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НАУКОВІ ДОПОВІДІ НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ БІОРЕСУРСІВ І ПРИРОДОКОРИСТУВАННЯ УКРАЇНИ

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Features of growth and generative development of *Campsis radicans* (L.) Seem. ex Bureau in the conditions of the Northern Black Sea region

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Abstract. The need to control the spread of introduced species with high adaptive potential in new ecological conditions necessitates the study of their biological properties. The aim of the study was to establish the biological characteristics of *Campsis radicans* (L.) Seem. ex Bureau plants in the Northern Black Sea region with the possibility of determining their potential ability to naturalise. The research material consisted of collections of *C. radicans* fruits and seeds, as well as observations of 40 *C. radicans* individuals of different ages, carried out during 2023-2025. The research found that *C. radicans* individuals go through three ontogenetic periods and seven age stages in their development. The vegetation period of *C. radicans* in the studied area lasts 240 days. *C. radicans* is characterised by a late start and end of vegetation and belongs to spring-summer-autumn green plants. It has been established that the carpological characteristics of *C. radicans* are consistent with the species norm. The fruits of *C. radicans* were 8-20 cm long (14.3 cm on average) and 2.0-3.3 cm wide (2.5 cm on average). The linear parameters of the seeds were 0.4-0.8 cm in length (0.5 cm on average) and 0.6-0.9 cm in width (0.8 cm on average). The weight of 1,000 seeds was 3.4 g. It was determined that the studied plants produced high-quality seed material. The germination and germination energy indicators of seeds in laboratory conditions were higher than in field conditions (94 and 90%, 86% and 77%, respectively). The acclimatisation index calculated according to four criteria was 90 points, which corresponds to the full degree of acclimatisation of *C. radicans* in the Northern Black Sea region. The identified features of growth and generative development of *C. radicans* indicate the significant adaptive capabilities of the species

Keywords: *Campsis radicans*; ontogenesis; seed sowing qualities; degree of acclimatisation; seed renewal

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Introduction

Campsis radicans (L.) Seem. ex Bureau, (*C. radicans*) – a woody deciduous vine of the *Bignoniaceae* family, which has high decorative qualities and is widely used for vertical gardening. Climbing up vertical supports, the plant forms decorative additions to the architecture in places where it is impossible to plant trees and shrubs. The species is characterised by very rapid, even aggressive growth in its natural habitat, so it was important to study its biological characteristics in the area of introduction. According to the POWO (Plants Of the Word Online) database (2025), the natural range of *C. radicans* is eastern and central North America. According to R.E. Mokni & D. Iamonico (2024), the vine is grown as an ornamental introduction in South America (Argentina and Ecuador), Europe (Belgium, Croatia, Germany, Italy), North Africa (Algeria, Libya, Tunisia), etc. In Europe, *C. radicans* was introduced in the 17th century, and since the 19th century it has been successfully cultivated in Ukraine, as noted by L.I. Boiko *et al.* (2024). In addition to its landscaping function, *C. radicans* is known as a good honey plant and, as G. Graves (2022) points out, plays a significant ecological role as a food source for rare and endangered bird species. The author of the work noted that the biological and geographical characteristics of *C. radicans* make the plant a promