of this clinical situation, and to disruptions in the molecular mechanisms of their endogenous synthesis in the liver cells, potentially stemming from a reduced energy potential in hepatocytes. As noted by P. Rada *et al.* (2020) and Y. Ni *et al.* (2023), most researchers' findings indicated that hepatic steatosis is primarily associated with alterations in the lipid composition within hepatocytes. Furthermore, according to the findings of numerous studies, including pharmacological and genetic research summarised in the scientific study of V.F. Williams *et al.* (2019), there is a prevailing consensus regarding the primary importance of the accumulation of triacylglycerols as a key etiological factor in the development of fatty hepatosis. However, as indicated by S.H. Park *et al.* (2020) and G. Targher *et al.* (2021), the pathophysiology of the drug-induced form of fatty hepatosis is exceedingly complex, and thus the accumulation of triacylglycerols alone is insufficient for the onset of this hepatic pathology. M. Welch *et al.* (2022) recommended a more in-depth investigation into the roles of various classes of lipids, particularly sphingolipids, phospholipids, and cholesterol, in the pathogenesis of fatty hepatosis.

In the case of artificially modelling drug-induced liver damage, disturbances were observed in the lipid profile of the native blood of affected rats (first experimental group, "Self-rehabilitation"), similar to the noted decrease in total lipid levels. In the rats undergoing self-rehabilitation (first experimental group), a significant reduction in the level of phospholipids in the native blood

was noted, amounting to 40.8% (Table 1), indicating the development of a deficient level of these lipids within the organisms of these animals. According to Y. Zhou *et al.* (2023), the liver serves as the primary site for the endogenous formation of phospholipids in mammals. Consequently, the established quantitative changes in phospholipids may be attributed to insufficient synthesis resulting from pathological alterations in liver function, as well as a concomitant reduction in the intensity of fatty acid utilisation for the formation of phospholipid molecules, along with shifts in the activity of relevant enzymes. Thus, as reported by M. Welch *et al.* (2022), the incorporation of fatty acids into phospholipid synthesis is hindered. At the same time, as noted by E. Calzada *et al.* (2016) and O. Ali & A. Szabó (2023), among all known phospholipids characteristic of animal organisms, the highest proportion is comprised of phosphatidylcholine and phosphatidylethanolamine, which dominate the structure of cellular membranes. Consequently, the stability of the structural organisation of the plasmalemma is maintained by the balance of these lipids, and any disruption of this balance can provoke the development of fatty liver disease. For instance, when the gene Pcyt1a, which encodes the enzyme limiting the intensity of phosphatidylcholine formation (CTP: phosphocholine cytidylyltransferase-α, or CTα), is blocked in the livers of mice, a sex- and diet-dependent effect on lipid transformation in the liver is observed, which can lead to hepatic steatosis. Overall, according to R.L. Jacobs *et al.* (2004), phosphatidylcholine plays a crucial role in the processes of triglyceride formation and secretion (very low-density lipoproteins, VLDLs), and an increase in the extracellular triglyceride content correlates with the development of liver steatosis and its fatty degeneration. Similar effects were noted by J. Li *et al.* (2023) in mice when the activity of phosphatidylethanolamine N-methyltransferase (PEMT−/−), which catalyses the unique hepatic pathway for phosphatidylcholine production, was inhibited. This inhibition resulted in a decreased molar ratio of phosphatidylcholine/phosphatidylethanolamine and an increase in triglyceride content in hepatocytes. Thus, abnormal alterations in the phospholipid composition of membrane structural organisation heighten the susceptibility of cellular membranes to various damages, including the effects of toxic lipids and activators, which initiate hepatic fat infiltration, the development of inflammatory responses, and cellular destruction.

In the native blood of the affected rats (first experimental group, "Self-rehabilitation"), deviations in the level of free fatty acids were also observed (Table 1). Specifically, a significant reduction in free fatty acid levels by 46.2% was noted compared to that in intact animals (the "Control" group), which was likewise reflected in the overall lipid levels in the blood. Furthermore, in line with findings from previous research (Gryshchenko *et al.,* 2019) on the fatty acid composition of hepatic lipids under drug-induced liver damage from toxic doses of this antibiotic, polyunsaturated fatty acids (PUFAs) were primarily affected. Consequently, the diseased animals exhibited a deficient level of eicosapentaenoic (20:5ω3), docosapentaenoic (22:5ω3), and docosahexaenoic (22:6ω3) acids, along with a decrease in the total saturated fatty acids (SFA) and an alteration in the ratio of saturated to unsaturated fatty acids by a factor of 1.3, as well as the ω3/ω6 ratio by 1.3.

The molecular mechanisms underlying deviations in the quantitative parameters of fatty acid composition in response to tetracycline-induced liver pathology remain insufficiently understood. The specifics of fatty acid intermediary metabolism in living organisms depend on the structural organisation of the tissue. Additionally, gene activity is influenced not only by fatty acids but also by other endocrine, paracrine, and autocrine factors within the internal environment, exemplifying the broader integration of metabolic processes.

Furthermore, as highlighted in the research by V.F. Williams *et al.* (2019), the liver is also the primary site for endogenous cholesterol synthesis in mammalian organisms. Consequently, liver

pathology is likely to lead to deviations in this sterol's concentration in the bloodstream. It is well-established that cholesterol metabolism involves over 300 proteins with enzymatic activity dependent on liver function. As noted by A.S. Mutlu *et al.* (2021), cholesterol, like phospholipids, is an essential structural component of biological membranes in mammals, playing a crucial role in transmembrane processes and signal transmission. Cholesterol synthesis occurs in the cytosol and endoplasmic reticulum of cells through the mevalonate pathway, using active acetate. 3-hydroxy-3-methylglutaryl coenzyme A reductase (HMGCR) is the rate-limiting enzyme for steroid biosynthesis. In addition, cholesterol esters are formed through the catalytic action of acyl-CoA acyl-transferase (ACAT), which limits the accumulation of free cholesterol in blood plasma and cellular membranes. Maintaining cholesterol homeostasis across the organism and within cells is a regulated process that prevents excessive accumulation or deficiency. The liver plays a central role in regulating blood plasma cholesterol levels via a complex metabolic pathway involving sterol transporters, nuclear and lipoprotein receptors, and transcriptional gene expression.

In rats with tetracycline-induced hepatosis (first experimental group, "Self-rehabilitation"), a significant reduction was observed in native blood levels of both free cholesterol (by 23.1%) and esterified cholesterol (by 32.0%) compared to the control group (Table 1). This finding effectively demonstrates disruptions in cholesterol biosynthesis within hepatocytes and other tissues, as well as certain impairments in the formation of esterified cholesterol and the corresponding lipoprotein complexes. According to P. Malhotra *et al.* (2019), disturbances in cholesterol metabolic pathways that govern its transport, synthesis, and conversion play a critical role in the development of hepatopathologies. Low-density and very-low-density lipoproteins, which are particularly rich in cholesterol, are primarily synthesised in the liver. Z. Li *et al.* (2023) suggested that the non-inflammatory intracellular accumulation of fat may result from an imbalance between lipid distribution and clearance from the liver. In turn, as noted by J. Aron-Wisnewsky *et al.* (2020), this imbalance can eventually lead to fibrosis, cirrhosis, and hepatocellular carcinoma.

Furthermore, in the native blood of rats with tetracycline-induced hepatosis (first experimental group, "Self-rehabilitation"), the triacylglycerol content decreased by 45.3% compared to the control group (Table 1). While these lipids hold limited diagnostic value, researchers such as P. Rada *et al.* (2020) and S. Lang & B. Schnabl (2020) have highlighted their importance as a metabolic fuel reserve for the organism. Consequently, analysis of triacylglycerol levels is commonly applied in laboratory diagnostics to study related animal diseases.

Therefore, as a result of a detailed analysis of the lipid profile of native blood in rats with experimental tetracycline-induced hepatitis (first experimental group, "Self-rehabilitation"), the formation of a deficient level of both total lipids and individual lipid fractions was established. The identified patterns of the native blood lipid profile in diseased animals may be the result of a decrease in appetite, insufficient digestion and absorption of lipids in the gastrointestinal tract, intensive energy expenditure by the organism, rapid depletion of lipid depots, impaired synthesis and utilisation of lipid molecules in hepatocytes, etc.

When rats were orally administered milk phospholipids in the form of the DS "FLP-MD" in a liposomal form (second experimental group, "Correction"), a restoration of total lipid content in native blood was observed, reaching the levels of intact animals (Table 2).

Table 2. *Lipid spectrum of native blood in experimental rats (M ± m, n = 8, mg%)*

Parameter	Group "Control"	Second experimental group "Correction"	Third experimental group "Healthy animals + DS "FLP-MD"
Total lipids	639.43 ± 49.56	607.90 ± 43.13	685.53 ± 51.82

Table 2. *Continued*

Parameter	Group "Control"	Second experimental group "Correction"	Third experimental group "Healthy animals + DS "FLP-MD"
Phospholipids	374.21 ± 29.12	355.31 ± 30.10	401.03 ± 27.23
Free fatty acids	41.42 ± 2.61	40.83 ± 2.32	46.93 ± 4.55
Free cholesterol	96.11 ± 7.32	90.12 ± 3.86	102.13 ± 9.12
Esterified cholesterol	99.34 ± 8.13	93.81 ± 4.33	107.58 ± 8.43
Triacylglycerols	26.35 ± 2.38	27.83 ± 2.52	27.86 ± 2.49

Note: P < 0.05 compared to the control group
Source: developed by the authors

This finding can be attributed to improved appetite in the experimental animals, which clinically distinguished them from the diseased rats of the first experimental group ("Self-rehabilitation"), as a result of the gradual restoration of exogenous lipid absorption processes in the intestine and their endogenous synthesis in hepatocytes. At the same time, the administration of milk phospholipids as a dietary supplement to clinically healthy animals led to a tendency towards an increase in total lipid content compared to the control. This research result is explained by the additional introduction of exogenous lipids (primarily phospholipids) contained in the dietary supplement into the organism of the experimental animals.

It should be noted that the phospholipid content in the native blood of rats in the second experimental group "Correction" and the third experimental group "Healthy animals + DS "FLP MD" (Table 2), which additionally received the dietary supplement, was characterised by normalisation of their parameters, even in animals with modelled tetracycline-induced hepatitis. In clinically healthy rats of the third experimental group "Healthy animals + DS "FLP MD", this indicator even showed a tendency to increase, which may indicate the effective absorption of exogenous phospholipids in the gastrointestinal tract. Similarly to the previously described indicators in the native blood of rats in both experimental groups, a lack of significant quantitative changes in free fatty acids was established. This confirms the corrective effect of the supplement on the intermediate stages of fatty acid metabolism in the experimental animals.

When determining the patterns of quantitative changes in individual cholesterol fractions in the native blood of the experimental rats, a normalisation of their content was established in animals of the second experimental group ("Correction") and a tendency towards an increase in the values of these indicators was observed in animals of the third experimental group ("Healthy animals + DS "FLP-MD") (Table 2) compared to the control. The established pattern may be the result of their additional intake into the body as part of the dietary supplement and activation of the intermediate metabolism of this steroid in the internal organs and tissues of clinically healthy rats. The established fact also indirectly indicates the detection of hepatoprotective effects of the phospholipid-containing dietary supplement "FLP-MD" and the absence of its toxic effect on liver cells. In the study of D.O. Melnychuk *et al.* (2014), the membrane-tropic and hepatoprotective properties of milk phospholipids were also described, which have a stabilising effect on the indicators of pigment metabolism during artificial irradiation of rats and the introduction of cadmium compounds into their organism, which was confirmed by a significant improvement in the functional state of the hepatobiliary system.

As with the previously discussed lipid profile parameters, a similar pattern was observed regarding the triacylglycerol content in the native blood of rats in the second experimental group "Correction" and the third experimental group "Healthy animals + DS "FLP-MD" (Table 2). Triacylglycerols are present in a small amount in the

dietary supplement, which may also contribute to the restoration of the pool of these substances, which are important for energy-supplying synthetic processes in the organism of diseased animals. The established results of the blood lipid profile correspond to the parameters in the animals of the control group, which, in combination with the results of other studies, suggests that the absence of a hepatotoxic effect of the components of the phospholipid-containing dietary supplement on liver cells and the organism as a whole, as well as its pronounced corrective effectiveness.

Therefore, as a result of an in-depth analysis of the lipid spectrum of native blood in laboratory rats with experimentally modelled tetracycline-induced hepatitis and the administration of the DS "FLP-MD" to both diseased and clinically healthy animals, an effective restoration of the content of total lipids and their individual fractions was established. This indicates the ability of milk phospholipids within the dietary supplement to exert a corrective and hepatoprotective effect in the event of drug-induced hepatopathology in animals.

Conclusions

This study presents a laboratory evaluation of the lipid composition of native blood in laboratory rats with experimentally modelled tetracycline-induced hepatitis and oral administration of milk phospholipids in the form of the DS "FLP-MD". The use of thin-layer chromatography allowed for the separation of total lipids in native blood into individual fractions in laboratory rats with modelled tetracycline-induced hepatitis. It was established that their qualitative composition remained unchanged and contained five classical fractions: phospholipids, free fatty acids, triacylglycerols, free and esterified forms of cholesterol. At the same time, the lipid composition of native blood in laboratory rats with experimental tetracycline-induced hepatitis (first experimental group "Self-rehabilitation") was characterised by a decrease in the content of both total lipids and individual components of the lipid profile. In particular, there was a deficit in total lipids – by 30.8%, phospholipids – by 37.0%, free fatty acids – by 46.2%, triacylglycerols – by 45.3%, free cholesterol – by 23.1% and esterified cholesterol by 32.0% compared to the corresponding control. The established disturbances in the lipid profile of native blood in diseased animals may be caused by appetite disorders in these patients, as well as insufficient absorption of dietary lipids at the level of the intestine, inhibition of the activity of specific enzymatic systems and the associated endogenous synthesis of them in liver cells.

Administration of the DS "FLP-MD" to diseased rats resulted in the restoration of both total lipid levels and individual fractions, demonstrating the pronounced corrective and hepatoprotective effects of the components of the milk phospholipid-based dietary supplement. Concurrently, the administration of the phospholipid-containing dietary supplement to clinically healthy laboratory rats was accompanied by the effective restoration of all lipid fractions and their total content. This effectively indicates the absence of a toxic effect of the dietary supplement components on the organism of laboratory rats, as well as a pronounced corrective and hepatoprotective effect, which allows recommending specified DS for use in diseased animals in cases of drug-induced hepatopathology. In addition, the use of thin-layer chromatography can be recommended for effective laboratory diagnosis of lipid metabolism disorders in the organism of diseased animals during the development of drug-induced hepatopathy and the determination of the pathogenesis of internal diseases, in particular, the liver at the molecular level.

In the future, it is planned to conduct studies of the fractional composition of blood proteins during the artificial modelling of drug-induced hepatopathology against the background of simultaneous determination of the effectiveness of corrective therapy using laboratory animals.

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None.

Conflict of Interest

None.

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Ліпідограма крові в щурів за тетрациклінового ураження печінки

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Анотація. Медикаментозно зумовлене ураження печінки спричинює значну кількість захворювань та смертності внаслідок розвитку небезпечних ускладнень, залишаючи його провідною причиною гострої печінкової недостатності в тварин. Серед препаратів з прямим цитотоксичним ефектом впливу на клітини печінки виділяють антибіотики тетрациклінової групи, некоректне застосування яких здатне викликати жировий гепатоз. Тому метою роботи було дослідити закономірності щодо змін у ліпідограмі нативної крові в лабораторних щурів за тетрациклінового ураження печінки з одночасним визначенням коригувальної здатності фосфоліпідів молока. Ліпідний склад нативної крові досліджували з використанням методу тонкошарової хроматографії. Встановлено, що у разі штучного моделювання в щурів тетрациклінового ураження печінки відмічали формування дефіцитного рівня усіх п'яти показників ліпідограми нативної крові, зокрема, зменшення вмісту загальних ліпідів – на 30,8 %, триацилгліцеролів – на 45,3 %, фосфоліпідів – на 37,0 %, вільних жирних кислот – на 46,2 %, вільного холестеролу – на 23,1 % та естерифікованого холестеролу на 32,0 % порівняно з відповідним контролем. Це можна пояснити погіршенням у хворих тварин апетиту, недостатнім засвоєнням ліпідів у травному каналі та інгібуванням їх ендогенного синтезу в печінці хворих щурів. Застосування хворим тваринам фосфоліпідів молока у вигляді біодобавки «FLP-MD» виявляло виражений коригувальний ефект, що проявлялося у відновленні кількісних параметрів усіх досліджуваних ліпідних фракцій та їх загального вмісту. У разі перорального введення цієї біодобавки клінічно здоровим щурам відмічали відсутність токсичного впливу її компонентів як на клітини печінки, так і на весь організм. При цьому відмічено тенденцією до зростання абсолютного вмісту більшості з досліджуваних фракцій загальних ліпідів крові. Таким чином, в результаті експериментального дослідження розкрито маркерні зміни ліпідограми нативної крові в лабораторних щурів, що може бути корисним у визначенні патогенезу тетрациклінового ураження в ссавців та при випробуванні новостворених лікарських засобів гепатопротекторної дії

Ключові слова: коригувальна терапія; фосфоліпіди молока; жировий гепатоз; тонкошарова хроматографія; фракції ліпідів

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Impact of mechatronic systems on accuracy and stability of vibration cleaning machines in the agricultural sector

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Abstract. The study was conducted to determine how the use of mechatronic systems can optimise the operation of vibration-cleaning machines and improve their performance in agricultural processes. Vibration accuracy measurement, automated load control, monitoring of operating parameters, wear assessment, energy efficiency analysis, and impact assessment to minimise human intervention were used in the study. A study conducted at BIG Harvest Group demonstrated that the introduction of mechatronic systems in vibration-cleaning machines significantly improves the accuracy and stability of their operation. The integration of automated control of the frequency and amplitude of oscillations has reduced energy consumption and increased the efficiency of seed cleaning compared to traditional methods. The study determined that the system of automatic monitoring and correction of parameters ensures stable machine performance even under variable load conditions. Reduced wear and tear on mechanical components ensure longer equipment life, reduced downtime and the need for manual

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intervention. In general, the results confirmed that mechatronic systems significantly increase the efficiency of vibration-cleaning machines, which has a positive effect on the quality of cleaning and economic efficiency in agriculture. The study also determined that automatic adjustment of operating parameters using mechatronic systems reduces fluctuations in machine performance, resulting in more uniform cleaning. The integrated monitoring system identified and eliminated faults, reducing maintenance time. As a result, improvements in the overall management of seed cleaning processes were achieved, which increased productivity and reduced equipment operating costs

Keywords: automated control; energy consumption; seed cleaning; wear of mechanical components; economic efficiency

Introduction

In the agricultural sector, the efficiency of seed treatment is critical to ensuring high product quality and optimising resources. Vibration cleaning machines, which are used to clean seeds from contaminants and impurities, are central to this process. However, traditional control systems often face problems with accuracy and stability, which can affect cleaning quality and operating costs. In this regard, mechatronic systems that combine mechanical, electronic and computer technologies have become a promising solution for improving the efficiency of vibratory cleaning machines. The introduction of such systems promises significant improvements in setup accuracy, operational stability, energy efficiency and reduced equipment wear.

In the agricultural sector, the precision and stability of vibration-cleaning machines are important aspects for improving the quality of seed processing and reducing operating costs. The problem is that traditional systems often do not provide sufficient accuracy and stability, which affects cleaning efficiency and increases maintenance costs. C. Cardona *et al.* (2024) investigate how the integration of mechatronic systems can increase the accuracy of vibration control in vibration cleaning machines, which has a positive effect on the quality of seed cleaning. Their study shows that automating settings reduces energy consumption and improves overall process efficiency. D. Xie *et al.* (2022) addressed automated oscillation frequency control, which provides a significant reduction in energy costs. Their research confirms that such systems increase cleaning efficiency and reduce operating costs. I. Hassan *et al.* (2024) studied the impact of sensors for monitoring vibration parameters on the stability of vibration-cleaning machines. The results show an increase in stability under varying load conditions due to automatic correction. L. Badita-Voicu *et al.* (2024) find that mechatronic systems significantly reduce wear and tear on mechanical components, which extends the life of the equipment. This reduces the need for frequent repairs and maintenance. E. Mincă *et al.* (2022) noted that the integration of mechatronic systems reduces downtime and the need for manual intervention. The study highlights the improvement in the overall performance of vibration-cleaning machines.

E. Aliiev & K. Lupko (2021) demonstrated that automatic parameter adjustment results in more uniform seed cleaning. This helps improve the quality of the final product and reduce processing costs. D. Essola *et al.* (2022) demonstrated how reducing vibrations in vibration cleaning machines can improve cleaning quality and reduce maintenance costs. Their results confirm the effectiveness of mechatronic systems in reducing operating costs. M. Romanssini *et al.* (2023) confirmed that the introduction of mechatronic technologies increases the energy efficiency of vibration-cleaning machines. This reduces energy costs and improves economic performance. D. Ionescu *et al.* (2022) determined that the

automated monitoring system can be used for quick detection and elimination of equipment malfunctions. This reduces the time required for maintenance and repairs. A. Hayat *et al.* (2022) proved that mechatronic systems can significantly reduce the cost of operating vibration cleaning machines. Research shows that these systems significantly improve economic efficiency in the agricultural sector. Thus, while research has revealed significant advantages of mechatronic systems in improving the accuracy and stability of vibration-cleaning machines, there are gaps, particularly in terms of economic benefits and specific operating conditions, that require further study.

The study aimed to investigate the impact of mechatronic systems on optimising the operation of vibration-cleaning machines and increasing their efficiency in the agricultural sector. Research objectives:

- to consider the introduction of automated control of vibration processes and its effect on energy costs and quality of seed cleaning;
- to study how mechatronic systems affect the accuracy and stability of vibration cleaning machines;
- to evaluate the results of the integration of sensor technologies and automatic monitoring, as well as their impact on operating costs and overall equipment performance.

Materials and Methods

The study, which focuses on the impact of mechatronic systems on the accuracy and stability of vibration-cleaning machines in the agricultural sector, comprehensively assessed the integration of these systems. The main areas of focus included precise adjustment of vibration parameters, automated load control, monitoring and correction of operating parameters, wear reduction, energy efficiency and minimisation of human intervention.

The study was conducted at BIG Harvest Group (Ukraine). The study examined seeds of several crops, including wheat, barley, corn and peas. Each of these seed types had its unique characteristics that affected their behaviour during the cleaning process. Experiments were carried out on samples of these crops to study in detail the effect of various vibration parameters, such as vibration frequency, vibration amplitude and vibration direction, on cleaning efficiency. This was used to analyse how the amplitude and frequency of oscillations affect the cleaning results of each type of seed, as well as to identify the optimal conditions for achieving the best performance.

To evaluate the precise adjustment of vibration parameters, Toshiba Vibration Cleaner X-1000 (Japan) equipped with mechatronic systems from Bosch Rexroth (Germany) was used. These machines allow for precise control of the frequency and amplitude of vibrations. Vibration levels were measured using high-precision Kistler sensors and a National Instruments data recording system.

The analysis of automated load control was carried out using Meyer Industries V-300 vibration cleaning machines (USA) equipped with Siemens S7-1200 mechatronic systems (Germany). In this case, Endress+Hauser sensors were used to monitor the amount of seed entering the cleaning process. The automatic load control was evaluated using Rockwell Automation's FactoryTalk software, which records and adjusts parameters in real time.

At this stage, the performance of the Haver Roto-Packer vibration cleaning machines from Haver & Boecker (Germany) was evaluated using Honeywell (USA) integrated sensors, which were used to monitor temperature, humidity and vibration levels. The data were collected using a LabVIEW data acquisition system and analysed using MATLAB software for automatic parameter correction.

Alapala VIB-500 vibration cleaning machines from Alapala (Turkey) equipped with Parker Hannifin mechatronic systems (USA) were used to assess wear reduction. Wear measurements of mechanical components were carried out using specialised Mitutoyo equipment (Japan). Wear was assessed by analysing differences in the physical characteristics of the components,

including measuring material thickness, determining the volume of worn parts and conducting dynamic vibration tests. A comparison with traditional Ocrim (Italy) machines without automatic systems was used to determine the impact of automatic control on equipment service life and maintenance costs.

The energy efficiency analysis was carried out using Satake MCH-100 vibration cleaning machines from Satake (Japan), which were used in tests with mechatronic systems from Schneider Electric (France). Electricity consumption was measured using Fluke energy meters (USA). The data was compared with the energy consumption of traditional Omas systems (Italy) to determine the effectiveness of optimising electricity consumption.

To analyse the impact of mechatronic systems on reducing human intervention, Groupe SEMA (France) vibration cleaning machines with Mitsubishi Electric (Japan) automated systems were used. Operator error rates and performance were assessed by observing the number of errors and their impact on machine performance.

A comprehensive approach to assessing the impact of mechatronic systems on various aspects of the operation of vibration-cleaning machines has provided detailed data on their effectiveness and benefits in the agricultural sector.

Results

In the modern agricultural sector, especially in the growing and processing of grain crops, optimisation of technological processes is critical. BIG Harvest Group, which specialises in growing and processing wheat, barley, corn and peas, has become one of the pioneers in implementing automated technologies to improve the efficiency of its production processes. In particular, the study of automated control of vibration processes has significantly reduced energy costs and improved the quality of seed cleaning (Table 1).

Table 1. *Effect of automated control of vibration processes on energy consumption and quality of seed cleaning*

Parameter	Before automation	After automation	Improvement (%)	Parameter
Power consumption (kW)	15-20	10-15	20-30	Power consumption (kW)
Electricity costs (UAH/hour)	45-60	30-45	25-33	Electricity costs (UAH/hour)
Level of seed contamination (%)	5-7	1-3	50-70	Level of seed contamination (%)
Seed cleaning accuracy (%)	85	95	10	Seed cleaning accuracy (%)

Source: compiled by the authors based on V. Ishchenko (2023)

The vibration processes used in the seed cleaning process are critical to achieving high quality in the final product. Traditional methods of seed cleaning are often associated with high energy consumption, which negatively affects the overall costs of the enterprise. The BIG Harvest Group has implemented an automated control system that can monitor vibration parameters in real-time. This solution is based on state-of-the-art mechatronic systems that ensure precision and efficiency in the seed cleaning process.

The introduction of automated control of vibration processes has brought significant benefits. It was possible to reduce electricity consumption by 20-30% as a result of optimising the operation of vibrating machines. Reducing energy costs not only helped to increase the company's profitability but also had a positive impact on the environmental component of production. The advanced system can adjust vibration to the type of seed being processed, which also reduces unintended energy consumption. Vibration frequency

and amplitude control optimise machine performance by preventing unnecessary vibrations that are not required for a particular type of seed. This reduces energy consumption as the machine operates at maximum efficiency, using only as much energy as necessary to achieve optimum results.

The automated control has also improved the quality of seed cleaning. Precise control of the vibration parameters achieves greater efficiency in the process of separating impurities from the seeds. The quality of wheat, barley, maize and pea seeds has improved significantly, which has had a positive impact on their marketability and consumer characteristics. In particular, the company was able to reduce the level of seed contamination to the minimum permissible standards, which increased the competitiveness of its products in the market.

Mechatronic systems significantly increase the accuracy and stability of vibration-cleaning machines in the agricultural sector by integrating mechanical, electronic and computer components. The precise adjustment of vibration parameters in vibration-cleaning machines is a key factor in ensuring an efficient seed-cleaning process in the agricultural sector. Mechatronic systems that combine mechanical, electronic and computer components open new possibilities for precise control of the frequency and amplitude of vibrations. Thanks to the introduction of such systems, vibrating machines can operate at optimal parameters, which significantly improves the quality of cleaning various types of seeds, even under variable operating conditions.

The main advantage of mechatronic systems is the automatic adjustment of vibration parameters depending on the type of raw material being cleaned. Each type of seed has its characteristics – density, size, texture, and contamination (Brown *et al.*, 2021). For instance, smaller or lighter grains (wheat, barley) may require less intense vibrations, while larger or heavier grains (corn, peas) may require higher amplitude and frequency for effective cleaning. Mechatronic systems automatically adjust these parameters, reducing the need for manual intervention, which reduces the risk of errors and productivity losses.

The automatic parameter adjustment system also accounts for external factors such as humidity or temperature that may affect the cleaning process (Amertet *et al.*, 2023). This ensures even vibrations and, as a result, uniform seed cleaning. By precisely controlling the frequency and amplitude of vibrations, vibration cleaning machines operate with greater stability and efficiency, which has a positive effect on the final product quality.

In addition, precise adjustment of the vibration parameters reduces wear on machine components (Table 2). Vibration amplitudes that are too high or too low can put additional stress on mechanical parts, causing additional wear. Mechatronic systems keep vibration cleaning machines operating within a safe range, which extends equipment life and reduces maintenance costs.

Table 2. *Precise adjustment of vibration parameters*

Parameter	Vibration cleaning machines with mechatronic systems	Vibration cleaning machines without mechatronic systems
Oscillation frequency (Hz)	30-60	25-55
Oscillation amplitude (mm)	2-5	3-6
Sensor	Kistler sensors	Kistler sensors
Data recording system	National Instruments	National Instruments
Cleaning efficiency (%)	90	80

Source: compiled by the authors

The introduction of mechatronic systems in vibration cleaning machines renders the seed cleaning process not only more efficient but also cost-effective. Automation of vibration settings significantly improves equipment accuracy, reduces human error and ensures stable operation

even under variable load conditions. This makes mechatronic systems an integral part of modern technological processes in the agricultural sector, ensuring high-quality seed cleaning and increasing agricultural productivity.

Automated load control is one of the key functions of modern mechatronic systems, enabling vibration-cleaning machines to maintain stable performance even under variable operating conditions. Given the importance of precision and efficiency in the agricultural sector, the ability to automatically adjust the workload is crucial to ensure the smooth operation of the equipment and high-quality seed cleaning.

Mechatronic systems equipped with integrated sensors and software allow for continuous monitoring of the amount of raw materials entering the treatment (Kuntoğlu *et al.*, 2021). This is especially relevant in situations where the amount of seed or grain being loaded into the machine is constantly changing. Instead of the operator having to constantly monitor the process, the system automatically adjusts to the changing load parameters to ensure the optimum performance of the vibration cleaning machine. This reduces the human factor and ensures consistent performance even if the amount of seeds or grain varies.

Thanks to automated load management, mechatronic systems also enable better management of machine energy consumption (Table 3). As the load changes, the system can adjust the vibration intensity and processing speed, which minimises energy consumption without compromising cleaning quality. Such adaptability contributes to the energy efficiency of the entire process, which is important for reducing overall production costs and increasing the economic efficiency of an agricultural enterprise.

Table 3. *Automated load management*

Parameter	Vibration cleaning machines with mechatronic systems	Vibration cleaning machines without mechatronic systems
Load range (kg/h)	500-1000	400-900
Load regulation	Automatic	Manual
Sensors	Endress+Hauser	Endress+Hauser
Software	Rockwell Automation FactoryTalk	None
Performance stability (%)	95	85

Source: compiled by the authors

Another important advantage of automated load management is the ability to maintain stable machine operation regardless of external conditions (Ullah *et al.*, 2021). In real-life conditions, in particular, in field farms, humidity, seed type and outside temperature can vary. This can affect the quality of the cleaning process if the machine is not able to adapt to these changes. Mechatronic systems can compensate for these external factors by precisely controlling the workload, which makes it possible to maintain high machining quality regardless of the conditions.

In addition, automated load management systems increase the reliability of the equipment. Vibration cleaning machines can be overloaded or underloaded due to fluctuations in the amount of material being processed, which can reduce efficiency or cause breakdowns. Automatic load control ensures even load distribution, which reduces the risk of failure and helps to extend the service life.

Thus, the automated load control implemented in modern vibration cleaning machines provides several important benefits for agricultural production. It helps maintain a stable cleaning process efficiency, reduces the need for manual control, and ensures energy efficiency and adaptation to external changes. This not only improves the quality of seed processing but also ensures greater reliability and stability of the equipment,

which is an important factor for agricultural enterprises seeking to increase their productivity and economic efficiency.

Monitoring and correction of operating parameters using mechatronic systems is a key aspect of increasing the efficiency and stability of vibration-cleaning machines in the agricultural sector. Integrated sensors that monitor parameters such as temperature, humidity and vibration levels enable precise control of the cleaning process. Thus, the system can automatically adjust the operation of the machines to ensure consistent performance despite changes in environmental conditions or raw material parameters.

One of the main advantages of this feature is the ability to collect and analyse machine performance data in real-time. For instance, an increase in seed moisture content can affect the quality of cleaning, as wet raw materials are more difficult to separate (Müller *et al.*, 2022). Integrated sensors detect this indicator and, if necessary, the mechatronic system adjusts the vibration frequency, increasing or decreasing the intensity of the vibrations depending on the current conditions. As such, high cleaning quality can be achieved, even with variable material characteristics.

In addition, temperature monitoring is another important aspect that affects process efficiency. Vibration cleaning machines operating at too high or low temperatures can lose performance due to reduced lubrication or increased wear and tear on mechanical components (Martínez-Parrales & del Carmen Téllez-Anguiano, 2022). The monitoring system can detect temperature deviations on time and implement measures to reduce the impact of negative factors. For instance, it can automatically reduce the load on the machine or increase the coolant volume to avoid overheating.

Another important component is the control of vibration characteristics. If the vibration level exceeds the permissible limits, it damages the machine or is a reason for ineffective seed cleaning (Sinha *et al.*, 2023). Integrated sensors detect such deviations in time, and the system corrects the machine to restore stable operation. This automatic correction capability is highly relevant in the agricultural sector, as it ensures high machine performance without the need for constant operator monitoring.

Automatic correction also reduces the risk of accidents and equipment damage. Mechatronic systems can prevent critical loads or overheating by reacting to changing parameters in a timely manner. This not only increases the efficiency of the production process but also significantly reduces maintenance and repair costs.

Thus, monitoring and correction of operating parameters with the help of mechatronic systems is an important component of ensuring the stable performance of vibration-cleaning machines. These systems automate the control process, ensuring the uninterrupted operation of machines even in the face of changes in external conditions or raw material parameters. Accordingly, the integration of such technologies into the agricultural sector significantly improves the quality and reliability of the seed-cleaning process, which contributes to the overall increase in agricultural production efficiency.

Reducing wear and extending the operational life of vibration-cleaning machines is an important advantage of introducing mechatronic systems in the agricultural sector. One of the main factors affecting the durability of equipment is the constant load on mechanical components. Without automated parameter control and overload prevention, wear and tear on parts is significantly accelerated, leading to frequent breakdowns, efficiency losses and increased maintenance costs. Mechatronic systems provide automatic parameter adjustment to avoid these problems and extend the service life of machines.

One of the key functions of mechatronic systems is the ability to continuously monitor and correct operating parameters such as vibration frequency and amplitude (Tsai *et al.*, 2021). If an overload risk is detected, the system automatically reduces the work intensity, which reduces the load on the machine components. This approach reduces the likelihood of premature wear of moving

parts, which is necessary for stable and long-term operation of the equipment.

Automatic parameter adjustment minimises excessive loads on the most vulnerable parts of the machine, such as bearings and joints. When the vibration parameters are outside the optimum range, the risk of damage to these components increases dramatically. Mechatronic systems, using integrated sensors, detect these deviations and automatically adjust the operation of the equipment, reducing the intensity of the load on problem areas. This can ensure a stable workflow without the risk of serious breakdowns.

Another important advantage is the reduction in maintenance costs (Table 4). As mechatronic systems monitor the condition of the vibration-cleaning machine's components and can predict potential problems, companies are able to carry out preventive maintenance in a more efficient manner. This helps avoid emergencies and unexpected downtime that could result in serious damage.

Table 4. *Reduce wear and tear and extend equipment life*

Parameter	Vibration cleaning machines with mechatronic systems	Vibration cleaning machines without mechatronic systems
Level of wear and tear on mechanical components	5%	10%
Service life (years)	8	5
Wear measurement equipment	Mitutoyo	Mitutoyo
Model	Alapala VIB-500	Ocrim
Maintenance costs (UAH/year)	10,000	15,000

Source: compiled by the authors

Thanks to the integration of mechatronic systems, the need to replace or maintain specific components can be identified in time. This reduces the cost of general maintenance, as businesses can plan it in a way that minimises the impact on the production process. In addition, extending the service life of equipment without significant investments in repairs allows for more efficient use of resources.

Mechatronic systems also help optimise energy consumption, which has a positive effect on the overall condition of the mechanisms. When the equipment is not overloaded, its power consumption is reduced, which in turn reduces the level of heat exposure to machine parts. Heat load reduction is another important factor in extending the service life of equipment, as constant temperature changes can cause material degradation.

Thus, automatic parameter adjustment and overload prevention by means of mechatronic systems are central to reducing wear and extending the service life of vibration-cleaning machines. These systems not only ensure stable machine operation but also significantly reduce maintenance and repair costs. Due to the effective control of operating parameters, the mechanical components of the equipment receive optimal conditions for long-term and uninterrupted operation, which contributes to the overall efficiency of agricultural production.

Energy efficiency is one of the key advantages of implementing mechatronic systems in vibration-cleaning machines in the agricultural sector. Modern technologies require more and more rational use of energy, and mechatronic systems help to achieve this by optimising equipment processes. With energy prices on the rise and the need to reduce carbon dioxide emissions, energy savings are becoming a strategic advantage for agricultural companies.

Mechatronic systems can adapt the operation of vibration-cleaning machines to changing conditions in real-time. This is achieved through the integration of sensors that measure various parameters of the seed cleaning process, such as the amount of material being processed, its

condition, moisture level and other indicators. The automatic control systems analyse this data and optimise the machine's operating parameters to ensure maximum productivity with minimum energy consumption. This negates excessive power consumption when processing smaller quantities of seed or when maximum power is not required.

Another important aspect of energy efficiency is the ability to precisely control the frequency and amplitude of vibration vibrations. This allows the vibration cleaning machines to operate at the power level that best suits the current process requirements. This means that unnecessary energy is not wasted on maintaining redundant parameters when it is not necessary. For example, when processing fewer seeds, the system can automatically reduce the intensity of the machine, which directly reduces energy consumption (Ji *et al.*, 2021).

In addition, the mechatronic systems can recognise when the machine is in a standby state or paused between seed treatments and automatically switch it to a power-saving mode. This minimises energy loss during downtime, which also contributes to overall operational efficiency. Thus, mechatronic systems reduce energy costs even in situations where the machine is temporarily out of active operation.

Energy efficiency not only reduces direct energy costs but also reduces overall maintenance and repair costs. Machines that operate with optimum energy consumption typically experience lower levels of wear and tear because their components are not subjected to excessive loads. This means that parts last longer, reduce the risk of unexpected breakdowns, and reduce maintenance and replacement costs.

Another important advantage is the environmental aspect of energy efficiency. The use of mechatronic systems not only reduces electricity consumption but also reduces carbon dioxide emissions arising from energy production. This helps reduce the negative impact on the environment, which is becoming an increasingly important factor for the agricultural sector. Modern enterprises are striving to meet the requirements of sustainable development, and the introduction of energy-efficient technologies is an important step in this direction.

Thus, optimising energy consumption with mechatronic systems not only reduces production costs but also ensures a more environmentally friendly operation of vibration cleaning machines (Table 5). Automatic control and regulation systems, adaptation of equipment operation to changing conditions, and switching to economical modes during downtime make these technologies indispensable for achieving high efficiency in modern agricultural production. Mechatronic systems help companies not only save resources but also remain competitive in the market while taking care of the environment and future generations.

Table 5. *Comparison of energy efficiency of vibration cleaning machines with and without mechatronic systems*

Parameter	Vibration cleaning machines with mechatronic systems	Vibration cleaning machines without mechatronic systems
Power consumption (kW)	10-15	15-20
Electricity costs (UAH/hour)	30-45	45-60
Energy sensors	Fluke	Fluke
Test model	Satake MCH-100	Omas
Improved energy efficiency (%)	20	0

Source: compiled by the authors

Minimising human intervention is one of the key aspects of implementing mechatronic systems in vibration-cleaning machines in the agricultural sector. Process automation simplifies

the management of complex technological operations, reducing the risk of human error and increasing overall production efficiency.

Thanks to mechatronic systems, most routine and difficult tasks that previously required constant supervision by operators can now be performed automatically. For instance, setting the parameters of the vibration system, adjusting the amplitude and frequency of oscillations, as well as monitoring temperature and humidity, are all done without the need for direct human intervention. This reduces the error probability that could occur due to operator fatigue, inattention or lack of experience.

The automation of vibration cleaning processes also ensures precise and stable operation. Mechatronic systems can independently adapt to changing production conditions, quickly responding to changes in raw material volumes or machine parameters. Operators are no longer forced to constantly check and adjust the machines, which avoids shortcomings that could have been caused by delays or incorrect settings. This ensures that the seed or grain cleaning process is uninterrupted, which increases overall productivity and processing quality.

Another advantage of automation is improved workplace safety. Vibrating equipment, especially under heavy loads, can be dangerous for the operator due to the high frequency of oscillations or possible overloads. Thanks to mechatronic systems that monitor and adjust operating parameters automatically, the risk of accidents is significantly reduced. Modern systems can also detect critical situations, such as excessive wear and tear on parts or overloading, and automatically stop the machine to prevent breakdowns.

Minimising human intervention also has a positive impact on the economic performance of enterprises (Bolaños *et al.*, 2021). Since mechatronic systems perform most operations automatically, this reduces the need for additional manpower to monitor the equipment. Thus, companies can save on costs related to salaries, staff training and workplace safety. In addition, the reduction of errors and the increase in machine efficiency reduces maintenance and repair costs.

Automated mechatronic systems also contribute to improved resource and time management. Operators can focus on more strategic tasks, such as optimising production processes or scheduling work, rather than routine technical operations. This helps improve the overall efficiency of management and, ensures flexible response to changing operating conditions.

However, it is worth noting that full automation may have certain limitations. For instance, in the event of malfunctions or unforeseen situations, the system may not always react as flexibly as a human would. It is important that mechatronic systems are properly programmed and able to adapt to a variety of operating conditions. In addition, given the complexity of modern technology, qualified personnel are needed to maintain these systems, monitor their operation and respond quickly to possible failures.

As a result, minimising human intervention with mechatronic systems opens new opportunities to improve the efficiency of vibration-cleaning machines, reducing the risk of errors and costs. This is an important step towards the modernisation of the agricultural sector, enabling businesses to operate more efficiently, safely and economically.

In general, the introduction of mechatronic systems in vibration cleaning machines not only increases their efficiency but also ensures more reliable and stable operation, which is especially relevant in improving the quality of seed cleaning and optimising agricultural production.

Discussion

The study determined that the introduction of mechatronic systems has significantly increased the accuracy and stability of vibration-cleaning machines in the agricultural sector. The automated vibration parameter control systems were used to precisely control the frequency and amplitude of vibrations, which has resulted in more uniform seed cleaning. This ensured a better quality of the cleaning process compared to traditional

methods, where such parameters were adjusted manually. Thus, the results of the study confirmed the assumption that the efficiency of equipment operation will increase as a result of the introduction of modern technologies. This was also investigated by M. Mohd Ghazali & W. Rahiman (2021), confirming that the accuracy and stability of vibration-cleaning machines are critical to achieving high standards of seed cleaning. This is achieved by fine-tuning the amplitude and frequency characteristics of vibrations and improved mechanism design. The use of modern materials also reduces vibration loads and ensures uniformity of operation. A. Linenko *et al.* (2021) also demonstrated that mechatronic systems increase the efficiency of vibration-cleaning machines by automating the adjustment of vibration parameters. The integration of sensors and controllers enables real-time monitoring and adaptation. This results in shorter processing times and improved cleaning quality.

The integration of mechatronic systems into vibration-cleaning machines not only automates processes but also increases their accuracy and reliability. However, the results of the study indicate that there are technical issues and additional maintenance costs that could reduce overall efficiency. This underscores the need for a comprehensive approach to the introduction of new technologies, accounting for both their benefits and risks. Therefore, it is necessary to study in detail all aspects of mechatronic system integration to achieve optimal results in the agricultural sector.

One of the key findings was the reduction of the impact of variable factors, such as different quantities and types of raw materials, on the stability of the vibration-cleaning machines. Automated real-time parameter adjustment ensured effective adaptation to changing operating conditions. As a result, constant productivity was achieved, even in the presence of significant fluctuations in the characteristics of raw materials. This underlined the importance of mechatronic systems for maintaining a high level of stability in agricultural processes. Y. Li *et al.* (2022) concluded that the automation of real-time adjustment of the parameters of vibration cleaning machines allows for accurate and fast adjustment of vibration amplitudes and frequencies following changing processing conditions. This improves the efficiency of the cleaning process, as the system can respond quickly to changes in the characteristics of seeds or impurities. Thanks to this automation, the human factor is reduced, which reduces the risk of errors and improves the overall quality of processing. V. Adamchuk *et al.* (2021) determined that reducing the impact of external factors such as temperature, humidity or voltage fluctuations on the performance of vibration cleaning machines is an important aspect of ensuring stable operation. The use of modern sensors and controllers that account for these factors helps reduce their negative impact on the efficiency of the cleaning process. This ensures a consistent high-quality finish regardless of external conditions.

These results confirm the study, as the automation of real-time parameter control improves the accuracy and stability of vibration-cleaning machines. However, the impact of external factors can vary depending on the operating conditions. The results of the study indicate the need to adapt the systems to specific processing conditions, which may require additional adjustments and optimisation. Hence, while automation increases efficiency, it is important to consider all the variables to achieve maximum results.

In addition, the study showed that the use of integrated sensors to monitor key parameters such as temperature and humidity can quickly detect deviations in machine performance. Automatic parameter adjustment helped avoid overloads and ensure uninterrupted operation of the equipment. These results indicate a significant impact of mechatronic systems on improving the reliability and stability of vibration-cleaning machines. Z. Ma *et al.* (2023) also determined that monitoring and correcting key parameters such as vibration amplitude and frequency are critical to ensuring the stable operation of vibration-cleaning machines. Monitoring systems can detect any

deviations from the established norms and make prompt adjustments to maintain optimal performance. This not only improves the quality of cleaning but also reduces the risk of equipment breakdowns and malfunctions. J. Lee *et al*. (2023), in turn, concluded that integrated sensors are central in improving the reliability of vibration cleaning machines by providing continuous monitoring and accurate measurement of critical parameters. They identify and resolve problems that could affect cleaning efficiency or cause malfunctions in time. The system can automatically adjust parameters in real-time, which contributes to the durability of the equipment and its stability.

This data confirms the importance of monitoring and correcting key parameters for the stable operation of vibration-cleaning machines. The integrated sensors demonstrate the effectiveness of automated control in real-time, following the requirements. However, despite the benefits, the study results point to challenges in adapting technologies to specific working conditions. Therefore, it is necessary not only to introduce modern technologies but also to constantly adapt them to maintain high performance and reliability of the equipment.

Another important result of the study was the identification of the positive impact of mechatronic systems on reducing the wear of mechanical components of equipment. Load regulation and overload prevention have significantly extended the service life of the machines and reduced maintenance costs. This not only reduces the overall costs of agricultural enterprises but also increases the environmental sustainability of production through longer use of equipment. S. Kharchenko *et al*. (2022) also conducted a study that confirmed that reducing the wear of vibration cleaning machines is achieved using advanced technologies that ensure uniformity of vibrations and reduce the mechanical load on components. This extends the service life of the equipment and reduces the frequency of repairs and maintenance. Technical improvements contribute to greater machine reliability and lower maintenance costs. P. Onu *et al*. (2024) also determined that mechatronic systems offer significant economic benefits, including reduced energy and maintenance costs due to increased operational efficiency. The environmental benefits include reduced waste and a lower environmental impact due to more precise process control and reduced emissions. This makes mechatronic systems a favourable choice in terms of sustainability and resource savings.

Based on the results obtained, it is possible to argue that the introduction of modern technologies, in particular mechatronic systems, significantly improves the technical, economic and environmental characteristics of vibration-cleaning machines. Reduced wear and tear and extended equipment life reduce repair and maintenance costs. In addition, economic benefits, such as reduced energy consumption, as well as environmental benefits, such as reduced emissions, underline the overall benefit of implementing these systems. Thus, the results of the study confirm the effectiveness of mechatronic systems integration for sustainable development and productivity improvement.

Energy efficiency was also central in the survey results. Mechatronic systems optimised the energy consumption of vibration cleaning machines by adapting to changing conditions. This significantly reduced electricity consumption, which is especially important for businesses seeking to reduce costs and improve environmental performance. This aspect demonstrated that mechatronic systems not only increase the efficiency of equipment but also improve the overall energy efficiency. S. Afolalu *et al*. (2021) concluded that energy efficiency is one of the key advantages of mechatronic systems, as they reduce energy consumption through optimised process control. By precisely controlling parameters and reducing energy losses, these systems help reduce energy costs and increase the overall efficiency of the equipment. This not only reduces operating costs but also has a positive impact on the environmental sustainability of production facilities. S. Ogonowski & P. Krauze (2022) determined mechatronic systems

optimise the energy consumption of vibration-cleaning machines by precisely controlling vibrations and automating processes. The integration of sensors and controllers reduced energy losses by adapting the operation of machines to real conditions and needs. This ensures more efficient use of energy, which leads to lower overall costs and an improved environmental balance.

Analysis of the study results shows that mechatronic systems significantly improve the energy efficiency of vibration-cleaning machines. Their ability to optimise energy consumption and provide precise process control confirms significant economic and environmental benefits. The implementation of such systems not only reduces energy costs but also contributes to sustainable development and reduces environmental impact. However, to fully utilise these benefits, it is necessary to address the challenges associated with adopting new technologies.

Overall, the study results confirmed the effectiveness of mechatronic systems for the agricultural sector. They provide accuracy, stability, reduced maintenance costs and energy efficiency. This allows agricultural enterprises not only to increase productivity but also to make production processes more sustainable and cost-effective in the long term.

Conclusions

The introduction of mechatronic systems in vibration cleaning machines has significantly improved their accuracy and stability in the agricultural sector. The integration of mechatronic systems has made it possible to achieve a significant increase in the accuracy of vibration parameters, which has had a positive impact on the seed-cleaning process. Thanks to precise control of the frequency and amplitude of vibrations, automatic adjustment systems ensure uniform cleaning of different types of raw materials, which reduces product losses and improves overall quality.

Automated real-time load control ensures consistent cleaning efficiency, accounting for variable parameters such as seed or grain volume. This reduces the impact of external factors such as fluctuations in the flow of raw materials, which can negatively affect the stability of traditional machines. Monitoring and correction of operating parameters by means of integrated sensors ensures consistent machine performance even under changing operating conditions. This quickly identifies and corrects deviations, reducing the risk of malfunctions and increasing the overall reliability of the equipment. Reducing wear and tear on mechanical components by automatically adjusting parameters and preventing overloading not only extends machine life but also reduces maintenance costs, which has a positive economic impact. Energy efficiency achieved through optimising electricity consumption also reduces overall production costs. A study conducted based on the agricultural enterprise BIG Harvest Group demonstrated that the introduction of automated control of vibration processes has a significant positive impact on energy costs and seed cleaning quality. This decision not only improved the efficiency of production processes but also became an important step towards the sustainable development of the agricultural sector. Thus, automation of technological processes is the key to successful production modernisation and meeting modern market requirements.

In general, the introduction of mechatronic systems in vibration cleaning machines in the agricultural sector demonstrates significant benefits, including increased accuracy, stability and cost-effectiveness. This confirms the importance of continuing research and innovation in this area to further improve seed-cleaning technologies.

The limitation of the study is the coverage of only one type of vibration cleaning machine, which may limit the generalisability of the results for other models or designs of equipment. It is necessary to further study the impact of mechatronic systems on the long-term reliability and efficiency of vibration-cleaning machines under various operating conditions, including different types of raw materials and climatic conditions.

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Conflict of Interest

None.

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Вплив мехатронних систем на точність і стабільність роботи віброочисних машин у аграрному секторі

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Анотація. Дослідження було проведено для визначення того, як використання мехатронних систем може оптимізувати роботу віброочисних машин і покращити їх продуктивність у сільськогосподарських процесах. У цьому дослідженні застосовувалися методи вимірювання точності вібрацій, автоматизованого регулювання навантаження, моніторингу робочих параметрів, оцінки зносу, аналізу енергоефективності та оцінки впливу на мінімізацію людського втручання. Дослідження, проведене на підприємстві «BIG Harvest Group», продемонструвало, що впровадження мехатронних систем у віброочисні машини значно підвищує точність і стабільність їхньої роботи. Інтеграція автоматизованого регулювання частоти та амплітуди коливань дозволила зменшити енергоспоживання та підвищити ефективність очищення насіння порівняно з традиційними методами. Виявлено, що система автоматичного моніторингу і корекції параметрів забезпечує стабільну продуктивність машини навіть при змінних умовах навантаження. Зменшення зносу механічних компонентів вказує на подовження терміну служби обладнання, а також зниження частоти простоїв і потреби в ручному втручанні. Загалом, результати підтвердили, що мехатронні системи значно підвищують ефективність віброочисних машин, що позитивно впливає на якість очищення та економічну ефективність у сільському господарстві. Дослідження також виявило, що автоматичне коригування робочих параметрів за допомогою мехатронних систем дозволяє зменшити коливання в роботі машини, що забезпечує більш рівномірне очищення. Система інтегрованого моніторингу дозволила оперативно виявляти і усувати несправності, зменшуючи час на технічне обслуговування. В результаті, були досягнуті покращення в загальному управлінні процесами очищення насіння, що сприяє підвищенню продуктивності і зниженню витрат на експлуатацію обладнання

Ключові слова: автоматизоване регулювання; енергоспоживання; очищення насіння; знос механічних компонентів; економічна ефективність

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Welfare requirements for horse keeping

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Abstract. This study aimed to determine the optimal conditions for horse care, ensuring their physical and psychological welfare by analysing housing, nutrition, medical care, physical activity, and socialisation. The study examined the horse care conditions at farms and equestrian clubs in the Kyiv region (Ukraine), including "Aliur", "Grand Prix", "Kniazhyi Dvir", "Impuls", and "Olimp". The theoretical analysis described horse care conditions, the size and state of the facilities, feed quality, medical care, and aspects of physical activity and socialisation. The study's main findings indicate that all the analysed establishments provide a high level of comfort for horses, a crucial factor for their care and wellbeing. However, it is important to note that various approaches to horse care revealed unique features and advantages. For instance, the farm "Aliur" demonstrated an effective combination of high-quality housing conditions, including spacious stables with proper lighting and ventilation, balanced nutrition tailored to the individual needs of each animal, regular medical care ensuring timely prevention and treatment, and socialisation that fosters the emotional development of the horses. At the same time, the equestrian farm "Grand Prix" stands out for its high standards of sports care, which include specialised training and preparation of horses for competitions, ensuring their competitiveness in the sporting arena. The farms "Impuls" and "Olimp" distinguish themselves by implementing modern ventilation systems that improve air quality in the stables, as well as by providing high-quality training facilities that meet international standards, allowing not only the maintenance of horses' physical fitness but also ensuring their overall health and welfare. The analysis showed that the introduction of new monitoring technologies, the individualisation of feeding approaches, and social programmes could further enhance horse welfare. The findings highlight the importance of a comprehensive approach to horse care in ensuring their physical and psychological well-being, which can be useful for practical recommendations in the equine industry

Keywords: agriculture; animal husbandry; industrial agriculture; farm; livestock

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Introduction

Since the 2000s, significant attention in equine studies has been devoted to ensuring the physical and psychological welfare of horses. This issue has become particularly relevant in light of the growing popularity of equestrian sports and leisure activities, highlighting the need for appropriate conditions for the care of these animals. Despite numerous studies in this field, there remains a need for a comprehensive analysis of horse care conditions that affect their health and behaviour. Many existing research focus on individual aspects of this topic, such as nutrition, physical activity, or social interactions, which does not provide a complete picture.

The issue addressed in this study lies in the lack of a systematic approach to assessing the comprehensive conditions for horse care at modern farms and equestrian clubs. It is important to consider not only the physical factors, such as space, feed quality, and veterinary care, but also the psychological factors that may influence horse behaviour, including group social structure, stress levels, and opportunities for natural behaviour. Thus, conducting a thorough investigation will be a crucial step towards improving horse welfare, which, in turn, will have a positive impact on their performance and overall health.

J. Grzyb *et al*. (2022) investigated bacterial aerosols and foreign particles in the air composition of stables in Poland, highlighting concerns about air quality in equine facilities. A similar study was conducted by I. Rodzyń *et al*. (2024), identified the presence of chemical pollutants and biological aerosols in enclosed horse environments. However, despite these studies, there is still insufficient information regarding the impact of specific microclimatic parameters on horse health. J.M. Thompson *et al*. (2023) examined the financial pressures brought about by COVID-19 and their effect on the willingness to spend on horse care. This points to the economic aspect of animal care, yet further research is needed to explore the impact of economic factors on horse care conditions and welfare.

K.L. Luke *et al*. (2023) examined the complex relationships between horse welfare, rider safety, and the fulfilment of rider needs. W. Krupa *et al*. (2022) explored attitudes towards keeping horses outdoors and in groups, revealing differing perspectives on horse care. However, there is limited understanding of how various care regimes affect horse welfare across different countries. Z. Kelemen *et al*. (2021) investigated horse activities about care conditions, emphasising the importance of optimising conditions for elderly horses and those with chronic orthopaedic conditions. G.A. Keller *et al*. (2022) analysed the impact of weather on horse activity in pastures. Nevertheless, these studies do not always consider the combined effect of multiple factors on horses' recovery from exertion. M. Connysson *et al*. (2021) studied the effect of care conditions on the recovery of horses' musculoskeletal systems after exertion. However, there is a need for a comprehensive consideration of all factors influencing horses' physical recovery.

L. Kjellberg *et al*. (2024) presented a study detailing automated feeding stations and the measurement of feed consumption rates in active open stables. A. Akimbekov *et al*. (2023) demonstrated the use of trackers in horse breeding in Kazakhstan. However, more data is needed on the effectiveness of new technologies in monitoring horse care conditions. T. Sharapatov *et al*. (2023) examined ways to increase milk productivity in Kazakh horses. This research is significant for understanding the specifics of milk production in different horse breeds, but there is insufficient information regarding the impact of care conditions on milk yield.

I. Janczarek *et al*. (2020) examined the impact of temperature and humidity on the physiological parameters of horses, emphasising the importance of microclimate control. However, there is a need for a comprehensive analysis of the effects of various microclimatic factors on horse health. A. Géry *et al*. (2024) assessed the impact of aerobic fungi and bacteria on the horse environment. This

highlights the need for a deeper understanding of the influence of environmental factors on horses, though there is limited information on their effects on horse welfare in different conditions.

This study aimed to provide a comprehensive assessment of horse care conditions across various establishments, considering all factors that affect their welfare, and to compare care practices in different facilities, identify their strengths and weaknesses, and develop recommendations for improving the living conditions of horses.

Materials and Methods

The study was conducted through a detailed theoretical review of existing standards and practices related to horse care and management. This was exemplified by farms and equestrian clubs in the Kyiv Region (Ukraine), including "Aliur", "Grand Prix", "Kniazhyi Dvir", "Impuls", and "Olimp". The analysis examined the main types of feed used in horse nutrition, such as hay, compound feed, and concentrates. These feeds are crucial components of the diet, providing the necessary nutrients for normal development and maintaining the health of the animals. Additionally, grooming tools, such as brushes and hoof knives, were analysed as essential instruments for maintaining hygiene and overall horse welfare. Medical products, including vitamins, which enhance the animals' overall endurance, and deworming medications, necessary for the prevention of parasitic diseases, were also reviewed.

Additionally, attention was given to temperature control equipment, specifically digital thermometers (Digital Thermometer – Extech Instruments, USA), which allow for accurate measurement of horses' body temperature, crucial for the timely detection of potential illnesses. Hygrometers (Extech 445815 – Extech Instruments, USA) were examined for monitoring humidity levels in stables, as maintaining optimal humidity is crucial for preventing the development of diseases. The use of video cameras (Nest Cam Outdoor – Google Nest, USA) for monitoring horse behaviour was also included in the study, allowing owners and veterinarians to observe the animals' condition in real time, enabling prompt responses to any changes in behaviour or health. Thus, a comprehensive approach to studying these factors contributes to improving the care and management conditions for horses.

An evaluation was conducted on various aspects such as stable dimensions, ventilation, temperature, and humidity. The assessment of nutrition was based on the analysis of feed composition, feeding frequency, and regime, along with observations of horse behaviour during feeding. The evaluation of medical care included a review of the schedule of veterinary check-ups and procedures, as well as an analysis of medical histories. Physical activity assessment involved monitoring time spent on walks and free play, with video surveillance used to analyse movement patterns. Socialisation was assessed through observations of interactions between horses and with humans.

The data were systematised using statistical methods such as regression analysis and analysis of variance (ANOVA). This enabled a comparison of the care conditions and their impact on the health and behaviour of the horses, as well as identifying possible correlations between the care conditions and welfare indicators. The study also analysed the following regulatory documents: the Law of Ukraine No. 2498-XII (1992), Council Directive No. 98/58/EC (1998) and the Law of Ukraine No. 3447-IV (2006).

Results

Horse welfare is a complex concept encompassing the physical, psychological, and social well-being of the animals. The legal framework regulating the conditions of horse care is crucial for ensuring their welfare and health. The Law of Ukraine No. 3447-IV (2006) is a key legislative act regulating the conditions of care, management, and protection of animals, including horses, in Ukraine. This law aims to provide comprehensive protection against cruelty, which can manifest in various forms such as physical abuse, inadequate living conditions, and insufficient or poor-quality medical care. According to the provisions of this

law, horse owners are required to create conditions that meet the animals' physiological and psychological needs. This includes providing appropriate housing that is safe and comfortable, as well as adequate nutrition that meets the specific dietary requirements of horses. The law also emphasises the importance of regular medical care, including preventive check-ups and timely treatment of illnesses. An important component of the law is the provision for animal socialisation, which promotes emotional well-being, and ensures opportunities for physical exercise, which is crucial for maintaining the health of horses. The law outlines the responsibilities of owners to comply with these requirements, fostering a humane approach to animals within society.

State sanitary norms and regulations for the management of horses establish specific requirements for the conditions in which these animals should reside. Such standards stipulate that horse accommodation must provide a comfortable environment for the animals. The regulations mandate that stables must be clean, dry, and well-ventilated. It is crucial to ensure adequate lighting and ventilation to prevent the accumulation of harmful gases and to maintain an optimal microclimate. The bedding should be sufficiently soft and dry to provide a comfortable resting place for the horse. It is recommended to use straw, wood shavings, or specialised bedding materials that are easy to clean and possess good absorbent properties. To ensure space and comfort, horses must have enough room to avoid conflicts and minimise stress. European directives, such as Council Directive No. 98/58/EC (1998), have also had a significant impact on Ukrainian legislation. The directive aims to ensure a high level of animal welfare in all EU member states. According to this document, owners must assess potential risks to a horse's health and take steps to mitigate them; prevention and treatment of diseases – the regulations require regular veterinary checks and timely treatment of illnesses; socialisation and exercise – horses must have opportunities for regular physical exercise and social interaction with other horses.

The implementation of regulatory frameworks has a significant impact on the practical aspects of horse keeping, as regulations help to ensure comfortable conditions for horses, including quality nutrition, clean premises, and appropriate veterinary care. Regular veterinary checks and timely treatment help to prevent diseases and improve the overall health of horses. Regulations governing socialisation and exercise help to reduce stress in horses, providing them with opportunities for natural behaviour. Legislation and standards contribute to increasing horse owners' awareness of the importance of animal welfare, which can lead to improvements in husbandry and care practices. The regulatory framework is a crucial tool for ensuring equine welfare. Legislative acts and sanitary standards establish the foundations for their management and care, providing horses with conditions that meet their physiological and psychological needs. The implementation of European standards and regular monitoring of compliance contribute to improving the living conditions of horses, which in turn has a positive impact on their overall health and quality of life.

Horse husbandry is a complex and multifaceted process that requires attention to detail, careful planning, and the fulfilment of numerous requirements. The proper management of equine living conditions directly impacts their physical and psychological health, making the study of husbandry conditions extremely important. In Ukraine, there are a significant number of farms and equestrian clubs that provide varying levels of comfort and welfare for horses. Each establishment has its unique approach to horse husbandry, which can range from simple to complex systems depending on resources and goals.

The "Aliur" farm houses 40 horses in stables measuring 3×4 meters. Each stable is equipped with a ventilation system that ensures regular air exchange. Humidity in the stables is monitored by hygrometers and maintained at 60%. The temperature in the stables ranges between 10 and 15°C, which is a comfortable range for most

horse breeds, ensuring their health and comfort throughout the year. The bedding is cleaned daily to maintain a high level of hygiene and prevent the development of diseases.

The horses' diet consists of hay, compound feed, and concentrates. Feeding occurs twice daily: in the early morning and the evening. Hay provides the horses with the necessary fibre for healthy digestion, while compound feed and concentrates supplement the diet with proteins, minerals, and vitamins. Regular monitoring of the horses' diet and needs allows for adjustments to be made based on their physical activity and health. The farm conducts veterinary checks every three months. Anthelmintics and vitamin supplements are used for prevention and treatment. The examination includes checking the horses' general health, as well as the condition of their hooves and skin, allowing for the early detection and treatment of diseases. The horses have access to pasture for two hours every day, allowing them the opportunity for free movement and physical activity. In addition, the horses are regularly exercised in the arena, which helps to develop stamina and coordination. These conditions help to maintain the physical fitness and psychological well-being of the animals. The animals are kept in groups of 5-6 individuals, allowing them to interact with each other. This is important for reducing stress and ensuring normal social development. Social interactions between horses also help in the development of natural behavioural traits, such as group hierarchy and communication.

The "Aliur" farm has demonstrated a successful approach to horse management by combining high-quality living conditions, balanced nutrition, regular veterinary care, adequate physical activity, and effective socialisation. These factors ensure a high level of physical and psychological well-being for the horses. However, there is always potential for further improvement, particularly in enhancing the individualised care provided to each horse and implementing new technologies and practices that could increase the farm's management efficiency.

The "Grand Prix" equestrian club accommodates 35 horses in stables measuring 4x5 metres. The stables are equipped with automatic ventilation and heating systems, ensuring stable conditions throughout the year. Humidity levels are maintained at 50%, while temperatures range between 15 and 20°C. These conditions provide a comfortable environment, particularly for sport horses that require optimal conditions for recovery after training. The horses' diet consists of hay, specialised compound feeds, and grains. Feeding occurs three times a day: in the morning, afternoon, and evening. The specialised feeds offer a high level of protein and vitamins, which are essential for active and competitive horses. The feeding regimen is tailored to the physical needs and condition of each horse, promoting their optimal development and performance.

Veterinary check-ups are conducted monthly. Modern medical treatments, including anthelmintics and vitamin supplements, are used for prevention and treatment. This ensures timely treatment and maintains the horses' high level of athletic performance. The animals have access to an arena and training areas, where they exercise for 1-2 hours daily. This includes both structured training and free play. Such conditions ensure a high level of physical activity, which is important for maintaining physical fitness and achieving sporting goals. Horses are kept in small groups, which promotes the development of social skills and reduces stress. Interactions between horses and humans also stimulate socialisation, which is important for the overall well-being of the horses and their readiness for work.

At the "Kniazhyi Dvir" farm, the horses are housed in stalls measuring 3×3 metres, accommodating a total of 30 horses. Ventilation is achieved through open windows, without the use of automatic systems. Humidity in the stalls is maintained at 65%, while the temperature ranges from 5 to 10°C. The bedding is cleaned daily, which helps to uphold hygienic conditions. The horses' diet consists of hay and compound feeds, with feeding occurring twice a day to provide

essential nutrients. Hay supplies the necessary fibre for digestion, while the compound feeds supplement the diet with proteins and minerals. Feeding may be adjusted according to the season and the horses' level of physical activity. Veterinary examinations are conducted every six months, and basic medical treatments are employed for the prevention and treatment of diseases. This infrequent oversight may limit the opportunities for timely detection and treatment of illnesses. The horses have access to pasture for four hours each day, allowing them the freedom to move and engage actively. However, access to the arena is limited, which may reduce their overall level of physical activity and welfare. The horses are kept individually or in small groups, which may negatively impact their social adaptation and increase stress levels. Limited social interaction can lead to isolation and behavioural issues.

The "Kniazhyi Dvir" farm provides a high level of comfort and care for the horses through optimal housing conditions, balanced nutrition, regular medical care, sufficient physical activity, and effective socialisation. Implemented measures, such as modern ventilation systems, regular veterinary examinations, and organised physical exercise, significantly contribute to the physical and psychological well-being of the horses. However, as with any farm, there are opportunities for further improvement, particularly in expanding the possibilities for social interaction among the horses and introducing new technologies for monitoring and managing their health.

The "Impuls" farm provides horses (50 animals) with stables measuring 4×4 metres. The stables are equipped with modern ventilation systems that ensure regular air exchange and prevent the accumulation of harmful gases. Humidity in the stables is maintained at 55%, while the temperature fluctuates between 12 and 18°C. These conditions create a comfortable climate for the horses, which is particularly important during periods of extreme temperatures. The horses at "Impuls" are fed a diet that includes hay, compound feeds, concentrates, and vitamin supplements. Feeding occurs three times a day – morning, noon, and evening – ensuring a stable and balanced diet for the horses. The compound feeds consist of high-quality ingredients to support optimal physical condition and health.

Veterinary check-ups are conducted monthly on the farm. A high standard of medical care is ensured through the use of modern drugs for the prevention and treatment of diseases. Regular examinations help to identify health problems promptly and maintain a high level of equine health. The animals have access to large paddocks and training areas where they exercise for 2 hours daily. This includes both structured training and free play, which helps to maintain high levels of physical fitness and stamina. Horses are kept in large groups, which promotes their socialisation. Interaction between horses and humans also stimulates social adaptation and reduces stress, ensuring the overall psychological well-being of the animals.

The "Impuls" farm provides a high level of comfort and health for the horses through optimal living conditions, a balanced diet, regular medical care, sufficient physical activity, and effective socialisation. A systematic approach to managing the conditions in which the horses are kept contributes to their physical and psychological well-being. However, even in such a successful establishment, there is potential for further improvement. In particular, opportunities could be explored to optimise the social interactions of the horses, implement new technologies for monitoring their health, and increase the variety of physical activities to enhance the overall welfare of the animals.

The "Olimp" farm houses 45 horses in stables measuring 5x5 metres. The stables are equipped with heating and ventilation systems that maintain a comfortable temperature throughout the year. Humidity levels in the stables are monitored and maintained at 50%, while temperatures range between 10 and 15°C. This ensures stable and comfortable conditions for the horses. The horses' diet consists of hay, compound feeds, concentrates, and additional vitamins. Feeding occurs

three times a day, providing the horses with optimal and balanced nutrition (Table 1). The added vitamins and supplements contribute to maintaining the overall health and productivity of the horses. Monthly veterinary examinations are conducted on the farm. Modern medical treatments are employed for the prevention and treatment of diseases, ensuring high-quality medical care and prompt responses to health issues. The horses have access to large paddocks and training areas, where they engage in daily activities for 2 hours. This includes active exercise and training, which helps maintain their physical condition and endurance. Horses are kept in large groups, allowing them to interact with each other and with humans. This interaction helps reduce stress and ensures normal psychological well-being for the horses. Social interactions contribute to the development of natural behavioural traits and enhance the overall welfare of the animals. Overall, the conditions under which horses are kept play a crucial role in their quality of life (Table 2).

Table 1. *Horse diet in different farms*

Farm	Number of feedings per day	Feed types
Aliur	2	Hay, compound feeds, concentrates
Grand Prix	3	Hay, specialised compound feeds, grain
Kniazhyi Dvir	2	Hay, compound feeds
Impuls	3	Hay, compound feeds, concentrates, vitamins
Olimp	3	Hay, compound feeds, concentrates, vitamins

Source: compiled by the author

Table 2. *Comparison of horse-keeping conditions*

Parameter	Aliur	Grand Prix	Kniazhyi Dvir	Impuls	Olimp
Number of horses	40	35	30	50	45
Stable size	3×4 m	4×5 m	3×3 m	4×4 m	5×5 m
Temperature	10-15°C	15-20°C	5-10°C	12-18°C	10-15°C
Humidity	60%	50%	65%	55%	50%
Diet	Hay, compound feeds, concentrates	Hay, specialised compound feeds, grain	Hay, compound feeds	Hay, compound feeds, concentrates, vitamins	Hay, compound feeds, concentrates, vitamins
Feeding frequency	2 times a day	3 times a day	2 times a day	3 times a day	3 times a day
Veterinary check-ups	Monthly	Monthly	Every six months	Monthly	Monthly
Physical activity	2 hours daily (pasture, arena)	1-2 hours daily (arena, training arena)	4 hours daily (pasture)	2 hours daily (paddocks, training areas)	2 hours daily (paddocks, training areas)
Socialisation	Groups of 5-6 horses	Small groups	Alone or in small groups	Large groups	Large groups

Source: compiled by the author

Based on the analysis of the conditions for keeping horses at the farms "Aliur", "Grand Prix", "Kniazhyi Dvir", "Impuls", and "Olimp", it can be concluded that all the farms provide a high level of comfort for the horses through optimal housing conditions, balanced nutrition, regular veterinary care, sufficient physical activity, and effective socialisation. However, there are opportunities for further improvement, particularly through the implementation of new monitoring technologies,

individualised approaches to feeding, and social programmes aimed at enhancing the overall welfare of the animals.

Discussion

This study analysed the conditions of horse keeping on Ukrainian farms. Several key findings were obtained that can be compared to international research on various aspects of equine care, welfare, and social adaptation. Researchers D.J. Mellor & M. Burns (2020) highlighted the importance of managing breeding stallions with a focus on animal welfare. This study supports their findings regarding the necessity of maintaining optimal conditions for breeding horses to ensure their comfort and health. The research indicates that the conditions of horse management in the "Aliur" and "Grand Prix" farms align with these recommendations, as evidenced by satisfactory living conditions and adequate veterinary care.

The findings of M. Jobusch (2022) indicate the usefulness of existing protocols for the rapid assessment of the welfare of semi-wild horses. These results confirm that the evaluation protocols used on the "Olimp" and "Impuls" farms are effective for monitoring the welfare of horses; however, it has been noted that these protocols require adaptation to suit different management conditions. According to the work of D.H. Sigler (2024), the social and reproductive challenges faced by wild stallions are significant for understanding the social structure within a herd. The results of this study indicate that the socialisation of horses on the "Kniazhyi Dvir" and "Grand Prix" farms aligns with recommendations for social interactions and adaptation, which are crucial aspects for their mental well-being.

P.M. Bogossian *et al*. (2024) investigated the accuracy of assessing social dominance in domestic horses, a crucial aspect of equine group management. Observations at the "Impuls" and "Grand Prix" farms revealed that individuals can accurately assess social dominance, although there is potential for improvement in evaluation methods. Highlighting the quality of life for chronically ill and elderly horses, D. Householder & P.G. Gibbs (2024) emphasised the importance of regular physical activity and veterinary care. Findings confirmed that all studied farms provided adequate levels of physical activity and veterinary attention for horses, aligning with these recommendations.

M. Long *et al*. (2024) conducted a study focused on assessing the quality of life of old and chronically ill horses in Austria. They found a significant diversity of approaches to determining how long horses should live with chronic diseases, with a focus on quality of life as a key decision-making factor. This research on Ukrainian farms revealed that while the quality of life is considered important, it is often not a priority in cases of chronic diseases or ageing horses. The scientists emphasised the importance of a comprehensive approach to assessing equine quality of life, which should be considered when planning future research and recommendations in the field of equine welfare in Ukraine.

Research conducted by R. Smith *et al*. (2022) revealed that owners of leisure horses in the UK have diverse perceptions of their animals' welfare, which can influence their management and care. This research confirms that a similar variability in attitudes towards equine welfare exists in Ukrainian farms, although the data indicate a greater emphasis on physical care and less on psychological aspects. This may be a result of differences in cultural and economic contexts. The study of changes in horse behaviour during interventions related to equine therapy was conducted by F. Dai *et al*. (2023). They found that such interventions can have varying effects on equine behaviour. The results indicate that horses at the farms "Aliur" and "Grand Prix," which also participate in equine therapy, exhibit positive changes in behaviour, consistent with the findings of this research.

J. Fiedler & J. Slater (2024) utilised remote cameras to assess the welfare of free-ranging horses, emphasising the significance of continuous monitoring of equine conditions. Data on horse management practices in Ukrainian farms indicates that monitoring is conducted periodically

but not always in real time. J.C. Seabra *et al*. (2023) introduced a ten-step protocol for assessing the welfare of unconfined wild animals. This study reveals that the "Impuls" and "Kniazhyi Dvir" farms employ similar protocols for welfare assessment, although their approach requires adaptation to the specific conditions in Ukraine.

For an effective assessment of equine welfare, it is crucial to have a profound understanding of the fundamental knowledge concerning their needs and responses, as highlighted by M. Baumgartner *et al*. (2021). They emphasised that a comprehensive evaluation of welfare must consider not only the physical condition of horses but also their behaviour and social interactions. This study, aimed at evaluating horse management practices in Ukraine, revealed that many farmers predominantly focus on the physical condition of the horses, while aspects of behavioural and social needs are often overlooked. This indicates a necessity for enhancing knowledge in this area among Ukrainian specialists and implementing more holistic approaches to welfare assessment. Researchers L. Greening & S. McBride (2022) investigated weight management in horses on Prince Edward Island, emphasising the emotional aspects of this process. The results indicate that weight management practices at the "Aliur" and "Grand Prix" farms are more technical and less focused on emotional considerations, which may reflect a difference stemming from varying cultural approaches to animal management.

L.R. Tufton *et al*. (2023) described the impact of the COVID-19 pandemic on horse management, emphasising the necessity of maintaining animal welfare even in crisis situations. This study confirms that the "Aliur" and "Grand Prix" farms were able to adapt their management practices during the pandemic, reflecting their flexibility and prioritisation of equine welfare. T. Sundra *et al*. (2024) investigated the use of SGLT2 inhibitors for treating metabolic syndrome in horses and its effect on laminitis, which is significant for managing metabolic-related diseases. The authors note the positive impact of this treatment on improving horses' quality of life, as corroborated by the observations of horse owners. This study supports their findings, as similar positive effects from the administration of medications were recorded, albeit with some differences in the specifics of the application.

P. Kic *et al*. (2024) described the long-standing experience of managing free-ranging horses in Poland, particularly the Konik Polski breed, and their adaptation to environmental changes. The authors emphasised the importance of preserving traditional management methods to ensure equine welfare. This study indicates that there is also a need in Ukraine to integrate traditional approaches with modern management methods, which could enhance overall equine welfare. H. Milewska (2023) developed a new tool for assessing horse welfare, encompassing a wide range of criteria. This study demonstrated that the farms "Olimp" and "Grand Prix" utilise similar monitoring tools, but tend to focus more on physical indicators rather than a comprehensive assessment of welfare.

The results of this research corroborate the majority of conclusions reached by international scholars, particularly regarding crucial issues such as managing horse housing conditions, physical activity, veterinary care, and the socialisation of these animals. This indicates a widely accepted understanding of the importance of these aspects in ensuring equine welfare. However, the research identified several discrepancies in the practices employed across different farms. These discrepancies highlight the need for refinement of existing protocols and approaches used on individual farms to improve horse management and ensure their physical and psychological well-being. This may involve revising training methods, organising more effective veterinary care, and creating optimal conditions for horse socialisation, which is critical for their development and health.

Conclusions

The study of horse management conditions at the farms "Aliur", "Grand Prix", "Kniazhyi Dvir", "Impuls",

and "Olimp" has identified key factors influencing animal welfare. The examined farms demonstrate various approaches to ensuring horse comfort, allowing for an assessment of the effectiveness of different management methods. All the studied establishments provide a high level of welfare for the horses through well-organised stables, balanced nutrition, and regular veterinary care. However, significant differences exist between the farms in their management and care approaches, which are reflected in varying levels of animal socialisation, physical development, and overall health.

The data obtained confirm that successful horse care relies on an optimal combination of physical conditions (stable size, ventilation system, temperature and humidity control), nutritional quality (feeding system and diet type), and regular veterinary care. The results emphasise the importance of a comprehensive approach to ensuring horse welfare, which encompasses not only physical conditions but also social aspects and physical activity. Future research should focus on developing individual care and feeding programmes for horses, taking into account their specific needs. The implementation of modern health monitoring technologies will contribute to more effective management of the horses' well-being. Additionally, it is essential to enhance the conditions for horse socialisation, particularly in establishments with limited opportunities for group interactions.

The study has certain limitations, including the variability in housing conditions and the resources available to each establishment. Seasonal changes and differing levels of technical equipment may influence the results, necessitating further consideration in future research. Overall, the conducted research underscores the importance of a comprehensive approach to horse care, emphasising that only a systematic and holistic strategy can ensure optimal conditions for these animals. The study highlights opportunities for improving care practices, which may encompass enhancements in nutrition, physical activity, socialisation, and veterinary care, thereby contributing to the overall welfare of the horses – an essential factor for their productivity and longevity.

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Conflict of Interest

None.

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Добробутні вимоги до утримання коней

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Анотація. Метою даного дослідження було визначення оптимальних умов утримання коней для забезпечення їх фізичного та психологічного добробуту шляхом аналізу житлових умов, харчування, медичного обслуговування, фізичної активності та соціалізації тварин. Було проаналізовано умови утримання коней фермерських господарств і кінних клубів Київської області (Україна), зокрема «Алюр», «Grand Prix», «Княжий двір», «Імпульс» та «Олімп». У рамках теоретичного аналізу було описано умови утримання коней, розміри і стан приміщень, якість кормів, медичне обслуговування, а також аспекти фізичної активності і соціалізації. Основні результати проведеного дослідження свідчать про те, що всі проаналізовані господарства забезпечують високий рівень комфорту для коней, що є важливим аспектом їхнього утримання та благополуччя. Однак, варто зазначити, що різні підходи до утримання коней виявили свої унікальні особливості та переваги. Наприклад, фермерське господарство «Алюр» продемонструвало ефективну комбінацію якісних житлових умов, що включають просторі стайні з належним освітленням та вентиляцією, збалансованого харчування, яке враховує індивідуальні потреби кожної тварини, регулярного медичного обслуговування, що забезпечує своєчасну профілактику та лікування, а також соціалізації коней, що сприяє їхньому емоційному розвитку. У той же час, конярське господарство «Grand Prix» виділяється високими стандартами спортивного обслуговування, які включають спеціалізовані тренування та підготовку коней до змагань, що забезпечує їхню конкурентоспроможність на спортивній арені. Господарства «Імпульс» і «Олімп» відрізняються впровадженням сучасних систем вентиляції, що покращує якість повітря в стайнях, а також високоякісними тренувальними умовами, які відповідають міжнародним стандартам, дозволяючи не лише підтримувати фізичну форму коней, але й забезпечувати їхнє загальне здоров'я та добробут. Аналіз показав, що впровадження нових технологій моніторингу, індивідуалізація підходів до харчування та соціальних програм можуть ще більше покращити добробут коней. Отримані результати підкреслюють важливість комплексного підходу до утримання коней для забезпечення їхнього фізичного і психологічного добробуту, що може бути корисним для практичних рекомендацій у сфері кінного господарства

Ключові слова: сільське господарство; тваринництво; агропромисловий комплекс; ферма; худоба

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Morphological composition and quality characteristics of carcasses of Ukrainian Black-and-White dairy breed bulls depending on muscle tissue colour

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Abstract. In numerous global standards, muscle tissue colour is used as a key criterion in evaluating the quality of beef carcasses and determining their market value. The relevance of this study lies in establishing the relationship between beef colour and carcass quality characteristics. The objective was to determine slaughter metrics, morphological composition, and quality traits of carcasses from 18- to 24-month-old bulls of the Ukrainian Black-and-White dairy breed based on muscle tissue colour. Following a 24-hour fasting period with free access to water, the slaughter of bulls was conducted at the slaughterhouse in Kalynivka village, Brovary District, Kyiv Region. Muscle tissue colour was assessed using a seven-point scale by the methodology of the Japan Meat Grading Association. Carcasses were divided into two groups: scores of 1 to 5 (n = 24) and scores of 6 to 7 (n = 10). It was established that animals with higher live weight after fasting exhibited superior muscle tissue colour. A tendency is observed towards a reduction in slaughter yield (carcass) by 0.3 percentage points, the proportion of muscle tissue by 0.3 points, including a decrease in extra (by 0.9) and first rates (by 1.3) cuts, fat tissue (by 0.1), bones (by 0.1 points), marbling (by 3.8%), and the loin eye area (by 17.0%). Conversely, the proportion of muscle tissue at the second rate increases by 2.2 points. With a more intense muscle tissue colour, a significant increase (P > 0.999) is observed

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in the percentage of tendons and ligaments (by 0.5 points), carcass conformation (meatiness) (by 43.3%), fat cover (by 25.0%), subcutaneous fat thickness (by 42.9%), and the colour intensity of fat tissue on the carcass (by 17.8%). The practical significance of this study lies in its applicability for meat processing enterprises to classify carcasses of Ukrainian Black-and-White dairy breed animals according to intended use. Consumers are also provided with additional information for making an informed choice of beef based on the relationship between muscle colour and carcass quality traits

Keywords: meat productivity; global standards; beef colour; carcass classification; beef

Introduction

The colour of beef is a critical factor that significantly influences consumer choice, as it is often used as an indicator of freshness and quality. Research by J. Yang *et al.* (2024) demonstrates that consumers typically prefer a bright red meat colour, evenly distributed across the surface, with minimal moisture loss, as it signifies freshness. This colour strongly motivates consumers to purchase beef, whereas any deviation from a bright red appearance tends to elicit a negative response and discourages purchase.

However, meat colour is not always a reliable indicator of its textural properties, particularly shear force (Pacheco *et al.,* 2024). As no definitive correlation between beef colour and tenderness was identified, the authors conclude that visual assessment alone cannot accurately predict the softness or toughness of the product after cooking. This is important for consumers who prioritise specific textural properties of beef and may experience a discrepancy between expected and actual results after purchase.

The colour of muscle tissue is determined by a combination of chromatic and achromatic (colourless) attributes, which together shape its overall appearance. Chromatic attributes depend on the concentration of the pigment myoglobin, which influences the intensity of the red colour. Achromatic attributes, such as light reflectance, contribute to the gloss and brightness of the colour. These contributions can be quantitatively assessed using absorption and scattering coefficients, which characterise the meat surface's light reflection properties. These metrics, or their ratios, are used (Gagaoua *et al.*, 2024) as combined indicators to evaluate the colour perceived by consumers.

The external appearance of the final product is influenced by factors such as cattle diet, rearing conditions, genotype, sex, and others. Research by M. Hastie *et al.* (2024) indicates that beef from cattle fed a concentrate-based diet exhibited less dark colouring. It was significantly ($P < 0.01$) brighter, making it more appealing to consumers (Correa *et al.*, 2024). This highlights the substantial impact of cattle diet on the visual properties of meat, which in turn affects consumer preferences. Studies by A.M. Romo-Valdez *et al.* (2024) demonstrated that increasing the space allowance per animal from 14 m^2 to 16 m^2 improved carcass weight without affecting key quality characteristics of the carcass or beef (such as marbling, pH, and colour).

Research by J. Nusri-Un *et al.* (2024) established that Holstein-Friesian crossbreeds produce higher-quality beef compared to Charolais crossbreeds, despite exhibiting similar meat colour. This finding highlights the relationship between breed-specific traits and meat quality characteristics. It has been demonstrated (Blanco *et al.,* 2020) that beef from heifers is lighter in colour compared to that from bulls and steers. This indicates a correlation between the sex of the animals and meat colour, which could serve as a valuable criterion in breeding programmes. M.M. Krauskopf *et al.* (2024) identified that issues with abnormal meat colour, linked to pH variations, result in as much as 13.9% of beef on the market being categorised as dark, leading to

substantial financial losses. These findings emphasise the importance of monitoring pH and meat colour throughout various stages of production.

Therefore, determining the impact of muscle tissue colour on the morphological composition and quality characteristics of beef carcasses is a pressing issue in Ukraine. This study aimed to assess slaughter performance, morphological composition, and quality traits of carcasses depending on muscle tissue colour in bulls from Ukrainian Black-and-White dairy breed cows (UBWDB).

Materials and Methods

The study was conducted between 2014 and 2016 at the Zhuravushka farm in the Brovary District of Kyiv Region, using 34 carcasses from 18- to 24-month-old bulls of the UBWDB. Data processing, analysis, and synthesis, as relevant to the study's title, were completed in October 2024. All experimental research adhered to established methodological approaches and met the requirements and standards outlined in DSTU ISO/IEC 17025:2005 (2006). The housing of cattle and all related procedures were carried out in compliance with the provisions of the Procedure for Conducting Scientific Experiments on Animals (Law of Ukraine No. 249, 2012) and the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986). The pre-slaughter live weight of the bulls was determined by weighing them following a 24-hour fasting period with free access to water.

The slaughter of the animals was conducted at a slaughterhouse located in Kalynivka village. Within one hour after slaughter and hide removal, the carcasses were weighed using calibrated scales. Certified experts with extensive experience visually classified carcass conformation into the classes E, U, R, O, and P, following the Commission Regulation (EC) No. 1249/2008 (2008). This ensured a high level of classification accuracy and compliance with international standards. In addition to conformation, the assessment considered the external appearance of the carcasses, their symmetry, and the degree of muscle tissue development. Fat cover on the external surface and in the thoracic cavity was classified into five categories based on the same regulatory system. Muscle and fat tissue colour were evaluated using colour scales ranging from 1 to 7, following the Japan Meat Grading Association (2000) standards (Fig. 1). To eliminate the influence of external factors, such as lighting levels or viewing angles, colour assessments were performed under standardised lighting conditions. This approach ensured objective information regarding beef colour, a critical indicator of meat quality.

Figure 1. *Muscle tissue colour grading scale*
Source: Japan Meat Grading Association (2000)

Based on muscle tissue colour, the 34 carcasses were divided into two groups: Group 1 (scores 1-5, n = 24) and Group 2 (scores 6-7, n = 10). This grouping facilitated a detailed examination of differences in marbling, the physicochemical properties of muscle tissue, and other meat quality indicators depending on colour intensity. Immediately after the division of carcasses into quarters, marbling of the *m. longissimus dorsi* between the 12th and 13th ribs was assessed according to the Japan Meat Grading Association (2000) standard across 12 classes. This assessment utilised visual grading scales, which enhanced evaluation accuracy and ensured standardisation across different carcasses.

Between the 12th and 13th ribs, the length and depth of the *m. longissimus dorsi* (loin eye) were measured using a ruler. The loin eye area was calculated using the equation (1) according to Order of the Ministry of Agrarian Policy of Ukraine No. 290, 2004):

$$S = L \times D \times 0.8, \quad (1)$$

where S is the loin eye area, cm^2; L is the length of the loin eye, cm; and D is the depth of the loin eye, cm. This method serves as a reliable tool for predicting muscle mass and potential meat quality. All measurements were conducted twice to minimise errors, ensuring precise and reproducible data. Statistical analysis was performed using Microsoft Excel 2016, encompassing the determination of mean values, standard errors, and reliability criteria.

Results and Discussion

The colour of the muscle tissue received a higher score, corresponding to a slightly greater live weight of bulls after fasting (by 2.4%, Table 1). Improved muscle tissue colour was also associated with a tendency for increased carcass weight (by 1.7%).

Table 1. *Slaughter characteristics and morphological composition of bull carcasses based on muscle tissue colour intensity*

Characteristic	Muscle tissue colour, points	
	1-5 (n = 24)	6-7 (n = 10)
Live weight after fasting, kg	422 ± 4.7	432 ± 22.1
Carcass weight, kg	193.3 ± 3.46	196.6 ± 10.91
Slaughter yield (carcass), %	45.8 ± 0.12	45.5 ± 0.53
Muscle tissue, %	71.6 ± 0.62	71.3 ± 0.98
Including extra, %	23.0 ± 0.73	22.1 ± 1.23
-//- first rate, %	47.0 ± 0.52	45.7 ± 0.81
-//- second rate, %	30.0 ± 1.03	32.2 ± 1.85
Fat tissue, %	3.7 ± 0.43	3.6 ± 0.24
Tendons and ligaments, %	1.6 ± 0.08	2.1 ± 0.11***
Bones, %	23.1 ± 0.32	23.0 ± 1.13

Note: ***P > 0.999

Source: compiled by the authors

Examining the current state of knowledge regarding the quality of beef carcasses and meat, with a focus on factors influencing its production and processing, M.Á. CantareroAparicio *et al.* (2024) observed an improvement in muscle tissue colour with increasing carcass weight. These authors highlight the significant role of carcass weight as a factor that can influence the external characteristics of meat. Conversely, the research conducted by R. Kocyigit *et al.* (2023) presented contradictory findings, indicating that as carcass weight increased, the brightness of muscle tissue colour decreased significantly. The authors attributed this to enhanced fat deposition and a slower decline in glycogen levels in cattle, which supports lactic acid formation. As a solution, A. Poveda-Arteaga *et al.* (2023) suggested standardising the slaughter weight of animals to minimise substantial differences in meat colour. In this context, the United States Department of Agriculture (USDA) has implemented price deductions for carcasses exceeding 408 kilograms, reinforcing the importance of weight management in ensuring quality (USDA-ERS, 2024).

With the improvement in the evaluation of muscle tissue colour from 1-5 to 6-7 points, there is a significant increase (P > 0.999) of 0.5 points in the amount of tendons and ligaments in the carcass. Ukrainian Black-and-White dairy breed cattle are characterised by late maturity.

According to S. Raza *et al.* (2019), animals of this type exhibit higher calpastatin activity and a greater percentage of connective tissue. Tendons, ligaments, and bones do not affect the nutritional quality of beef; however, muscle and fat tissues have a significant impact, showing a tendency to decrease as muscle colour improves. Therefore, the results of current research suggest that the colour of beef can serve as an indicator for predicting its morphological composition.

With a more saturated (6-7 points) muscle tissue colour, the conformation (meatiness) of the carcasses improved by 43.3% (P > 0.999) (Table 2).

Table 2. *Basic physical and chemical parameters of raw materials (n = 4)*

Muscle tissue colour, points	Characteristics					
	Carcass conformation, points	Fat cover development on the carcass, points	Subcutaneous fat thickness, cm	Marbling of *m. longissimus dorsi*, points	Fat tissue colour on the carcass, points	Loin eye area *m. longissimus dorsi*, cm^2
15 (n = 24)	3.0 ± 0.19	2.4 ± 0.08	0.7 ± 0.08	5.4 ± 0.72	4.5 ± 0.12	86.1 ± 4.44
76 (n = 10)	4.3 ± 0.27***	3.0 ± 0.22***	1.0 ± 0.10***	5.2 ± 1.00	5.3 ± 0.16***	73.6 ± 5.67

Note: ***P > 0.999

Source: compiled by the authors

According to G. Indurain *et al.* (2008), the effectiveness of meat colour for differentiating carcass conformation is 62%. With a more intense (6-7 points) muscle tissue colour, fat cover (by 25.0%) and subcutaneous fat thickness (by 42.9%) significantly increased (P > 0.999). The direct correlation between visual assessment of muscle tissue colour and fat cover development, its thickness, and carcass meatiness can be explained by the fact that fatter carcasses are obtained with higher conformation scores. According to L. Fiems *et al.* (2000), beef colour showed only limited predictive power (r < 0.15) for fat cover development in carcasses. The effectiveness of differentiating this trait is only 37% (Indurain *et al.,* 2008). This somewhat explains the results obtained in the current study and presented in Table 1, regarding the decrease in the content of extra and muscle tissue first rates with improved muscle colour. Better fat cover development and thickness on the carcass with a brighter beef colour reduces the amount of valuable edible parts in it.

With an increase in beef colour intensity, there is a tendency for a 3.8% decrease in its marbling (intramuscular fat), which during heat treatment gives the meat a specific flavour and lubricates its fibres, improving its consumer perception. Meat colour, along with the amount of visible fat (marbling), are the first characteristics that consumers consider when evaluating its quality (Geay *et al*., 2001). The lack of a relationship between the studied traits (meat colour and marbling) is the main reason for the negative impact of a better assessment of meat colour on its sensory properties (Kruk & Ugnivenko, 2024). Fresh meat contains deoxymyoglobin and oxymyoglobin. Deoxymyoglobin gives fresh meat its red pigmentation. In the presence of oxygen, it oxidises to oxymyoglobin, which gives the meat a bright pink-red colour. When deoxy- and oxymyoglobin are oxidised to metmyoglobin, the meat acquires a brown colour. The formation of metmyoglobin is promoted by a decrease in pH, which is caused by better fat deposition. The enzyme metmyoglobin reductase reduces the level of the undesirable form of myoglobin and thus stabilises the colour of muscle tissue. Beef, which is characterised by a lower content of intramuscular

fat, is tougher and drier (Clinquart *et al*., 2023). In carcasses with a low ratio of fat to muscle tissue, which are more prone to the DFD (Dark, Firm, Dry) meat defect, there may be a significant mismatch between meat colour and its quality during processing. With an increase in the score of beef colour, the colour of the fat tissue on the carcass significantly improved (P > 0.999) by 17.8%. In studies by H. Kim *et al.* (2023), no significant differences were observed in the quality characteristics of beef between animals in groups with normal fat cover colour and increased yellowness in Korean Hanwoo cattle. These data indicate that the yellowing of fat tissue on the carcass was not significantly correlated with poorer physical characteristics of beef or its chemical composition. Muscle tissue colour did not have a significant impact on the chemical composition, physicochemical, and sensory properties of beef in experiments by A. Moloney *et al.* (2022). The data obtained in the current study show that with an increase in colour intensity from 1-5 to 6-7 points, there is a tendency for a 17.0% decrease in the loin eye area *m. longissimus dorsi*, since there is a tendency for an inverse correlation between muscle tissue colour and the loin eye area (Kruk *et al.,* 2024). This peculiarity of darkening of muscle tissue and yellowing of fat in the experimental animals can be explained by feeding a small proportion of concentrate feed (21.1%) and a significant amount of green, succulent (32.3%) and roughage (30.4%) in the diet.

Therefore, there are problems with assessing beef colour in 18-24-month-old bulls obtained from Ukrainian Black-and-White dairy breed cows, including the deterioration of such characteristics as the proportion of muscle tissue, including extra and first rates, marbling, and the area of the loin eye area *m. longissimus dorsi*. Beef colour is influenced by breed, meat acidity (pH), moisture content, intramuscular fat, and connective tissue content (Pogorzelska *et al*., 2013). T. Sakowski *et al.* (2022) identified that the lifetime factors affecting muscle tissue colour include the sex and age of the animals, the duration of their feeding, seasonality, pre-slaughter stress, nutritional status, slaughter process, and meat maturation time after slaughter. Studying the influence of age and sex on the quality characteristics of carcasses and technological indicators of buffalo meat, A. Turan *et al.* (2021) found that the colour of beef in older animals was significantly darker (P < 0.001) than in younger ones. The meat of male buffaloes was lighter than that of females. Y. Bao & P. Ertbjerg (2019) explain the darker colour of meat to the larger diameter of muscle fibres, as a result of which the distance between the light bands is longer, which allows more light to pass into the centre of the muscles. A.M. Hanson (2023) considers the main disadvantage of beef from traditional dairy cattle to be a noticeably darker colour, rather than the "cherry-red" appearance of conventional beef, which consumers prefer. However, in studies by F. Giannico *et al.* (2024), neither the grazing system nor the slaughter age affected meat colour. Ageing beef leads to a significant increase in the red hue during storage. 19% of consumers make purchasing decisions about beef based on its colour (Realini *et al*., 2014). Beef colours DFD (Dark, Firm, Dry) and PSE (Pale, Soft, Exudative) are well-known. In the US beef industry, changes in beef colour result in annual losses of natural resources totalling USD 3.9 billion (Ramanathan *et al*., 2023). Despite global achievements in regulating the formation of muscle tissue colour in cattle to improve beef quality, this problem has not been sufficiently addressed in Ukraine and deserves further research.

A pressing issue as Ukraine moves towards joining the European Union is the justification for including meat colour as a quality indicator in regulatory documents for classifying beef carcasses. This would enhance beef production, promote consumer health, and reduce the consumption of natural resources and energy.

Parallel assessment of carcass quality based on meat colour is already in place in classification systems such as the Ministry of Agriculture, Food and Rural Affairs (n.d.) in Korea, Japan Meat Grading Association (2000) in Japan, the USDA Beef

Grading Scale (n.d.), and Meat Standards Australia (n.d.) in Australia.

This raises the question of how to produce high-quality beef while considering meat colour as a quality indicator for dairy cattle, which are frequently fattened for slaughter. Future research should also focus on determining the quantitative and qualitative characteristics of beef based on its colour in beef cattle breeds, as this would improve the visual quality of carcasses and meat. Research should also be conducted to identify management factors for raising cattle of common Ukrainian breeds to achieve an optimal beef colour that is appealing to consumers and can be combined with desirable technological, sensory, and chemical properties.

Conclusions

The results obtained from assessing the colour of beef from Ukrainian Black-and-White dairy breed bulls indicate a deterioration in many of its quality characteristics with an increase in colour intensity. With a higher live weight of Ukrainian Black-and-White dairy breed bulls after fasting, there is a tendency for an increase in muscle tissue colour. With an improvement in muscle tissue colour intensity, the percentage of tendons and ligaments significantly increased by 0.5 points ($P > 0.999$), carcass conformation (meatiness) by 43.3%, fat cover (by 25.0%), fat thickness (by 42.9%), and fat colour (by 17.8%). With an increase in the score of muscle tissue colour, there is a tendency for a decrease in slaughter yield (carcass) (by 0.3 points), percentage of muscle tissue (by 0.3), including extra (by 0.9) and first rates (by 1.3), fat tissue (by 0.1) and bones (by 0.1), beef marbling by 3.8% and the loin eye area by 17.0%, and an increase in second rate meat (by 2.2 points).

To improve the quality of beef from dairy cattle in Ukraine, it is necessary to consider including muscle colour as an indicator in regulatory documents for beef quality assessment. As the results show, colour intensity affects several quality characteristics that determine the product's consumer appeal. Further research should also be conducted on other cattle breeds common in Ukraine to improve beef production technologies with optimal colour indicators. This will allow for a more objective assessment of meat quality and the development of recommendations for producing products with high sensory characteristics that meet consumer preferences.

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None.

Conflict of Interest

None.

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Морфологічний склад та якісні ознаки туш бугайців української чорно-рябої молочної породи залежно від кольору м'язової тканини

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Анотація. У багатьох світових стандартах колір м'язової тканини застосовують під час оцінювання якості туш великої рогатої худоби для визначення їх вартості. Актуальність роботи полягає у визначенні зв'язку між забарвленням яловичини та якісними ознаками туш. Метою дослідження було визначити забійні показники, морфологічний склад та якісні ознаки туш 18-24 – місячних бугайців української чорно-рябої молочної породи відповідно до забарвлення м'язової тканини. Після 24-годинного голодування за вільного доступу до води, забій бугайців провели в забійному цеху с. Калинівки Броварського району Київської області. Колір м'язової тканини оцінили за шкалою від 1 до 7 балів згідно з методикою японської асоціації класифікації яловичини Japan Meat Grading Association та туші поділили на дві групи від 1 до 5 балів (n = 24) та від 6 до 7 балів (n = 10). Установили, що колір м'язової тканини кращий у тварин за більшої живої маси після голодного витримування. За цього проявляється тенденція до зменшення забійного виходу (туші) на 0,3 пункти, відсотка м'язової тканини на 0,3 у тому числі вищого (на 0,9) та першого (на 1,3) сортів, жирової тканини (на 0,1) та кісток (на 0,1 пункти), мармуровості (на 3,8 %) та площі «м'язового вічка» (на 17,0 %), збільшення на 2,2 пункти м'язової тканини другого сорту. За інтенсивнішого кольору м'язової тканини достовірно (P > 0,999) збільшуються відсоток сухожилок та зв'язок на 0,5 пункти, конформація (м'ясистість) туш (на 43,3 %), покриття їх жировим покривом (на 25,0) та товщина підшкірного жиру (на 42,9), колір жирової тканини на туші на 17,8 %. Практичне значення роботи полягає в можливості використання отриманих знань на переробних підприємствах, для сортування туш тварин української чорно-рябої молочної породи відповідно до призначення, а споживачам нададуть додаткову інформацію для об'єктивного вибору м'яса за урахування зв'язків між забарвленням м'язів та якісними ознаками туш

Ключові слова: м'ясна продуктивність; світові стандарти; колір яловичини; класифікація туш; яловичина

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Condition of the permanent forest seed base objects of the Slavuta Forestry branch of the State Enterprise "Forests of Ukraine"

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Abstract. The permanent forest seed base (PFSB) serves as the foundation for the procurement of improved selective seeds for forest regeneration and afforestation. Analysing the condition of PFSB objects enables the evaluation of the quality and quantity of valuable reproductive material used in forestry. This study encompassed: an analysis of the formation and localisation of PFSB objects under the conditions of the Slavuta Forestry branch; an investigation of the condition and

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selective structure of forest genetic reserves and plus stands; and an analysis of the dynamics of forest nursery production development within the branch. Within the forest fund of the branch, 27 plus trees of common oak and Scots pine were selected. The total area of permanent forest seed plots amounted to 71.3 hectares. The survey results indicated that the examined plus trees of common oak (7 trees) in the Partyzanske Forestry are in good to satisfactory condition, predominantly belonging to the 2nd selective category, and demonstrated a satisfactory level of reproduction. To establish permanent forest seed plots with optimal characteristics, it was recommended to gradually thin the stands and prune tree crowns. It had been determined that the seedling seed orchard of European larch (Zhukivske Forestry, compartment 8, plot 41, area 2.0 hectares, established in 2010) was in good condition, exhibits a high level of reproduction, and meets all required standards. Research findings indicated that the quality of forest seeds collected from PFSB objects was sufficiently high. Specifically, in 2021 and 2022, nearly all seeds (80% and 100%) were classified as Grade I and Grade II quality, with no substandard seeds detected. The efficiency of utilising permanent forest seed base objects within the enterprise was high, as in productive years, the maximum amount of seeds was collected, fully meeting the enterprise's needs. Data on the condition of PFSB objects are critically important for implementing measures related to forest regeneration and afforestation

Keywords: forest nursery production; genetic reserves; plus trees; forestry; forest restoration

Introduction

Research into the condition of permanent forest seed bases (PFSBs) and forest cultivation is essential for preserving the genetic diversity of forest ecosystems and ensuring sustainable forest management. It enables the evaluation of the effectiveness of forestry measures, the development of recommendations for their improvement, and contributes to the advancement of the scientific foundations of forestry. PFSBs serve as a strategic reserve of genetic material for forest tree species, used for forest restoration and the preservation of their biodiversity. Assessing the condition of PFSBs, seed quality, and the effectiveness of forest cultivation measures is a crucial task for forestry, as it determines not only the productivity of forests but also their ability to adapt to climate change and other anthropogenic factors.

The research by I. Neyko *et al.* (2022) on the condition of PFSB objects represents a significant step in their comprehensive assessment to determine their compliance with specific criteria. Since their initial creation and establishment in the 1970s and 1980s, a significant portion of these sites have lost their original importance and require replacement. In the 2000s, scientists at the Ukrainian Research Institute of Forestry and Forest Melioration (URIFFM) conducted assessments of most forest genetic reserves and plus trees, developing a corresponding methodology. However, field studies primarily focused on deciduous tree species, while clonal and seedling seed plantations were less studied. Therefore, a detailed examination of all PFSB sites within individual enterprises is urgently needed. Research on forest genetic resources by I. Neyko *et al.* (2022) indicates a certain deterioration of their condition, particularly regarding oak forests. Provenance tests and clonal seed orchards play a crucial role in studies aimed at assessing the impact of climate change on forest ecosystems. According to I. Neyko *et al.* (2022), the lack of a proper assessment of the condition and reproductive capacity of PFSB sites limits the possibility of obtaining high-quality forest seeds, especially under conditions of climate change and the spread of forest diseases and pests.

Clonal and seedling seed orchards have not been examined. In this regard, a detailed inspection

of all PFSB sites within individual enterprises is extremely important. A comprehensive study of all sites allows for a complete assessment of their condition and functioning, as well as an evaluation of the effectiveness of their use. Most studies of forest genetic resources indicate some deterioration of their condition and an increasing negative impact of external environmental factors. O.M. Danylenko *et al.* (2022) considered that the deterioration of the condition, growth, and development of forest stands is largely due to unfavourable site conditions. At the same time, M. Kohler *et al.* (2021) emphasise the significant impact of management activities, which often change the structure and functioning of ecosystems, leading to the degradation of forest soils and a decrease in biodiversity. According to G. Weithmann *et al.* (2021), climate change and soil droughts have a key impact on the condition of forest ecosystems, leading to a deterioration of the health and resilience of forest ecosystems. Similar trends were observed by B. Schuldt *et al.* (2020). The authors conducted a detailed assessment of the impact of the extreme summer drought of 2018 on Central European forests. They noted a significant weakening of tree stands, including reduced growth, defoliation, and increased tree mortality, which were consequences of soil moisture deficits. They emphasise that such droughts can lead to long-term changes in the structure of forest ecosystems, weakening the resilience of forests to future extreme weather events. In response to the challenges facing forest ecosystems, research is being conducted to select the most resilient species, populations, and genotypes of tree species. For example, J. Amaral *et al.* (2022) used an interdisciplinary approach to identify genetically resistant trees to biotic factors, considering the case of pine trees affected by canker. V. Dyshko *et al.* (2024) focused on studying populations of pine resistant to root rot, which will contribute to preserving the resilience of future pine forests in conditions of increased pathogenic activity.

V. Tkach *et al.* (2019) highlighted the importance of assessing the reproductive function of major forest-forming species in clonal and seedling seed orchards, especially in the context of global climate change. According to recent surveys by Y. Hayda *et al.* (2019), most seed orchards in the region are in good condition, and coniferous species exhibit relatively high seed productivity. However, there is a trend towards decreasing seed productivity in deciduous species, particularly common oak. The lack of a proper assessment of the condition and reproductive capacity of PFSB objects prevents the prediction of the possibility of harvesting high-quality, selectively improved forest seeds. The issue of forest restoration within seed zones is particularly relevant due to global challenges such as climate change, intensive development and the spread of forest diseases and pests.

This study aimed to assess the condition of the permanent forest seed base of the Slavuta Forestry branch, evaluate seed material quality, and analyse the effectiveness of measures implemented in forest nursery production.

Materials and Methods

The study of the condition and utilisation of permanent forest seed base (PFSB) objects was conducted during the vegetation seasons of 2020-2024 within the Slavuta Forestry, branch of the state enterprise "Forests of Ukraine". The primary research objects included plus trees, forest genetic reserves, plus stands, seedling and clonal seed orchards, as well as permanent and temporary forest seed plots and forest nurseries. The assessment of PFSB objects was carried out in the Partyzanske, Zhukivske, and Komarivske forestries. Additionally, the condition of open forest stands established using seedlings with containerised and bare-root systems was specifically studied under the conditions of the Holytske, Partyzanske, and Komarivske forestries.

Most of the objects were designated and established in conditions of fresh fairly fertile site type. Field studies involved the evaluation of both individual trees and entire stands. Sample plots were established, with their number determined

by factors such as stand age, species composition, and productivity. The sample plots were set up following standard forest inventory methodologies, predominantly as strip plots. These plots adhered to key requirements, ensuring the inclusion of at least 100 trees of the main tree species – common oak and Scots pine in this case.

Various approaches were employed during the inventory of forest genetic resources to assess the condition and selective value of individual trees, stands, or seed orchards as a whole. These included the Sanitary Rules in Forests of Ukraine (Resolution of the Cabinet of Ministers of Ukraine No. 748, 2024), forest monitoring methodologies, and tree condition assessment methods developed by URIFFM (Los *et al.,* 2019).

The study of forest genetic reserves, plus stands, and permanent and temporary forest seed plots involved the determination of their forest inventory parameters. For each tree, in addition to measuring DBH and assessing technical suitability, both the selection category and condition category were established. The selection category was determined using a 4-point scale, while the condition was evaluated using a 6-point scale by the Sanitary Rules in Forests of Ukraine. The selection category assessment considered factors such as growth intensity based on diameter, the presence or absence of curvature, and any damage or diseases. The condition categories also took into account the percentage of crown defoliation and dechromation. Tree condition categories were determined at the end of the vegetation period to reflect the cumulative influence of all environmental factors. For the stands, average values of the selection and condition categories were calculated. To refine forest inventory characteristics, temporary sample plots were established in the most representative locations.

For each plus tree, the following parameters were assessed: condition indicators (condition category 1-6), selection category (selection category 1-4), total height (m), height to the first dry and live branch (m), and any damage or diseases present (Los *et al.,* 2019). A general overview of the certified objects of PFSB is presented in Table 1.

Table 1. *Characteristics of PFSB in the Slavuta Forestry branch*

PFSB Objects	Last basic forest inventory	For the previous year before inspection (based on reporting)
Plus trees, pcs	27	27
Plus stands, ha	-	-=
PFSS, ha	71.3	71.3
Seed plantations, ha	-	2.0
Genetic reserves, ha	-	-

Source: developed by the authors based on the Official website of Slavuta Forestry branch (n.d.)

According to the available information, the anticipated seed yield in the Slavuta Forestry branch was calculated for the following species: Scots pine, common oak, and European larch. Permanent sample plots were established across all PFSB objects to monitor and account for the expected harvest. Seed harvest was carried out by private contractors under formal agreements. Upon completion, a delivery-acceptance report was issued. Additionally, seeds were gathered by forestry personnel. All harvested seeds were processed either manually or in the cone dryer at the Iziaslavske Forestry branch. Approximately 27 plus trees were selected within the enterprise's forest fund. The total area of permanent forest seed plots amounts to 71.3 hectares. A seedling seed orchard of European larch covering 2.0 hectares has been certified. In the Zhukivske Forestry (compartment 19, plot 32, area 5.0 hectares), a seedling seed orchard of common oak was estab-

lished in 2010. However, as of August 2023, this orchard remains uncertified. Information regarding forest cultivation activities in the Slavuta Forestry branch is provided in Table 2.

Table 2. *Dynamics of forest cultivation in the Slavuta Forestry branch*

Types of work	Last basic forest inventory	For the previous year before inspection (based on reporting)
Planting and sowing of forest, ha	112.5	118.9
Natural regeneration, ha	25.7	18.7
Complementation of forest cultures, ha	136.0	247.9
Care for forest cultures, ha	1,500	1,425
Availability of forest nurseries, pcs./ha	4/2.38	6/1.5
Amount of seed sown in nurseries, kg	1,920.0	4,832.5
Number of seedlings, thousands pcs.	924.2	1,233

Source: developed by the authors based on the Official website of Slavuta Forestry branch (n.d.)

Data from the latest forest inventory period indicate an increase in forest planting and sowing activities. Conversely, there has been a slight reduction in the areas designated for natural regeneration. The production of planting material has significantly increased over recent years. All research adhered to widely accepted ethical norms and guidelines (Convention on the Trade..., 1973; Convention on Biological..., 1992). The primary source of reproductive material for establishing seed orchards was the archive of common oak clones. This archive, established in the 1970s-1980s within the Vinnytsia Forestry branch, provided selectively improved seeds. Seedling seed orchards were established using acorns collected from this clone archive.

Results and Discussion

An assessment of the plus trees of common oak (7 trees) in the Partyzanske Forestry revealed that their condition is generally rated as good to satisfactory, predominantly within the 2nd selection category, and exhibits a satisfactory level of reproduction. One plus tree of common oak (No. 23/9), with a condition category of 5, requires removal and replacement with an equivalent tree within the compartment. The PFSS of common oak (Partyzanske Forestry, compartment 52, plot 11, area 17.0 ha) is in good condition, demonstrating a good level of reproduction and meeting the functional criteria. It is advisable to implement thinning measures for the undergrowth. The PFSS of common oak (Komarivske Forestry, compartment 60, plot 9, area 5.3 ha) is also in good condition, with a satisfactory level of reproduction. The stand meets the current standards. The PFSS of Scots pine (Zhukivske Forestry, compartments 8, plots 4, 12, 16, 26, 29, area 18.2 ha, established in 1971-1976) is in unsatisfactory condition and fails to meet the required height and density criteria. This PFSS has lost its functional purpose, is no longer used for seed harvesting, and requires replacement. The PFSS of European spruce (Zhukivske Forestry, compartment 8, plots 29, area 2.7 ha and 4.5 ha, established in 2011) is in good condition and exhibits a good level of reproduction.

To form a PFSS with optimal characteristics, it is necessary to carry out a phased thinning of the stands and pruning of tree crowns. The European larch seedling seed orchard (Zhukivske Forestry, compartment 8, plot 41, area 2.0 ha, established in 2010) was in good condition, had a high level of reproduction, and fully met all requirements. Crown pruning and row maintenance were carried out on the plot. The common oak seedling seed orchard (Zhukivske Forestry, compartment 19, plot 32, area 5.0 ha, established in 2010) is in good condition and has entered the reproductive stage. The FP meets the basic criteria and can be

certified for subsequent inclusion in the enterprise's PFSB and the State Register. Plus trees are in good condition. Individual trees exhibit certain signs of deterioration and drying (Table 3, Fig. 1).

Table 3. *Characteristics of surveyed plus trees of common oak within the Partyzanske Forestry*

Plus Tree No. (PT)	DBH, cm	Condition	Selection category (SC)	Crown parameters	Remarks
19/5	64	1	2.0	8*10	Curvature
18/4	47	3	2.5	7*9	Curvature
17/3	54	1	2.0	12*14	Curvature
89/6	56	3	2.0	-	Replaced tree
89/6	60	2.5	2.5	12*13	Curvature
23/9	66	6	-	-	Dry
16/2	64	1	2.0	13*14	Crown low-hanging
15/1	58	1		9*10	Crown low-hanging

Source: developed by the authors based on their own research

Figure 1. *The overall appearance of the plus trees of common oak*
Note: Slavuta Forestry branch, Partyzanske Forestry
Source: photo by the authors

According to Table 3, the average DBH of the selected plus trees of common oak is within 47-66 cm. These are mostly well-developed trees with crown parameters of 10-12 m. One tree is die and needs to be replaced. The selection category of most trees is 2.0, due to the presence of stem curvature. In some trees, the length of the knot-free (branchless) part is insignificant and does not exceed 25% of the total height.

The efficiency of using PFSB objects in the enterprise is high, as in productive years, the maximum amount of seed is harvested from

common oak PFSSs, which fully meets the needs of the enterprise. For example, in 2021, the enterprise harvested a total of 5,210 kg of seeds, of which 1,501 kg were from PFSB objects, which is 28.8% (Table 4). In 2022, the enterprise harvested a total of 2,426 kg of seeds, and no harvesting was carried out from PFSB objects.

Since the enterprise has PFSB objects not only for common oak but also for other species, the harvesting of seeds from these objects depends primarily on the periodicity of seed years for this species. The general view of permanent seed plots and seedling seed orchards is shown in Figure 2.

Table 4. *Assessment of the effectiveness of using PFSB objects within the Zhukivske Forestry branch*

Name of PFSB object	Forestry	Compartment	Plot	Area, ha/pcs.	Forest seeds collected over the past 3 years, kg		
					2021	2022	2023
Plus trees, pcs	-	-	-	-	-	-	-
Plus stands, ha	-	-	-	-	-	-	-
PFSS, ha	Zhukivske	17	27	9,3	1,500	-	-
	Zhukivske	8	28	2.7	-	-	1
Seed orchards, ha	Zhukivske	8	41	2.0	1.0	-	2
Genetic reserves, ha	-	-	-	-	-	-	-

Source: developed by the authors based on their own research

Figure 2. *General view of permanent seed plots and seedling seed orchards in the Slavuta Forestry branch*

Source: photo by I.S. Neyko

A seed harvesting plan is provided to each forestry at the beginning of the year. Thus, in 2021, with a plan of 5,000 kg, the enterprise harvested 5,210 kg of seeds, in 2022, with a plan of 1,720 kg, the enterprise harvested 2,426 kg, which indicates the fulfilment of the plan. The planned and actual harvesting of forest seeds by species in 2022-2023 is presented in Table 5.

Table 5. *Planned and actual harvesting of forest seeds in 2022-2023 by species*

No.	Species	Seed harvest plan, kg	Harvested and purchased with seed quality documents, kg	Tested for seed quality, kg
		2022		
1	*Coniferous - total*	20	33.5	26
	including: - Scots pine	20	28	26
	- European spruce	-	0.5	-
	- European larch	-	5	-
2	*Deciduous - total*	1,700	2,400	2,400
	including: - common oak	1,500	2,300	2,300
	- northern oak	-	-	-
	- common viburnum	4	4	4
	- small-leaved lime	24	24	24
	- spreading plum	-	-	-
	- European wild apple	-	-	-
	- common walnut	72	72	72
	- eastern American black walnut	-	-	-
	- common ash	-	-	-
	- horse chestnut	-	-	-
	-other deciduous	-	-	-
		2023		
1	*Coniferous - total*	3.4	3.4	3.4
	including: - Scots pine	-	-	-
	- European spruce	1	1	1
	- European larch	2	2	2
	- blue spruce	0.4	0.4	0.4
2	*Deciduous - total*	-	-	-
	including: - common oak	-	-	-
	- northern oak	-	-	-
	- common ash	-	-	-
	- Norway maple	-	-	-
	- spreading plum	-	-	-
	- European wild apple	-	-	-
	- small-leaved lime	-	-	-
	- common walnut	-	-	-
	- eastern American black walnut	-	-	-
	- horse chestnut	-	-	-
	- *other deciduous*	-	-	-

Source: developed by the authors based on the Official website of Slavuta Forestry branch (n.d.)

The seed harvesting plan for coniferous species was fulfilled 100%. The assortment of harvested forest seeds in the enterprise is quite high and amounted to 13 species in 2021 and 6 species in 2022. For 2023, according to the seed harvesting plan, the assortment is 8 species. The seed quality results of the first check, which was carried out by the separate department (SD) Vinnytsia Forest Seed Laboratory, are presented in Table 6.

Table 6. *Sowing qualities of seeds verified during the first inspection at the SD Vinnytsia Forest Seed Laboratory, 2021-2023*

Year of harvest	Total seeds harvested, kg	Of which checked in the year of harvest		Seed quality, kg/%		
		kg	%	I class	II class	III class
2021	5,200	5,200	100	198/4	5,002/96	-
including conifers	10	10	100	8/80	1/10	1/10
2022	2,400	2,400	100	2,400/100	-	-
including conifers	26	26	100	26/100	-	-
2023	-	-	-	-	-	-
including conifers	3.4	3.4	100	-	2/59	1.4/41

Source: developed by the authors based on their own research

According to the data obtained in Table 6, the quality of forest seeds is quite high. Thus, for 2021 and 2022, almost all seeds (80% and 100%) are of the first and second quality classes. There is no substandard seed. Coniferous seeds are of high quality, which can be explained by compliance with processing and storage requirements. In 2023, the enterprise harvested and checked 3.4 kg of coniferous species, 1.4 kg of spruce, and 2 kg of European larch. Of these, 3 kg were harvested from PFSB objects. At the time of the check, the enterprise did not have a balance of harvested coniferous seeds, but there were 12.4 kg of Scots pine seeds purchased from the Shepetivske Forestry branch. The seed moisture content at the time of the inspection is normal.

At the Holytske Forestry (compartment 31, plot 2.2, area 2.2 ha), forest stands established in 2020 using containerised common pine planting stock are thriving. The site is characterised as a fresh hornbeam-oak fairly fertile site type, with a planting pattern of 3.0×1.0 m. The condition of the forest stands is good (Fig. 3).

Figure 3. *General view of forest cultures at the Slavuta Forestry branch*

Source: photo by the authors

In compartment 31, plot 6.3 (0.5 ha), forest stands were established in 2023 using containerised seedlings. The forest type is characterised as a fresh hornbeam-oak fairly fertile site type, with a spacing scheme of 2.0×0.8 m and an alternating row composition: one row of common oak followed by one row of European spruce. The condition of the forest stands is good. In

compartment 31, plot 2.7 (0.9 ha), forest stands were established in 2022 in a similar fresh hornbeam-oak fairly fertile site type. The planting arrangement alternates one row of common pine with one row of European spruce. Both containerised and bare-root seedlings were used for planting. An inventory conducted in 2022 revealed a 92% survival rate for seedlings planted with containerised root systems. The trees planted with containerised seedlings exhibited greater height and root collar diameter compared to those planted with bare-root seedlings.

In the Partyzanske Forestry, compartment 42, plot 4.1 (3.0 ha), forest stands established in 2020 in a fresh hornbeam-oak fertile site type are performing well. The planting scheme is 3.0×1.0 m, with a row composition of four rows of common oak interspersed with one row of coniferous species, including European larch, European spruce, silver fir, and Douglas fir. All seedlings were planted using containerised root systems, and the condition of the forest stands is good.

In the Komarivske Forestry, compartment 62, plot 12 (1.1 ha), forest stands established in 2023 in a fresh oak fairly infertile pine site type are thriving. The spacing scheme is 2.0×0.8 m, with a composition of eight rows of common pine followed by two rows of common oak. The stands was established using containerised seedlings and is in good condition.

A comparison of growth rates and overall health between forest stands established using bare-root and containerised seedlings revealed a significant advantage in growth for the latter. Containerised seedlings exhibited a growth rate up to 30-40% higher in terms of height. However, no substantial differences were observed in overall plant health. The superior growth of containerised seedlings can be attributed to their cultivation method, which ensures a consistent supply of moisture and nutrients. It is anticipated that this growth advantage will diminish over time.

As noted by S.A. Los *et al.* (2019), a comprehensive approach is required for the establishment and management of PFSBs in the context of adapting to current climate conditions. Climate change, characterised by rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events, is significantly impairing the reproductive functions of major forest tree species. Under these conditions, the selection of genetically resistant populations and genotypes is of paramount importance. According to a comprehensive assessment of the current state of forest genetic resources conducted by V.P. Tkach *et al.* (2019), the conservation and restoration of these resources is a critical priority. This is particularly important in the context of implementing the principles of sustainable forest management and preserving biodiversity at both the species and genetic levels.

The restoration of oak stands remains a critical issue, especially given the decline in natural regeneration within genetic reserves (Danylenko *et al.*, 2022). This can disrupt the natural evolutionary process of oak forests, leading to an increased reliance on artificially created stands. The lack of reliable natural regeneration necessitates the implementation of various harvesting techniques, including measures to promote the successful growth and development of oak stands, as outlined in the research by V. Lukyanets *et al.* (2023).

Most forest genetic reserves in the region consist primarily of oak stands, with some oak-pine mixtures. There is a concerning trend of inadequate natural regeneration in oak forests. O.B. Bondar *et al.* (2020) attributed this to factors such as site conditions, stand composition and productivity, seed years, and harvesting activities. B. Kanjevac *et al.* (2021) highlighted the significant impact of competition from herbaceous and woody vegetation on the successful growth and development of natural oak regeneration, as competing vegetation can reduce resource availability. Z. Govedar *et al.* (2021) emphasised the substantial influence of silvicultural treatments, such as thinning and tending, on the condition of young oak stands, creating more favourable conditions for their development. O.M. Danylenko *et al.* (2023) also confirmed the importance

of using containerised seedlings to improve the growth of oak in the Kharkiv Forestry. V. Lukyanets *et al.* (2023) argued that effective restoration of oak forests requires not only ensuring the emergence of natural regeneration but also implementing measures to promote its sustained growth. A significant portion of research by V. Lukyanets *et al.* (2022) focuses on evaluating the biometric characteristics and health of oak stands established using various methods and planting materials, which are crucial for the successful restoration of oak forests in the southeastern Forest-Steppe of Ukraine.

One of the most significant components of forestry research involves progeny tests. The majority of these progeny tests, like many other breeding objects, were established during the mid-20th century (Los *et al.,* 2019). Most of these were created under uniform forest growth conditions, limiting the applicability of the "genotype-environment" model to separate genetic and environmental influences. As a result, the establishment of progeny tests remains a critical area of focus. Current methodologies outlined by V. Andreieva *et al.* (2020) include specific guidelines for the creation of progeny tests to apply modern approaches for selecting superior populations and genotypes of primary forest-forming species. S.A. Los *et al.* (2019) utilised comprehensive methods to assess progeny in progeny tests, including hybrids.

Provenance tests are particularly significant (Petrík *et al.,* 2023). S.A. Los *et al.* (2019) noted that evaluating the productivity and condition of Provenance tests enables the assessment of global climate change impacts on forest ecosystems and populations of primary forest-forming species.

Research by Y. Hayda *et al.* (2019) on the functioning of seed orchards underscores the importance of assessing their reproductive performance. A crucial aspect involves studying the development of generative organs across phenological forms. It has been observed that tree ageing often leads to reduced seed productivity in seed orchards. This highlights the need for the establishment of new clonal and seedling seed orchards to sustain genetic diversity and productivity.

Trial progeny tests are essential for identifying the most promising genotypes (Andreieva *et al.*, 2020). However, no such progeny tests have previously been established within the forest fund of the Slavuta Forestry branch, underscoring the need for their creation. Trial cultures facilitate long-term studies and the evaluation of selected genetic material. They enable the identification of superior genotypes that can subsequently be used for forest regeneration. Furthermore, the establishment of progeny tests is crucial for enhancing the resilience of forest stands to climate change, diseases, and pests. Progeny tests should be established in various forest growth conditions, allowing the application of the "genotype-environment" model to select the most favourable specimens (Neyko *et al.*, 2022). Most researchers note similar trends regarding the condition of PFSB objects established in Ukraine.

Research conducted on the condition of PFSBs has corroborated findings from previous studies indicating a significant decline in the health and reproductive capacity of major forest tree species. It was determined that various ecological factors, such as climate change, droughts, and anthropogenic pressures, have led to a decrease in the natural regeneration capacity of these species, negatively impacting their resilience and productivity. Furthermore, it was found that forest species populations within genetic reserves are experiencing considerable stress, hindering their natural regeneration process and necessitating additional measures to ensure the long-term sustainability of ecosystems. These results underscore the need to develop new forest management strategies that include active interventions to restore and conserve genetic resources.

Conclusions

Research findings have revealed that most genetic units are in good condition. A total of 27 plus trees have been identified within the enterprise's forest fund. The majority of these plus trees are

classified as the 2nd selection category, necessitating further efforts to identify and select trees of a higher (first selection) category. All plus trees exhibit a satisfactory level of reproduction. However, one plus tree of common oak (No. 23/9), classified as being in the condition category of 5, requires removal and replacement with an equivalent tree within the same compartment. The total area of permanent forest seed stands (PFSSs) is 71.3 hectares. Oak PFSSs are in good condition and fulfil their functional purpose. For most oak PFSSs, thinning is required to ensure a higher level of reproduction. Scots pine PFSSs are in unsatisfactory condition and most do not meet the basic criteria. The dense pine stands and high crowns prevent the harvesting of reproductive material. Therefore, there is a need to select and establish new Scots pine PFSSs. European spruce PFSS is in good condition and characterised by a high level of reproduction. Seedling seed orchards of common oak and European larch are in good condition and have entered the reproductive phase. A seedling seed orchard of common oak was established in 2010 within the forest state of the Zhukivske Forestry (compartment 19, plot 32, area 5.0 hectares). As of August 2023, the seed orchard has not been certified. Overall, the procurement of reproductive material from genetic units within the branch is quite high, ensuring the corresponding productivity of newly established stands.

A critical next step for further research involves the regular inspection of PFSB objects to gather information on their condition and reproductive capacity. Such research will facilitate the selection of superior genotypes for future use, contributing to the cultivation of highly productive stands.

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Conflict of Interest

None.

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Стан об'єктів постійної лісонасіннєвої бази філії «Славутське лісове господарство» Державного підприємства «Ліси України»

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Анотація. Постійна лісонасіннєва база (ПЛНБ) є основою для заготівлі покращеного селекційного насіння для лісовідновлення та лісорозведення. Аналіз стану об'єктів ПЛНБ дає можливість оцінити якість та обсяги отримання цінного репродуктивного матеріалу, який використовується у лісокультурній справі. У статті проведено: аналіз формування та локалізації об'єктів ПЛНБ в умовах філії «Славутське лісове господарство»; досліджено особливості стану та селекційної структури лісових генетичних резерватів та плюсових насаджень; проаналізовано динаміку розвитку лісокультурного виробництва у філії «Славутське лісове господарство». У межах лісового фонду філії відібрано 27 плюсових дерев дуба звичайного та сосни звичайної. Загальна площа постійних лісонасіннєвих ділянок становила 71,3 га. За результатами обстеження встановлено: обстежені плюсові дерева дуба звичайного (7 дерев) у Партизанському лісництві перебувають у доброму та

задовільному стані, переважно 2-ї селекційної категорії та характеризуються задовільним рівнем репродукції. Для створення постійних лісонасіннєвих ділянок з оптимальними характеристиками рекомендовано поетапно зріджувати насадження та проводити обрізку крон дерев. Встановлено, що родинна плантація модрини європейської (Жуківське лісництво, кв. 8, вид. 41, площа 2,0 га 2010 року створення) перебуває у доброму стані, високого рівня репродукції та відповідає усім вимогам. Згідно з проведеними дослідженнями виявлено, що якість лісового насіння, зібраного із об'єктів ПЛНБ є достатньо високою. Так, за 2021, 2022 роки практично усе насіння (80 % і 100 %) було І-го і ІІ-го класу якості. Некондиційного насіння не виявлено. Ефективність використання об'єктів постійної лісонасіннєвої бази на підприємстві є високою, оскільки в урожайні роки з них збирається максимальна кількість насіння, яка повністю покриває потреби господарства. Дані щодо стану об'єктів ПЛНБ є надзвичайно важливими з огляду на необхідність виконання у заходів щодо лісовідновлення та лісорозведення

Ключові слова: лісокультурне виробництво; генетичні резервати; плюсові дерева; лісове господарство; відновлення лісів

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Integrated waste-free technology for the utilisation of acid tar

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Abstract. The significance of acid tar processing lies in the fact that it affects the environmental safety of both industrial regions and the planet overall. The purpose of this study was to utilise acid tar from storage ponds using conventional methods and membrane technology that uses the unique properties of pervaporation membranes. The current state of petroleum waste processing in the EU and Ukraine was reviewed and analysed. The study proposed a comprehensive waste-free disposal of petrochemical

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waste of the second class of environmental hazard – acid tar. The issue of multiple storage ponds around the world was outlined. The study addressed economically viable and promising aspects of obtaining secondary processing products. Technological stages of acid tar processing, both conventional and using membrane processes, were proposed. The physical and chemical parameters of pond acid tar and its group composition were presented in detail. A four-stage stage of acid tar utilisation was proposed. The study highlighted the physicochemical parameters after the deasphalting stage and the stage of deasphalting agent after the second deasphalting. At the stage of selective purification, a pervaporation membrane apparatus was used. The membrane technology for purification of acid tar from petroleum products with their subsequent fractional separation was presented. Based on the findings of the study on acid tar processing, the target products were obtained: lubricants, briquetted solid fuel, resins, and purified process water. It was emphasised that the specified temperature regimes for each stage should be observed: for the neutralisation and deasphalting stage, the temperature is 60-70°C; the selective purification stage requires maintenance within 50-60°C; the lubricant production stage – 100-120°C; pond water treatment stage – 30-35°C. The study proved an increase in the content of the lubricant fraction in stage-by-stage processing of acid tar for storage ponds. The study experimentally confirmed the production of pure components with the possibility of further use. The complete purification of pond water from organic impurities was demonstrated

Keywords: pervaporation membranes; target products; storage ponds; waste; recycling; petroleum waste

Introduction

Large-tonnage environmentally hazardous waste generated by petroleum refineries in the purification of medical, cosmetic, perfume, petroleum oils, paraffin, and high-quality motor fuels using sulfuric acid, the so-called acid tar, is drained and stored in "special ponds" of artificial origin in the open air. As a result, the surface of these ponds is covered with water in which sulphuric acid and sulphonic acids are dissolved. These ponds pose a major environmental threat to the environment, as they are classified as class 2 toxic. This 'burial' of acid tar causes environmental pollution, namely acidification of soil and water bodies and, as a result, the destruction of flora and fauna. The natural, spontaneous redox process causes the release of large amounts of sulphur dioxide, which pollutes the air and harms flora and fauna (Leonard *et al*., 2010)

The complexity of acid tar utilisation lies in the variable composition and changes in properties over time, the constant process of sulphuric acid emulsion generation, which requires an individual approach and selective removal from storage ponds with the reconfiguration of the neutralisation and utilisation process. Therewith, acid tar is a valuable secondary material resource.

In Romania, methods for treating sulphuric acid waste by encapsulating it with various additives have been proposed. M. Tita *et al*. (2023) observed the best results when they physically altered the waste by encapsulation and stabilisation *in situ*. The methods proposed in this study do not allow for the complete utilisation of acid tar.

A. Fedorov *et al*. (2023) proposed a comprehensive scheme for the neutralisation and utilisation of petroleum sludge, depending on its physical and chemical properties, which allows for the effective neutralisation of hazardous waste with the production of marketable products and non-toxic soil mixture. Ways of further use of the obtained substances were proposed. The presented technology of petroleum sludge utilisation does not allow processing acid tar since it contains a large variety of hydrocarbons. To process acid tar using the presented technology, it is

necessary to additionally carry out its neutralisation and deasphalting.

The possibility of mixing acid resin waste with coal as a method of beneficiation was also investigated. D. Musademba *et al.* (2022) considered different ratios of acid tar waste to coal. It was found that the acid tar waste shows high volatile and moisture content with low ash and carbon content compared to coal. It was proved that a two-component mixture of 1:3 yields a higher proportion of fixed carbon, which contributes to an increase in the calorific value of the fuel, which is an excellent factor for combustion. The utilisation of acid tar produces asphaltenes, which are excellent high-calorific fuels. The use of acid tar as an additive to coal is considered inefficient.

M.S. Lawan *et al.* (2023) analysed the wastewater treatment of petroleum refineries. Pollutants were clearly identified: oil and grease, petroleum hydrocarbons, phenols, ammonia and sulphides, their concentration, and the presence of organic and inorganic compounds. An overview of the methods and processes used for purification was given. It was proposed to use a photocatalytic process for the degradation efficiency of photocatalysts. The method of biological water treatment presented in the study does not consider the permissible concentration of harmful organic substances, the so-called "volley emissions".

Pre-treated produced water, after petroleum extraction, is increasingly being considered as an interesting resource, especially in water-scarce regions such as the Arabian Peninsula. F. Salem & T. Thiemann (2022) analysed the available methods for treating produced water, purifying it, or disposing of it after treatment. The proposed water treatment methods cannot be used to treat acidic pond water contained in the tar, as these methods are very costly for disposal.

F. Alsalem *et al.* (2024) evaluated produced water from petroleum and gas operations in Kuwait and industrial salts as a resource and alternative storage. Reverse osmosis is used to desalinate the water, using porous membranes that cannot be used for pond water treatment. This is because this water contains high amounts of finely dispersed solid asphaltenes.

The treatment of water produced from shale oil and gas is a challenging process as it contains a variety of organic compounds and inorganic impurities. L. Ogletree *et al.* (2021) outlined that conventional membrane processes, such as reverse osmosis and nanofiltration, are problematic if the produced water has high salinity. The researchers proposed the use of direct osmosis and membrane distillation to treat produced water. The use of direct osmosis and membrane distillation is very energy-intensive, and therefore these methods are ineffective for treating pond water, as it contains fine mechanical impurities.

D. Radovanovic *et al.* (2024) pointed out the hazardous properties of petrochemical waste: an emulsion of various organic compounds, sulphuric acid, and water, which persist decades after its creation. It was outlined that the specific chemical composition and physical properties stand in the way of unambiguously determining the methods and technological treatment. The researchers proposed a technology for the treatment of petroleum waste, namely acid resin, until its complete physical and chemical transformation into a dry powder with the characteristics of inorganic material. The researchers did not show the further use of this powder or its utilisation.

The purpose of this study was to dispose of acid tar from storage ponds using conventional methods and membrane technology using the unique properties of pervaporation membranes.

To fulfil the purpose, the following objectives were set:

- to perform complete neutralisation of acid tar together with pond water;
- to conduct deasphalting of tar with removal of asphaltenes, to remove resins from deasphalting agent, and to produce average industrial lubricants;
- to purify pond water from traces of asphaltenes, resins, and organic substances, and to prove that the resulting asphaltenes can be used as briquetted high-calorific solid fuel.

Materials and Methods

Experimental and practical research was conducted in 2018-2019 in four stages using specialised equipment: a unit for the utilisation of acid tar, a unit for selective treatment, a unit for the production of lubricant, and a unit for the treatment of pond water. The unit was designed and documented at the Department of Biotechnology and Engineering of Igor Sikorsky Kyiv Polytechnic Institute, and the experimental unit was manufactured at a machine-building plant in Brovary, Kyiv region. Considering that this unit is a symbiosis of conventional devices combined with structurally unique membrane modules, there is no mass production of such units. The experiment was performed in the membrane technology training laboratory at the Department of Biotechnics and Engineering, Faculty of Biotechnology and Biotechnics, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" (Ukraine). The use of membrane technology ensured the complete recovery of all organic solvents used in the disposal process. The fractional composition of the source tar, as well as stage products of acid tar processing (asphaltenes, resins, lubricating oil, purified pond water) were analysed in the laboratories of the Masma Research Institute in Kyiv.

The object of the study was the process of obtaining purified products of acid tar processing (asphaltenes, resins, oils, water). The subject of the study was an integrated approach to the utilisation of acid tar by combining conventional methods and unique membrane pervaporation technologies. A sample of pond acid tar was used for the study. To investigate the process of acid tar utilisation, samples were taken from storage ponds. The samples were analysed physically and chemically, and the following key parameters were determined in the initial samples: the content of oils, paraffins, asphaltenes, and sulphuric acids. The storage ponds were located in industrial areas of the western part of Ukraine.

The first stage of the study was performed using the acid tar utilisation unit. The technology of acid tar utilisation itself had the following stages: neutralisation and deasphalting stage; selective purification stage; lubricant production stage; pond water treatment stage. The technological process of the neutralisation and deasphalting stage was as follows (Fig. 1).

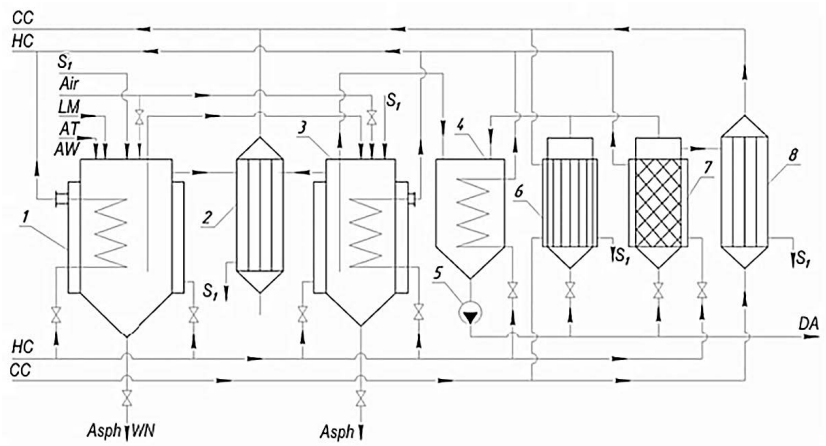

Figure 1. *Flow chart of the neutralisation and deasphalting stage*

Note: 1 – neutraliser-deasphalter; 2 – refrigerator-condenser; 3 – deasphalter; 4 – tank; 5 – pump; 6 – pervaporation apparatus; 7 – membrane adsorber; 8 – refrigerator-condenser; *AT* – acid tar; *AW* – acidic water; *LM* – lime milk; S_1 – solvent; *Air* – compressed air; *Asph* – asphaltenes; *WN* – water after neutralisation; *DA* – deasphalting agent; *HC* – hot coolant; *CC* – cold coolant

Source: developed by the authors of this study

Acid tar was loaded into the neutraliser-deasphalter *1* together with pond acid water, solvent was added, and lime milk was poured in. Solvent S_1 was added to deasphaltise and reduce the viscosity of the tar, as alkalisation of viscous lubrication systems results in stable, difficult-to-separate emulsions. Hot coolant was supplied to the jacket and coil of the neutraliser-deasphalter *1,* and the working mixture was boiled. Two processes took place simultaneously: neutralisation of acidic water and tar and asphaltene leaching. The vapour of solvent S_1, which was formed during boiling, was fed into the condenser-refrigerator *2*, where it was condensed and cooled.

After the boiling process was completed, the working mixture in the neutraliser-deasphalter was divided into three layers: the upper one was deasphalting agent; the middle one was neutralised water; and the lower one was asphaltenes. Then compressed air was supplied to the neutraliser-deasphalter and hot deasphalting agent with asphaltenes residues was fed through a transfer pipe to deasphalter *3*. Asphaltenes were discharged from the bottom of the neutraliser-deasphalter to be used for briquetting, and neutralised water with insoluble salts was drained and sent for further purification from organic impurities.

The process of deposition of asphaltene residues took place in the deasphalter *3*. For this, solvent S_1 was added to the apparatus, which was formed after the refrigerator-condenser *2*, and hot coolant was supplied to the jacket and coil, and the process of boiling and deasphalting took place. After deasphalting, compressed air was supplied to the deasphalter and the deasphalter was fed through a transfer pipe into the tank *4* and then, using the pump *5*, was fed into the membrane pervaporation apparatus *6*, where the main amount of solvent S_1 was removed. Then, the deasphalting agent was fed to the membrane adsorber *7*, where the remaining solvent S_1 was absorbed by the membrane elements and, during regeneration, was supplied in the form of vapour to the refrigerator-condenser *8*, where it was condensed and cooled. Next, the purified deasphalting agent was fed to selective purification.

At the stage of selective purification, the chemical composition of the de-asphaltising agent was improved by extracting resinous compounds with a solvent. The technological process was as follows (Fig. 2).

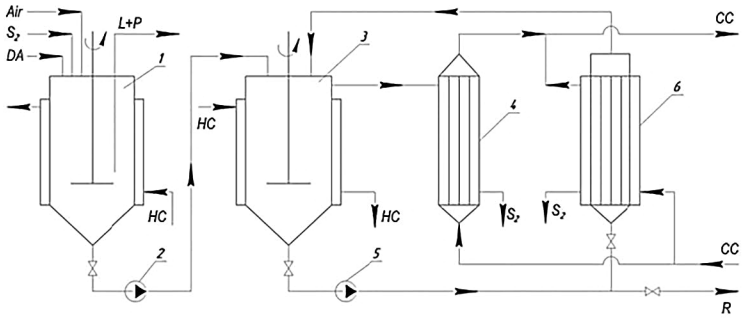

Figure 2. *Flow chart of the selective purification stage*

Note: *1* – extractor; *2*, *5* – pumps; *3* – distiller; *4* – refrigerator-condenser; *6* – membrane apparatus; *DA* – deasphalting agent; S_2 – solvent; *L+P* – lubricating fraction with paraffins; *R* – resins; *HC* – hot coolant; *CC* – cold coolant; *Air* – compressed air

Source: developed by the authors of this study

Deasphalting agent and solvent S_2 were loaded into extractor *1*. With constant stirring and heating of the mixture, the extraction of resinous substances by solvent S_2 took place. As a result, two layers were formed in extractor *1*: the upper one was a mixture of the lubricating fraction

with paraffins, while the lower one was a solution of resinous substances in solvent S_2. Then compressed air was supplied to the extractor, and the mixture of the lubricating fraction with paraffins was removed through the transfer pipe, which was fed to the stage of obtaining lubricant, while the solution of resinous substances was pumped by pump *2* to distiller *3*. In distiller *3*, solvent S_2 was distilled with constant stirring and heating, the vapour of which was fed into a refrigerator-condenser *4*, where condensation and cooling took place.

At the end of the distillation process, the resin was pumped by pump *5* to the pervaporation membrane apparatus *6*, where the residual solvent S_2 was removed. The purified resin was then sent for utilisation. In the future, it can be used in the production of bitumen.

At the third stage, acid tar was utilised to produce lubricating oil. The dewaxing process is designed to produce lubricants with the required pour point by removing paraffins from the raw materials (Fig. 3).

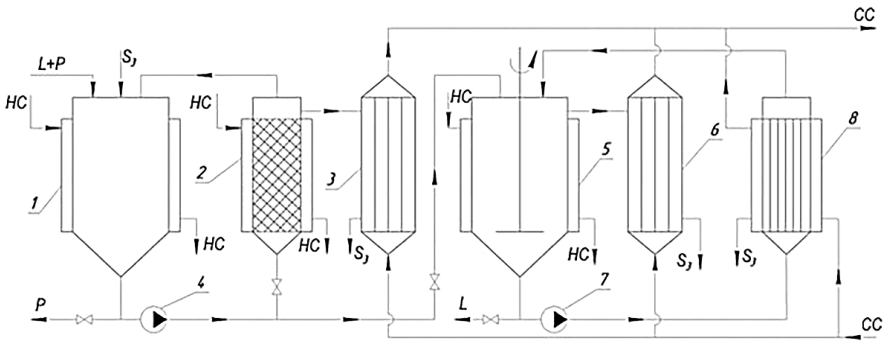

Figure 3. *Flow chart of the lubricant production stage*

Note: *1* – tank; *2* – adsorber; *3* – refrigerator-condenser; *4*, *7* – pumps; *5* – tank; *6* – refrigerator-condenser; *8* – pervaporation membrane apparatus; *L* – lubricant; *P* – paraffin; S_3 – solvent; *HC* – hot coolant; *CC* – cold coolant
Source: developed by the authors of this study

The lubricant fraction containing paraffins was loaded into tank *1*, heated and pumped through adsorber *2* by pump *4*. In adsorber *2*, the lubricant fraction was sorbed by membrane elements. After the absorption of the lubricant fraction was completed, paraffin waxes were left in the tank *1* and removed to the outside. Next, solvent S_3 was poured into tank *1*, which was pumped through adsorber *2* by pump *4*. The adsorber was used to displace the lubricant fraction from the membrane elements and fill them with solvent S_3. After the displacement of the entire lubricant fraction, the membrane elements were regenerated. For this, hot coolant was supplied to the adsorber jacket *2*, and when heated, solvent S_3 was removed from the membrane elements, which was supplied in the form of vapour to the refrigerator-condenser *3*, where it was condensed and cooled. The lubricating fraction with solvent S_3 was pumped from tank *1* by pump *4* into tank *5*, where the solvent was distilled with constant stirring and heating. Therewith, the vapour of the solvent S_3 was supplied to the refrigerator-condenser *6*, where it was condensed and cooled. At the end of the distillation process, the lubricant, together with the remaining solvent, was pumped from the tank *5* by the pump *7* through the pervaporation membrane apparatus *8*, in which the remaining solvent S_3 was removed from the grease. At the end of the pervaporation process, the purified lubricant was removed from the tank *5* and stored as a finished product.

The last stage for the disposal of acid tar was the pond water treatment stage (Fig. 4).

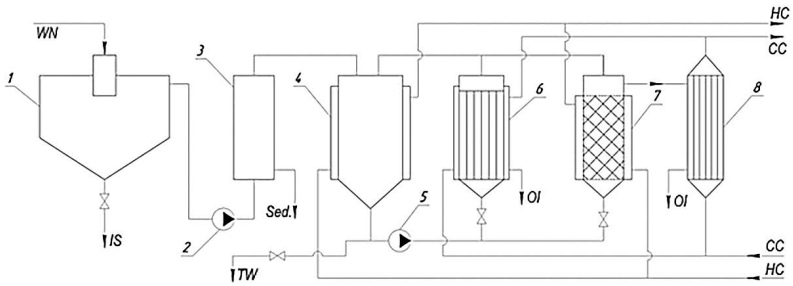

Figure 4. *Flow chart of the pond water treatment stage*

Note: *1* – settling tank; *2*, *5* – pumps; *3* – filter; *4*, *7* – pumps; *4* – tank; *6* – pervaporation membrane apparatus; *7* – membrane adsorber; *8* – refrigerator-condenser; *WN* – water after neutralisation; *IS* – insoluble salts; *Sed.* – sediment; *OI* – organic impurities; *TW* – treated water; *HC* – hot coolant; *HT* – cold coolant

Source: developed by the authors of this study

The neutralised pond water was treated as follows. The pond water containing insoluble salts and organic impurities from the neutralisation and deasphalting stage was fed into the settling tank *1*. Insoluble salts settled at the bottom of the settling tank, while water from the top of the settling tank was pumped by pump *2* through filter *3*, where the microfiltration process took place, and fed into tank *4*. From tank *4*, heated water was pumped by pump *5* through a pervaporation membrane apparatus *6*, where most of the organic impurities were removed.

Then the partially purified water from the tank *4* was pumped by the pump *5* through the membrane adsorber *7*, where the final purification from organic impurities took place. After the sorption process, the membrane elements in the adsorber were regenerated by supplying hot coolant to the jacket of the latter. The vapour of organic impurities was supplied to the refrigerator-condenser *8*, where it was condensed and cooled. The purified pond water was drained from the tank *4*.

Results and Discussion

After analysing the material from the four storage ponds for the processing of acid tar, their characteristics, composition, and volume were determined. Detailed information on the extracted acid tar is presented in Table 1.

At the neutralisation and first deasphalting stage, sulphonic acids and asphaltenic acids are neutralised and most of the asphaltenes are removed. The composition of the deasphalting agent after this stage is presented in Table 2.

Table 1. *Physical and chemical parameters of pond acid tar and their group composition*

No.	Indicators % (wt.)	Pond No.			
		1	2	3	4
1.	Lubricants fraction with paraffins	13.75	26.06	11.10	11.23
2.	Resins	29.50	17.65	30.65	31.25
3.	Asphaltenes	3.43	10.38	5.96	5.13
4.	Sulphonic acids	42.05	42.34	39.85	38.89
5.	Asphaltenic acids	1.33	1.95	1.63	1.87
6.	Carbenes, carboids, mechanical impurities	9.94	1.62	10.81	11.63
7.	Density, g/cm^3	1.238	1.090	1.201	1.302
8.	Acid number, m^2 KOH/g	41.30	67.28	40.21	41.05

Source: developed by the authors of this study

Table 2. *Physical and chemical parameters after deasphalting and their group composition*

No.	Indicators % (wt.)	Pond No.			
		1	2	3	4
1.	Lubricants fraction with paraffins	25.85	57.49	21.12	20.75
2.	Resins	49.65	35.48	53.13	52.67
3.	Asphaltenes	5.81	3.46	5.18	5.08
4.	Carbenes, carboids	18.69	3.57	20.57	21.50

Source: developed by the authors of this study

As Table 1 shows, the fractional composition of acid tar from the storage ponds was as follows: lubricant fraction with paraffins 11.10-26.06% (wt.); resins 17.65-31.25% (wt.); asphaltenes 38.89-42.34% (wt.); asphaltenic acids 1.33-1.95% (wt.); carbenes, carboids, mechanical impurities 1.62-11.63% (wt.); acid number 40.21-67.28% (wt.).

After neutralisation and the first stage of deasphalting, sulphonic acids, asphaltenic acids, and a considerable part of asphaltenes were completely removed from the tar. The mechanism of this process was as follows. Acid tar is loaded into the deasphalter together with pond water, a lime suspension, and solvent S_1. The process requires constant stirring at 10-12 rpm and heating, with the mixture beginning to boil. In this process, neutralisation occurs, and three layers are formed: the upper one is deasphalting agent with solvent S_1; the middle one is neutralised water; the lower one is asphaltenes together with salts formed during neutralisation.

These layers are formed because they have different densities. The asphaltenes released from the deasphalting agent sink into the lower layer, passing through a layer of water that forms a buffer zone separating the deasphalting agent and the asphaltenes. Composition of the deasphalting agent after the second deasphalting is presented below (Table 3).

Table 3. *Physicochemical parameters of deasphalting agent after the second deasphalting and its group composition*

No.	Indicators % (wt.)	Pond No.			
		1	2	3	4
1.	Lubricants fraction with paraffins	34.24	61.84	28.44	28.26
2.	Resins	65.76	38.16	71.56	71.74

Source: developed by the authors of this study

After the second deasphalting, a membrane apparatus is used to remove the remaining solvent S_1 from the deasphalting agent. This is because the pervaporation membranes can remove solvent S_1 from the highly viscous medium, which is the resin-derived deasphalting agent. After the second deasphalting, the working mixture has the following composition: lubricant fraction with paraffins 28.26-61.84% (wt); resins 38.16-71.74% (wt).

The composition of the lubricants fraction after selective purification is presented in Table 4.

Table 4. *Physical and chemical parameters of the lubricants fraction Wafter selective purification and its group composition*

No.	Indicators % (wt.)	Pond No.			
		1	2	3	4
1.	Lubricants fraction	78.30	90.20	84.86	81.79
2.	Paraffins	21.70	9.80	15.14	18.22

Source: developed by the authors of this study

At the stage of selective purification, resins are removed from the mixture using solvent S_2, and the pervaporation membrane apparatus is used to regenerate the solvent. The mixture after this stage has the following composition: lubricant fraction 78.30-90.20% (wt); paraffins 9.8-21.70% (wt). To remove the lubricant fraction, sorption by membrane elements of the lubricant during heating is used, because with increasing temperature, the viscosity of the lubricant decreases and the diffusion coefficient increases. Unlike mineral sorbents, which lose their sorption properties with increasing temperature, the properties of the pervaporation membrane elements increase due to their structure. Therefore, the absorption of the lubricant fraction from the mixture occurs in the membrane adsorber. To remove the lubricant fraction from the membrane elements, the method of displacing the latter with a more active sorbent-solvent S_3 is used. Therefore, after the membrane elements are saturated, solvent S_3 is fed into the adsorber, which displaces the lubricant fraction from the membranes. At the outlet of the adsorber, a highly concentrated solution of the lubricant fraction in solvent S_3 is formed, from which solvent S_3 is removed using conventional methods, for example, distillation.

The increase in the lubricant fraction content as a result of the stage-by-stage processing of acid tar is presented in Figure 5.

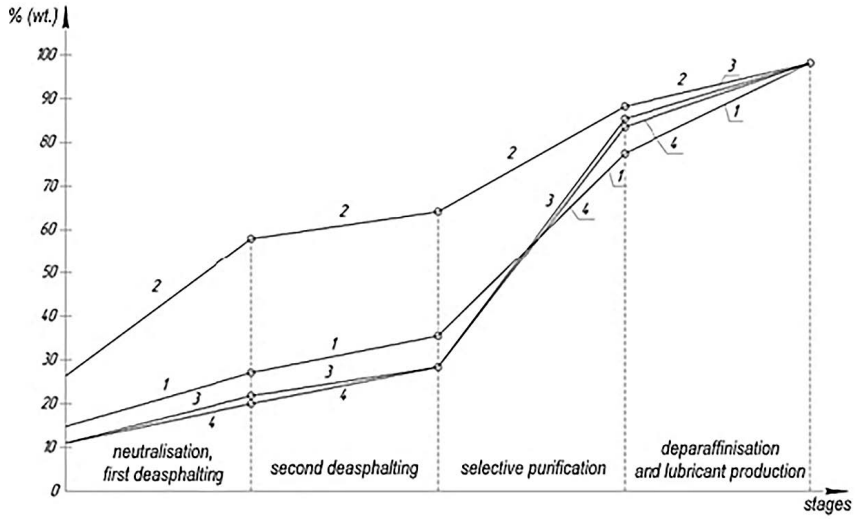

Figure 4. *Diagram of the growth of the lubricant fraction*

Note: 1, 2, 3, 4 – Numbers of the acid tar storage ponds
Source: developed by the authors of this study

As the diagram shows, after selective purification, the content of the oil fraction in the samples taken from the four storage ponds ranges within 78.3-90.2%. The difference in the lubricant content in the samples is small and equals 11.9%. Therefore, the rate of increase in the concentration of the lubricant fraction during deparaffinisation for all four experiments is approximately the same and amounts to 0.25% per 1 min (determined experimentally).

Neutralised pond water contains fine asphaltene and resin inclusions. Therefore, before the water is fed into the settling tank, a coagulant is added to it, which binds the fine inclusions, and they settle out. The water is then fed to filtration and then undergoes complete purification from organic impurities in membrane apparatus.

The asphaltenes that settled out at the deasphalting stage are briquetted and used as fuel.

The physicochemical composition of acid tar waste is important in the evaluation and development of processing options for its further utilisation. C.H. Chihobo *et al.* (2015) used gas chromatography/mass spectrometry (GC/MS), Fourier transform infrared (FTIR), and scanning electron microscopy with energy dispersive X-ray (SEM/EDX) to characterise the acid tar waste from crude benzene refining. Organic analysis of the aromatic fraction of the acid tar waste revealed a wide range of compounds, including polycyclic aromatic hydrocarbons, furans, phenols, thiophenes, and biphenyls. These findings can be useful in the design and development of technological processes that can utilise acid tar waste. Notably, these findings are encouraging, but they do not consider all the constituents of acid tar. X. Lu & U. Isacsson (2000) obtained polymer-modified bitumen by mixing bitumen with various thermoplastic polymers. It was found that the morphology and rheological properties of modified binders are influenced by the characteristics and content of the polymer and the nature of the bitumen. The rheological changes in the materials, which are associated with bitumen oxidation and/or polymer degradation, were outlined. However, the researchers relied on the structure of polymeric materials, which allows them to bind to bitumen. However, the asphaltenes that are part of the tar do not have the same structure as polymeric materials, and therefore they will not bind to bitumen and improve its structure.

According to I.A. Burtna *et al.* (2006), the utilisation of acid tar is still a serious environmental and technological problem due to its complex chemical composition, high reactivity, and corrosiveness, which complicate the development of a universal method of its treatment. The high viscosity and sulphonic acid content of tar makes it impractical to use standard diesel fuel desulphurisation technologies for their utilisation. The cracking and distillation methods discussed in D.D. Milne *et al.* (1986), specifically, using anhydrous $AlCl_3$ as a catalyst, open prospects for converting petroleum residues into volatile petrol fractions. However, these studies did not focus on the problems arising from the supply of acidic resin to the combustion nozzles.

According to I.A. Burtna *et al.* (2011), acid tar residues were previously stored in landfills near oil refineries, and their remediation has become a critical environmental issue. Meanwhile, the problem of organic impurities in acidic wastewater from storage ponds stays unresolved. I. Knapkova & D. Samesova (2017) discussed the utilisation of acid tar to reduce environmental pollution, but the problem is not completely eliminated.

The use of gas chromatography-mass spectrometry to analyse the composition of acid tar, as noted by G.V. Krymets *et al.* (2022), can reveal its S-organic content, which hinders the production of fractions that meet petroleum product standards. Researchers also pointed to the possibility of reusing polymeric waste and natural bitumen to modify acid tar, but their implementation in industry is still challenging.

Membrane technologies, including reverse osmosis, are used for water treatment in the petroleum and natural gas industry due to their resistance to aggressive environments (Le & Nunes, 2016). However, these membranes are not effective for treating acidic water from storage ponds, as fine asphaltenes can clog pores. An analysis of the environmental impacts of tar waste on groundwater by H. Xu (2007) indicates possible risks, but effective disposal methods have not yet been developed.

Thus, the available research shows a variety of approaches to the utilisation of acid tar, but the need for further investigation and development of effective methods to reduce the environmental burden stays urgent.

After analysing the methods of processing acid tar, it becomes clear that there is no single technology that can combine these processing methods and create a closed cycle of their utilisation. Therefore, instead of the four areas of acid tar processing – high-temperature thermal decomposition, low-temperature decomposition, hydrolytic decomposition with water or vapour,

and neutralisation with alkali metal hydroxides – four stages have been proposed to form a single technology for acid tar processing. These are the following stages: neutralisation and deasphalting, selective purification, lubricant production, and treatment of pond water. Let us consider the advantages of using these stages.

Increased production of petroleum-containing water and its treatment has become a challenge due to the complexity and quantity of waste generated. Such unwanted wastewater needs to be treated before final disposal or for burial in the environment. T.C. Nonato *et al.* (2018) reviewed technologies for the recovery of petroleum and other toxic agents and the treatment of produced water from petroleum. This study did not consider methods for the disposal of hazardous waste generated during the treatment of petroleum-containing water.

At the stage of neutralisation and deasphalting, two processes take place simultaneously in the apparatus called a neutraliser-deasphalter: neutralisation of acid tar with pond water and deposition of asphaltenes. The supply of solvent S_1 to the neutraliser-deasphalter reduces the viscosity of the tar, as there is tar that is almost solid, and creates conditions for the neutralisation and deasphalting processes. According to C. Danha *et al.* (2014), such conditions can considerably reduce solvent consumption by 5-7 times and carry out the process at atmospheric pressure compared to conventional technologies, where the pressure in the apparatus is maintained at 2-5 MPa. This stage produces asphaltenes that can be used as briquetted solid fuels. Membrane devices are used to completely remove solvent P_1 from the deasphalter, without which this process would be impossible.

At the stage of selective purification, the extraction is carried out using solvent S_2. A membrane apparatus is used for its complete extraction from the lubricant fraction. The use of solvent S_2 instead of forfuryl or phenol (according to conventional technology) allows reducing solvent consumption by 4-9 times.

At the stage of dewaxing or obtaining the lubricating fraction, unique membrane redistillation processes are used: adsorption of the lubricating fraction from its mixture with paraffins by membrane sorbents; the effect of displacement of the lubricating fraction from the membrane sorbents by the solvent S_3; purification of the lubricating fraction from S_3 residues by redistillation. In this case, the process of purification of the lubricating fraction from paraffins using conventional technology takes place at a temperature from -30°C to -57°C, while the sorption of the lubricating fraction by membrane sorbents takes place at a temperature within 100÷120°C, the energy costs for maintaining which are much lower.

The stage of pond water treatment was also performed using membrane pervaporation apparatuses. This became possible after the use of a coagulant proposed by the authors of the present study. Its use allows pre-treating water from mechanical contaminants – finely dispersed asphaltene particles.

The following target products were obtained during the utilisation of acid tar: briquetted asphaltenes (can be used as solid fuel); resins (used in bitumen production); lubricating fractions (used in the automotive and other industries); and purified industrial water. Thus, the stages considered allow stating that an integrated non-waste technology for the utilisation of acid tar was developed.

Conclusions

The study considered the problem of utilisation of acid tar. The existing methods of acid tar processing were analysed. These methods have many disadvantages, and therefore they are not widely used. A new non-waste technology for the utilisation of acid tar was proposed, which employs conventional and membrane processes.

The proposed combined waste-free technology with conventional extraction processing of tar and production of lubricants gave the following results: deasphalting stage: solvent S_1; process temperature 70-80°C; working pressure 0.1 MPa; solvent-tar ratio (by volume) 0.3:1; stage of

selective cleaning: solvent S_2; process temperature 15-20°C; solvent-deasphalting agent ratio (by volume) 0.4:1; stage of deparaffinisation: solvent S_3; saturation temperature 150°C with displacement 20°C; dilution ratio (by weight) 0.4:1.

Comparing the indicators of stage-by-stage processing of tar by the proposed and conventional technology, it was proved that the volume of solvent S_1 is 16-20 times less than the volume of propane, while the pressure in the apparatuses is 20-50 times less. At the stage of selective cleaning, the volume of solvent S_2 is 4-9 times less than the volume of farfurole or phenol. At the deparaffinisation stage, the mass consumption of solvent S_3 is 3.5-8 times less than that of the corresponding solvents. The saturation process at this stage takes place at 150°C, the energy consumption to maintain which is an order of magnitude less than that required to obtain and maintain the temperature of -57°C using conventional technology.

The proposed technology is much less energy-intensive and less expensive in terms of hardware design than the conventional and already known technology.

The results of the processing of acid tar were presented, which resulted in the following target products: briquetted asphaltenes that can be used as fuel; resins that can be used in the production of bitumen; lubricants that can be used in automotive equipment and other industries.

There are ways to further improve the developed utilisation technology, namely: recycling of contaminated waste (wood, leaves, etc.) on the surface of the storage ponds by pyrolysis to produce synthesis gas; use of anaerobic biological treatment of pond water after sedimentation of mechanical impurities to produce biogas using bioreactors.

Acknowledgements

None.

Conflict of Interest

None.

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Комплексна безвідходна технологія утилізації кислих гудронів

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Анотація. Важливість переробки кислих гудронів полягає в тому, що від неї залежить екологічна безпека як промислових регіонів, так і планети в цілому Метою дослідження було утилізація кислих гудронів із накопичувальних ставків за допомогою традиційних методів та мембранної технології, що використовує унікальні властивості первапораційних мембран. Розглянуто та проаналізовано сучасний стан переробки нафто відходів в країнах ЄС та в Україні Запропоновано комплексну безвідходну утилізацію відходів нафтохімічних виробництв другого класу екологічної небезпеки – кислих гудронів. Окреслено питання множинності ставків-накопичувачів по всьому світу. Акцентується увага на економічно вигідних та перспективних питаннях отримання вторинних продуктів переробки. Запропоновано технологічні стадії переробки кислих гудронів, як традиційних так і за допомогою мембранних процесів. Докладно представлено фізико-хімічні показники ставкових кислих гудронів та їх груповий склад. Запропонована чотиристадійна стадія утилізації кислих гудронів. Висвітлено фізико-хімічні показники після стадії деасфальтизації та стадії деасфальтизата після проведення другої деасфальтизації. На стадії селективної очистки використано первапараційний мембранний апарат. Представлено мембранну технологію очистки кислих гудронів від нафтопродуктів с подальшим їх пофракційним розділенням. За результатами проведених досліджень переробки кислих гудронів одержано цільові продукти: мастила, брикетоване тверде паливо, смоли, очищена технічна вода. Наголошується на дотриманні заданих температурних режимів для кожної стадії: для

стадії нейтралізації та деасфальтизації температура 60-700°C; стадія селективної очистки вимагає дотримання в межах від 50-60°C; стадія одержання мастила: 100-120°C; стадія очистки ставкової води: 30-35°C. Доведено зростання вмісту мастильної фракції в процесі постадійної переробки кислого гудрона для ставків-накопичувачів. Експериментально підтвердженно отримання чистих компонентів з можливістю подальшого використання. Засвідчено повне очищення ставкової води від органічних домішок

Ключові слова: лісокультурне виробництво; генетичні резервати; плюсові дерева; лісове господарство; відновлення лісів

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Bioproductivity of pine forests in Polissia

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Abstract. The purpose of this study was to determine the bioproductivity of pine forests in Polissia and their carbon sequestration capacity depending on the age structure of the stands. The study was conducted at 15 experimental sites in the Zhytomyr and Rivne regions during the spring and summer season of 2023. Tree biometrics such as diameter at breast height (DBH) and tree height were measured, and wood samples were analysed to determine the phytomass of the trunk, bark, and crown. It was found that bioproductivity increased significantly with age: in young forests (10-30 years old), biomass averaged 25 t/ha, in middle-aged forests (40-60 years old) – 65 t/ha, while in mature forests (80-100 years old) it reached 120 t/ha. The correlation analysis showed a pronounced dependence of biomass on tree diameter and height, with the strongest relationship between trunk volume and wood phytomass (r = 1.00). The carbon-absorbing capacity of forests also increased with age: young forests absorbed about 12.5 t/ha of carbon, middle-aged forests – 32.5 t/ha, while mature forests – up to 60 t/ha. Furthermore, the study found that climatic factors such as rainfall and average temperature substantially affect bioproductivity. When precipitation fell below 550 mm per year, a 15-20% decrease in biomass was observed. Thus, the findings emphasised the significance of sustainable management of pine forests in Polissia, considering their role in global carbon sequestration processes, making them a valuable tool for combating climate change and environmental challenges

Keywords: ecology; phytomass; correlation analysis; forest management; carbon

Introduction

The conservation and sustainable management of forest resources is one of the key challenges in the modern world, considering their indispensable role in reducing the impact of climate change and maintaining environmental stability. Forests, specifically pine stands, are important ecosystems that contribute to carbon sequestration, water cycle regulation, and biodiversity. In Ukraine, the

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pine forests of Polissia play a key role in shaping the regional landscape and are of great significance to the country's economy and environment. However, due to climate change, anthropogenic factors and ecosystem degradation, forest productivity is declining, which necessitates a more in-depth study of the bioproductivity of pine forests and the development of effective approaches to their management.

The relevance of investigating the bioproductivity of pine forests in Polissia is conditioned by several key factors. Firstly, pine forests cover a sizeable area in the region, and their productivity directly affects economic and environmental performance. Secondly, climate change, including rising temperatures and changing precipitation patterns, can substantially affect the growth and bioproductivity of pine forests, which requires detailed research. Thirdly, the current challenges associated with the degradation of forest ecosystems require the development of scientifically sound forest management methods that factor in their ability to absorb carbon and ensure sustainable forest management.

Recent studies show that forest bioproductivity, i.e., the ability of forests to produce biomass, is a key parameter for assessing ecosystem services such as carbon sequestration and woody mass formation. The study of bioproductivity offers a better understanding of the mechanisms of tree growth, the effect of various factors on their productivity, and the role of forest ecosystems in the global carbon cycle. A. Shvidenko *et al.* (2014) showed the significance of Ukraine's forest ecosystems for reducing the country's carbon footprint, while M. Lesiv *et al.* (2019) demonstrated the great potential of Ukraine's forests for carbon sequestration in the context of climate change. However, despite the considerable number of studies, the relationship between the age structure of forests, their bioproductivity, and the effect of climate factors is still open.

The scientific literature already contains numerous studies on the bioproductivity of forests in many different regions, including Poland. R. Petráš *et al.* (2019) provided an in-depth analysis of the wood density of different pine species, enabling the estimation of their contribution to the total biomass and productivity. Z. Pilarek *et al.* (2007) focused on the biomass of pine stands in mixed coniferous forests, which was important for comparison with the findings of the present study. R. Wojtan *et al.* (2011) investigated the biomass and carbon sequestration capacity of pine forests in Poland, which allowed for parallels with Ukrainian research.

Scientific sources also point to the significance of analysing climate factors in the context of assessing the productivity of forest ecosystems. According to D. Kweon & P.G. Comeau (2023), temperature and precipitation are the determining factors for the growth of pine forests. In Ukraine, climate change can substantially affect forest bioproductivity, particularly due to changes in temperature and reduced precipitation. C. Constandache *et al.* (2021) focused on the productivity of pine forests on degraded lands, showing that even in unfavourable conditions, pine stands can recover productivity through proper management and the application of modern reforestation techniques.

Studying the impact of forest age structure on forest productivity is a prominent aspect of forestry research. S. Gwal *et al.* (2020) conducted a study on the Himalayan region, demonstrating that the age structure of forests is a crucial factor affecting their biomass and productivity.

J.A. Stanturf *et al.* (2019) demonstrated the successful use of spatial explicit models to assess the bioproductivity and economic attractiveness of short-rotation tree crops in the eastern regions of the United States. This approach can be employed to analyse the bioproductivity of pine stands in Polissia and assess their economic efficiency in the context of sustainable forest management. V. Moroz & Y. Nykytiuk (2020) conducted the most detailed study of the carbon sequestration capacity of pine stands in Volyn Polissia, concluding that these stands play a major role in the fight against carbon emissions.

The purpose of this study was to assess the bioproductivity of pine forests in Polissia, considering the age structure of stands and climatic factors. Objectives of the study:

1. To determine the phytomass of wood, bark, and crown of pine forests in different age groups.

2. To analyse the carbon-absorbing capacity of pine forests depending on the age structure of the stands.

3. To assess the impact of climatic factors on the bioproductivity of pine forests in Polissia.

Furthermore, it was vital to assess the impact of anthropogenic activities on forest bioproductivity, as active forest management can considerably reduce the carbon-absorbing potential of young and middle-aged stands.

Materials and Methods

The study of the bioproductivity of Polissia pine forests was conducted in the spring and summer season of 2024 in the forests of Zhytomyr and Rivne regions, and followed international ethical standards, specifically, the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1973). This ensured compliance with all standards in the field of nature protection and biological diversity, which is particularly important when conducting ecological and forestry research. To complete the objectives of this study, 15 experimental plots of 1 hectare each were selected. Each plot represented pine forests of different ages, ranging from young (10-15 years) to mature (80-100 years). This enabled the assessment of the impact of the age structure of the stands on their bioproductivity, including three main age groups: young pine forests (10-30 years), middle-aged (40-60 years), and mature (80-100 years). The field surveys were conducted by selectively taxing the stands to measure key tree growth parameters such as diameter at breast height (DBH) and total tree height. All measurements were performed at each site using specialised forestry equipment: a Haglöf Mantax Precision 2019 dendrometer tape (Sweden) was used to measure tree trunk diameters at a height of 1.3 metres (DBH); a Haglöf Vertex IV 2020 Sundvall altimeter (Sweden) was used to determine tree heights. A Garmin GPSMAP 66i 2021 tablet GPS navigator (USA) was used to accurately determine the geographical coordinates of each site and to record the location of individual trees.

At each site, 10 trees were selected for further laboratory analysis. Trees were sampled with the following inclusion criteria in mind: tree diameter and height should correspond to the average values for each age group. In the young pine forests, the DBH varied within 10-20 cm, while the height of the trees – within 8-12 m. In middle-aged pine forests, the DBH ranged within 20-35 cm, while their height was within 15-20 m. In mature pine forests, the DBH varied within 35-50 cm, while the height reached 20-30 m. This approach ensured a representative sample and enabled an accurate estimation of bioproductivity for each age group.

To determine the age and wood density of each sampled tree, a coring method was employed using a Pressler Haglöf Increment Borer 2018 (Sweden). The wood samples were delivered to the laboratory, where they were further analysed using a WinDendro 2020 forestry biomass analyser (Canada). Allometric equations adapted for Polissia conditions were used to determine the phytomass of wood, bark, and crown in a completely dry state (1):

$$m_{wood} = V_{wood} \times \rho_{basic}, \quad (1)$$

where m_{wood} is the phytomass of wood (kg); V_{wood} is the volume of wood (m^3); ρ_{basic} is the basic density of wood (kg/m^3).

Equation (2) was used to calculate the crown phytomass:

$$m_{crown} = 8.379 + 0.087 \times m_{trunk}, \quad (2)$$

where m_{crown} is the crown phytomass (kg); m_{trunk} is the trunk phytomass (kg).

The total phytomass of a tree was defined as the sum of the phytomass of individual fractions: bark, wood, and crown. To estimate the

carbon-absorbing capacity of pine forests, the study used conversion factors that determine the ratio of the mass of phytofractions to the total stock of stem wood. These coefficients depend on the age of the stand and were obtained from studies by A. Shvidenko *et al.* (2014) and M. Lesiv *et al.* (2019). Formula (3) for calculating the amount of carbon sequestered by trees:

$$R_y = Mf_r/M_{stock}, \quad (3)$$

where R_v is the conversion factor for each phytofraction, M_{fr} is the weight of the phytofraction (t/ha), and M_{stock} is the stock of stem wood (m^3/ha).

Statistical methods were employed to process the collected data. Student's t-test and Mann-Whitney U-test were applied. The relationship between tree height, trunk diameter, and total biomass was determined using correlation analysis. Statistical calculations were performed using R software version 4.1.2.

Results

General characteristics of pine forest age groups

Young forests are characterised by relatively low biomass compared to other age groups. DBH parameters varied within 10-20 cm, while tree heights ranged within 8-12 m. Measurements showed that the average biomass for trees in this group was 35 t/ha (Table 1). It is also shown that the bioproductivity of young forests depends mainly on the density of stands, as individual tree growth is limited by dense competition.

Table 1. *Dependence of biomass of pine forests of Polissia on age structure*

Age group	Average diameter (cm)	Average height (m)	Biomass (t/ha)
Young forests	14	9.5	25
Middle-aged forests	30	18	65
Mature forests	42	25	120

Source: compiled by the author

The middle-aged forests had a noticeably higher biomass. DBH ranged within 20 35 cm, while the height of the trees was 15-20 m. The biomass of middle-aged forests reached 75 t/ha, which is almost twice that of young forests. There was an increase in the share of individual tree productivity in this age group, which suggests the completion of the main competitive processes and an increase in the efficiency of photosynthesis at the individual level.

In mature forests, biomass reached the highest values, which corresponds to the stage of maximum stand development. DBH of trees in this age group varied within 35-50 cm, while the height of the trees reached 20-30 m. The average biomass of mature forests was 120 t/ha. The data showed that mature forests reach peak bioproductivity due to balanced tree growth and stabilisation of ecosystem processes.

Influence of age structure on bioproductivity

The results of the study showed a clear dependence of the bioproductivity of pine forests in Polissia on the age structure of the stands: the average biomass of forest plots increases with the age of the stand, which confirms the hypothesis that age plays a vital role in shaping the overall productivity of forest stands. The dynamics of biomass growth is as follows. Young pine forests (10-30 years old) demonstrate low individual productivity despite high stand density. The reason for this is competition for resources (light, water, nutrients), which limits the growth of individual trees. In this phase of development, biomass is mainly accumulated in the trunk of trees. However, the overall productivity of the forest is still low, at around 25 t/ha.

The transition from young to middle-aged forests (40-60 years old) is characterised by a

sharp increase in biomass. During this period, a natural thinning process takes place, when weaker trees fall out of the stands, leaving room for the remaining trees to develop better. This leads to an increase in the individual productivity of each tree and a rise in total biomass to 65 t/ha.

In mature forests (80-100 years old), the process of biomass accumulation reaches its peak, while growth rates begin to slow down. However, stable growth, completion of the main competitive processes and balanced development of all parts of the tree (crown, trunk, and root system) ensure the highest biomass yields of about 120 t/ha. Mature forests also demonstrate high individual productivity, as tree stand resources are used more efficiently.

These results confirm the general pattern: with increasing stand age, the total biomass increases substantially, reaching maximum values in mature forests. The stable accumulation of biomass in this phase is explained by the end of the main competitive processes and more efficient use of resources.

Distribution of biomass by components

The analysis of wood cores showed that with the age of pine trees, the distribution of biomass between the key components of the tree: trunk, branches, and leaves, changes substantially. As forests grow, from young to mature, the priorities of resource use change, which affects the share of each component in the total biomass of the tree (Table 2).

Table 2. *Basic physical and chemical parameters of raw materials (n = 4)*

Age group	Share of trunk biomass (%)	Share of branch biomass (%)	Share of leaf biomass (%)
Young forests	70%	20%	10%
Middle-aged forests	60%	25%	15%
Mature forests	55%	25%	20%

Source: compiled by the author

Young pine forests are dominated by trunk biomass, which accounts for up to 70% of the total phytomass of the tree. This is explained by the active growth of the tree in height and the volume of wood that forms the basis of biomass. During this period, trees invest most of their resources in trunk growth, which helps them quickly become competitive for light. The proportion of branches and leaves is 20% and 10% respectively, as photosynthetic processes and maintenance of leaf mass are less important in the early stages of development.

In middle-aged forests, the ratio between components changes. The biomass of the trunk slightly decreases to 60%, while the share of biomass of branches and leaves increases to 25% and 15%, respectively. During this period, trees begin to use resources more efficiently to support the crown and expand the leaf surface to increase photosynthesis. This provides the necessary energy for the further development of the trunk and branches.

In mature pine forests, the distribution of biomass stabilises, and the proportion of trunk decreases to 55%. The share of biomass from branches and leaves increases considerably, reaching 25% and 20%, respectively. This stage of tree development is characterised by stable growth and maximum photosynthetic activity, which is aimed at maintaining the viability of a large crown. In mature forests, the significance of maintaining green mass for photosynthesis increases, which explains the increased proportion of biomass in leaves and branches.

Statistical analysis of bioproductivity

Based on the conducted studies and calculations, using formulas (1) and (2), the phytomass of wood, bark, and crown of Scots pine was determined. For further analysis, a correlation matrix was

constructed between the key biometric parameters of the tree (age, diameter, height) and aboveground phytomass in a completely dry state. The findings of the analysis are presented in Table 3.

Table 3. *Correlation matrix of the key biometric parameters of pine stands and aboveground phytomass in a completely dry state*

Indicators	Age, years	Density	Quality class	Average height, m	Average diameter, cm	Trunk volume in bark, m^3	Wood phytomass, kg	Bark phytomass, kg	Crown phytomass, kg
Age, years	1.00	–	–	–	–	–	–	–	–
Density	-0.408	1.00	–	–	–	–	–	–	–
Quality class	0.318	-0.198	1.00	–	–	–	–	–	–
Average height, m	0.811	-0.303	-0.176	1.00	–	–	–	–	–
Average diameter, cm	0.885	-0.350	0.031	0.935	1.00	–	–	–	–
Trunk volume in bark, m^3	0.865	-0.335	0.068	0.873	0.960	1.00	–	–	–
Wood phytomass, kg	0.865	-0.335	0.070	0.871	0.960	1.00	1.00	–	–
Bark phytomass, kg	0.864	-0.333	0.051	0.883	0.964	0.999	0.999	1.00	–
Crown phytomass, kg	0.865	-0.335	0.069	0.872	0.960	1.00	1.00	0.999	1.00

Source: compiled by the author

The correlation matrix shows a close relationship between the biometric parameters of trees (height, diameter) and their aboveground phytomass. The high correlation coefficients (r = 0.811 - 0.999) suggest that tree diameter and height are the key indicators affecting the total phytomass of wood, bark, and crown. The highest level of correlation was observed between stem volume and wood phytomass (r = 1.00), which confirms the significance of trunk volume in determining tree biomass.

Student's t-test was employed to compare mean biomass values between age groups (Table 4). The analysis showed that there are statistically significant differences between young and middle-aged forests ($p < 0.05$), which was confirmed by a substantial increase in biomass with age. Furthermore, the differences between middle-aged and mature forests were even more pronounced ($p < 0.01$), indicating a considerable accumulation of biomass in mature forests.

Table 4. *Comparison of biomass between age groups (Student's t-test)*

Age group	Average biomass (t/ha)	Difference (p)
Young forests	25	$p < 0.05$ (with middle-aged)
Middle-aged forests	65	$p < 0.01$ (with mature)
Mature forests	120	$p < 0.01$

Source: compiled by the author

The Mann-Whitney U test helped to estimate the variability of biomass between individual experimental plots. Local factors such as soil conditions and water availability substantially influence productivity: plots on sandy soils showed a 10-15% reduction in biomass compared to plots on loamy soils. Using the sample from the temporary plots, statistical parameters such as mean, standard error, standard deviation, and skewness were calculated (Table 5). The findings showed

that the distribution of density and height was symmetrically left-asymmetric, while the distribution of age, diameter, and biomass components showed a right-handed distribution.

Table 5. *Statistical characteristics of taxation indicators and aboveground biomass of pine trees in absolute dry state*

Indicator	Average ($\bar{X}$)	Standard error (Cv)	Standard deviation (σ)	Dispersion (D)	Kurtosis (E)	Asymmetry (A)	Coefficient of variation (V) %	Min	Max
Age (years)	65.5	2.8	26.4	697.6	-0.3	0.6	40.3	25	136
Density	0.7	0.0	0.1	0.0	6.3	-1.4	14.4	0.2	0.9
Average height (m)	19.8	0.6	5.8	32.0	0.4	1.2	28.6	5.0	31.0
Average diameter (cm)	25.6	0.9	8.6	74.3	0.0	-0.7	33.7	6.0	44.0
Trunk volume (m^3)	0.6	0.1	0.4	0.2	-0.6	-0.1	72.9	0.0	2.1
Biomass (wood, kg)	225.7	17.9	165.7	27,441.0	0.8	0.9	73.4	7.2	788.5
Biomass (bark, kg)	19.1	1.4	13.1	171.8	0.8	0.9	68.7	0.9	63.8
Biomass (crown, kg)	29.7	1.7	15.6	241.8	0.8	0.8	52.4	9.1	82.5

Source: compiled by the author

The indicators have a mixed asymmetry: left-handed asymmetry is observed in terms of density and average height (A = -1.4 and A = -0.7, respectively), which suggests the predominance of trees with high density and average height. The right-hand side asymmetry in age and phytomass suggests the presence of more young trees and trees with lower phytomass.

The kurtosis index shows that the distribution is skewed in terms of completeness (E = 6.3), which suggests a higher concentration of trees with medium completeness than expected from a normal distribution. All other indicators have a kurtosis value close to normal or flat-topped distribution (E = -0.6 for trunk volume), which means fewer extreme values.

The highest coefficient of variation was observed for the trunk volume (V = 72.9%) and wood phytomass (V = 73.4%). This suggests a considerable variability of these indicators in the sample. The lowest coefficient of variation was observed for density (V = 14.4%), which indicates the stability of this indicator within the sample.

Assessment of carbon sequestration capacity

The pine forests of Polissia have a significant potential for carbon sequestration, which depends on the age structure of the stands. To estimate the carbon-absorbing capacity, the study employed conversion factors that determined the proportion of carbon in the total phytomass of the tree. According to the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973), about 50% of the total phytomass of pine wood consists of carbon. This value is universal and is used in many international studies that assess the impact of forest ecosystems on the carbon cycle.

In young pine forests, where the total biomass is about 25 t/ha, the carbon sequestration capacity is 12.5 t/ha, which is relatively low because in the early stages of development forests have higher densities but lower individual biomass due to active competition for resources (Table 6). Middle-aged forests show a significant increase in both total biomass and carbon

sequestration. With a total biomass of 65 t/ha, the carbon sequestration capacity increases to 32.5 t/ha. During this period, the natural thinning of stands reduces competition and promotes better resource utilisation by individual trees, which increases their individual productivity.

Table 6. *Carbon sequestration by Polissia pine forests depending on age structure*

Age group	Biomass (t/ha)	Carbon sequestration (t/ha)
Young forests (10-30 years old)	25	12.5
Middle-aged forests	65	32.5
Mature forests	120	60

Source: compiled by the author

Mature forests reach their peak productivity in terms of both biomass and carbon sequestration. The average biomass in these forests is 120 t/ha, while the carbon sequestration capacity is 60 t/ha. This is supported by previous studies that showed that mature forests play a key role in reducing the carbon footprint due to their significant contribution to carbon sequestration (Convention on the Trade..., 1973).

The impact of environmental conditions on carbon sequestration

Apart from the age structure, other factors such as climate conditions, stand density, and soil characteristics also affect carbon sequestration. According to the conducted study, the highest carbon sequestration performance was observed in forests located in areas with moderately moist soils and optimum sunlight. This is because such conditions contribute to the efficient photosynthetic activity of trees, which leads to an increase in their ability to sequester carbon. Middle-aged forests, while having a lower carbon sequestration capacity than mature forests, are still highly effective in terms of sustainable forest management programmes. They can be used to optimise forest ecosystems during periods of forest regeneration and anti-deforestation. Furthermore, middle-aged forests provide the highest biomass growth, making them valuable for long-term carbon sequestration.

The data obtained for Polissia can be compared with other regions of Ukraine, including the Carpathians and the Forest-Steppe. For comparison, the average biomass of pine forests in the Carpathians is 80 t/ha, while their carbon sequestration capacity is up to 50 t/ha (Shvidenko *et al.*, 2014). This confirms that Polissia's forest ecosystems have a competitive advantage in carbon sequestration, thanks to the special environmental conditions that favour tree growth.

Impact of climatic conditions on bioproductivity

A study conducted in the spring and summer season of 2023 showed that climatic conditions in Polissia were favourable for the growth of pine forests (Table 7).

Table 7.*Influence of climatic conditions on the bioproductivity of pine forests in Polissia*

Parameter	Optimum value	Impact on biomass (t/ha)	Reduced performance in case of deviations
Precipitation (mm/year)	550–700	120 (me forests)	-15-20% with precipitation of less than 500 mm/year
Temperature (°C)	16-18	120 (mature forests)	-10-15% at temperatures >20°C or <14°C

Source: compiled by the author

According to the Ukrainian Hydrometeorological Centre (n.d.), the average temperature during the growing season (April-September 2023) was 17.5 C, which falls within the optimum range of 16-18 C recommended for pine forests. However, periodic temperature rises above 20 C negatively affected the young trees, leading to a decrease in their growth rate due to increased evaporation and moisture deficit. This phenomenon was particularly noticeable in young stands, where competition for resources is most acute. The amount of precipitation during this period was approximately 580 mm, which also meets the optimum values for maintaining a stable forest biomass, which should be 550-700 mm. These conditions ensured high stand productivity with a maximum biomass of up to 120 t/ha in mature forests. In areas with lower precipitation (less than 550 mm), a 15-20% decrease in biomass was observed, which confirms the significance of water regime for forest growth.

Discussion

The findings of the study of the bioproductivity of pine forests in Polissia offer a better insight into the dynamics of biomass accumulation in forest ecosystems and their carbon-absorbing capacity depending on the age structure. The key findings of this study suggest that the bioproductivity of pine forests increases considerably with stand age, which is consistent with the findings of many other studies, including B. Zhou *et al.* (2022), who investigated the primary productivity of forest ecosystems in the southwestern karst region of China. Both studies found that the age factor is critical in determining the bioproductivity of forest stands, which affects the ability of forests to sequester carbon and stabilise climate conditions.

The data showed that young pine forests in Polissia (up to 30 years old) have a relatively low biomass (about 25 t/ha), due to high stand density and competition for resources. This is consistent with the findings of T. Wang *et al.* (2023), who demonstrate that young trees have limited productivity due to competition for light, water, and nutrients, which reduces their individual growth capacity. Middle-aged forests of Polissia (40-60 years old) showed a significant increase in biomass (up to 65 t/ha), which can be explained by the natural process of thinning of stands and an increase in the individual productivity of each tree. Y. Li *et al.* (2023) made analogous conclusions in a study of bioproductivity in the Dinghushan National Nature Reserve in China, where it was noted that middle-aged trees have higher biomass due to reduced competition for resources and better photosynthetic activity. An increase in the share of individual productivity in middle-aged pine stands indicates optimisation of resource use, which is consistent with global trends in the development of forest ecosystems in comparable climatic zones.

At the final stage of forest stand development (80-100 years), the findings showed that biomass reaches its peak of about 120 t/ha. This can be explained by the balanced development of all tree components (trunk, branches, crown, and root system), which ensures maximum bioproductivity. These findings are consistent those of D.F. Riechelmann *et al.* (2023), who also observed an increase in bioproductivity in more mature forest ecosystems in Germany. In mature forests, biomass accumulation processes stabilise as competition between trees becomes almost non-existent and trees reach their maximum size.

The study found that climatic conditions substantially affect the bioproductivity and carbon sequestration capacity of forests. For example, a decrease in precipitation below 550 mm leads to a 15-20% decrease in biomass. G. Liobikiene *et al.* (2020) support these findings. The researchers analysed the impact of climate change on forest productivity in the European Union and found that climate stressors such as droughts and rising temperatures can substantially reduce forest productivity. G. Sukhbaatar *et al.* (2020) investigated the survival and growth of Scots pine (*Pinus sylvestris*) seedlings in the harsh continental conditions of northern Mongolia. Their findings confirmed the significant influence of climatic

conditions, specifically moisture and temperature, on the growth of young trees, which is consistent with the presented data on the dependence of bioproductivity on rainfall. L.E. Hankin *et al.* (2023) investigated the factors of successful reforestation of pine stands in the highlands of the United States and showed that the choice of seed origin and sowing environment considerably affect the success of reforestation measures. The present study complements the findings by also addressing the impact of local environmental factors, such as soil type and rainfall, on bioproductivity. Although Polissia is not a highland area, the conclusions on the significance of adapting planting methods to local environmental conditions are relevant for improving forest management. M. Lucas-Borja *et al.* (2022) worked in a similar area, investigating the impact of altitude gradients on the success of black pine (*Pinus nigra*) stands and found that climatic and altitude factors are key to forest adaptation to climate change. Although Polissia does not have such sharp elevation gradients, both studies emphasised the significance of considering regional climatic conditions to optimise forest management and plan for forest adaptation to climate change. M.P. North *et al.* (2019) examined the impacts of climate change on the resilience of pine forests in the arid western United States, pointing to the need for active measures to restore and maintain forests to improve their resilience to climate change. Although the study was conducted in a relatively humid area of Polissia, it was also noted that climate change can considerably affect the productivity of pine forests, highlighting the significance of planning measures to maintain bioproductivity in changing climatic conditions.

S. Balekoglu *et al.* (2020) investigated the influence of geoclimatic factors on the variability of pine seeds and seedlings in Turkey, showing that geographical location and climate play a key role in shaping the variability of both biometric indicators and forest productivity. These findings are in good agreement with data that showed significant variability in biomass depending on climatic conditions. K. Haghverdi & Y. Kooch (2020) discussed the long-term effects of reforestation for restoring degraded lands and combating climate change. The conclusions on the significance of stands for carbon sequestration and mitigation of negative climate impacts support the data on the carbon sequestration capacity of pine forests in Polissia. W.H. MacKenzie & C.R. Mahony (2021) proposed an ecological approach to selecting tree species for reforestation in the context of climate change. The study highlighted the significance of species adaptation to local climatic conditions to ensure the long-term sustainability of forest stands and is in line with conducted study that also showed that the success of pine forest regeneration and bioproductivity is highly dependent on local climatic conditions.

L. Hüblová & J. Frouz (2021) studied the effect of coniferous and deciduous tree species on soil carbon accumulation during reforestation of forest, agricultural, and post-mining areas, showing that conifers such as pine can considerably increase the carbon sequestration capacity of soils, which confirms the conclusions on the high productivity and ecological role of pine forests in Polissia in carbon sequestration processes. C. Looney *et al.* (2024) also conducted studies on mixed stands (*Pinus attenuata* and *P. radiata*) in different climatic conditions, investigating the effect of mixed stands on the early growth of hybrid pines. The conclusions that climatic conditions and seed origin substantially affect tree growth complement the findings of the present study regarding the significant influence of local climatic factors on the productivity of pine forests in Polissia.

M. Henneb *et al.* (2020) investigated studied the influence of regional climate, soil conditions, and substrates on the growth of black spruce and Scots pine in boreal forests and showed that soil composition and climatic conditions are key to tree productivity. The results showing that different soil conditions in Polissia subtantially affect tree biomass are consistent with these findings. Research has also been conducted in eastern Romania by R. Vlad *et al.* (2019), who investigated

the effect of climatic, local, and forest characteristics on pine forest parameters, and found that insufficient rainfall and hot temperatures can reduce tree biomass. G. Bonari *et al.* (2020) also investigated natural *Pinus pinea* forests in Turkey, finding that these forests are valuable for biodiversity conservation and can play a key role in climate change adaptation strategies. These conclusions echo the findings of the present study, as they also highlight the significance of Polissia's pine forests in reducing the carbon footprint and maintaining ecosystem resilience in the face of climate change.

A crucial factor in the development of pine and spruce stands is the time of planting and the type of planting material, which was investigated by I. Repáč *et al.* (2021) in the Carpathians. The researchers emphasised the value of choosing the correct planting time and type of planting material for successful reforestation. These findings are relevant to the present study, as the findings also emphasised the necessity of considering local environmental conditions to increase forest productivity. V. Moroz *et al.* (2021) also studied the climate stabilisation value of fir stands in the Carpathians. The results highlighting the high carbon sequestration capacity of fir forests correlate with the findings of high productivity of pine forests in Polissia in carbon sequestration. R. Testolin *et al.* (2023) modelled different forest management options under climate change for *Pinus nigra* stands in southern Italy. It was shown that adaptation of forest management practices to climate conditions is critical to ensure long-term forest productivity, which is in line with the findings of the Polissia pine forests.

Thus, the findings of the presented study confirm the significance of investigating the bioproductivity of pine forests in Polissia to improve forest management and combat climate change. The study of the dependence of bioproductivity on the age structure of stands offered a better insight into the dynamics of biomass accumulation and the effect of environmental conditions on the productivity of forest ecosystems. Further research should focus on analysing the impact of climate change on forest productivity and developing adaptive forest management strategies to ensure the resilience of forest ecosystems in the face of climate change.

Conclusions

The study demonstrated the vital role of the age structure of Polissia pine forests in determining their bioproductivity and carbon sequestration capacity. Young pine forests are characterised by a relatively low biomass of 25 t/ha, with a predominant proportion of stem, and are marked by intense competition between trees for light and nutrients, which limits individual productivity. The carbon sequestration capacity is only 12.5 t/ha, which is relatively low due to the limited development of the crown and leaves, which are key to photosynthesis.

Middle-aged forests show a significant spike in biomass, reaching 65 t/ha, due to the natural process of thinning. The carbon absorption capacity reaches 32.5 t/ha. This indicates the beginning of the efficient use of resources by trees, which positively affects their overall bioproductivity. Mature forests reach their peak in terms of bioproductivity and carbon sequestration capacity. Their biomass is 120 t/ha, while their carbon sequestration capacity reaches 60 t/ha, indicating the significance of photosynthetic processes and maintaining a large crown to ensure stable growth and high productivity. Such forests maximise resource efficiency and play a major role in reducing carbon emissions.

Statistical analysis showed a strong correlation between the biometric parameters of trees and their phytomass. Specifically, the highest level of correlation ($r = 1.00$) was observed between trunk volume and wood phytomass, which confirms the contribution of the trunk to the formation of the total biomass of trees. Comparison of mean biomass values between age groups using Student's t-test showed that the difference between young and middle-aged forests is statistically significant ($p < 0.05$), while the difference

between middle-aged and mature forests is even more pronounced ($p < 0.01$).

The analysis of biomass variability using the Mann-Whitney U test showed that tree productivity is considerably influenced by local environmental factors such as soil type and water availability, which highlights the necessity of considering soil and climatic conditions when planning forestry activities. The study showed that optimum precipitation and temperature conditions contribute to the maximum accumulation of biomass and increase the carbon sequestration capacity of forests.

Overall, the findings of this study confirmed the high ecological and economic value of mature pine forests in Polissia. Their ability to sequester carbon makes them an indispensable tool in the fight against climate change, and their high bioproductivity indicates the efficient use of natural resources.

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None.

Conflict of Interest

None.

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Біопродуктивність соснових лісів Полісся

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Анотація. Метою дослідження було визначення біопродуктивності соснових лісів Полісся та їх вуглецепоглинальної здатності залежно від вікової структури деревостанів. Дослідження проводилося на 15 експериментальних ділянках у Житомирській та Рівненській областях протягом весняно-літнього сезону 2023 року. Було здійснено вимірювання біометричних показників дерев, таких як діаметр на висоті 1,3 метра (DBH) та висота дерев, а також проведено аналіз зразків деревини для визначення фітомаси стовбура, кори та крони. Встановлено, що біопродуктивність значно зростає з віком: у молодих лісах (10-30 років) біомаса становила в середньому 25 т/га, у середньовікових (40-60 років) – 65 т/га, а у стиглих лісах (80-100 років) досягала 120 т/га. Кореляційний аналіз показав високу залежність біомаси від діаметра дерев та їхньої висоти, де найсильніший зв'язок виявлено між об'ємом стовбура та фітомасою деревини (r = 1,00). Вуглецепоглинальна здатність лісів також збільшувалася з віком: молоді ліси поглинали близько 12,5 т/га вуглецю, середньовікові – 32,5 т/га, а стиглі ліси – до 60 т/га. Крім того, дослідження виявило, що кліматичні фактори, такі як кількість опадів і середня температура, суттєво впливають на біопродуктивність. При зниженні кількості опадів нижче 550 мм на рік спостерігалося зниження біомаси на 15-20 %. Таким чином, результати підкреслюють важливість сталого управління сосновими лісами Полісся, враховуючи їхню роль у глобальних процесах фіксації вуглецю, що робить їх важливим інструментом для боротьби з кліматичними змінами та екологічними викликами

Ключові слова: екологія; фітомаса; кореляційний аналіз; лісокористування; вуглець

НАУКОВІ ДОПОВІДІ НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ БІОРЕСУРСІВ І ПРИРОДОКОРИСТУВАННЯ УКРАЇНИ

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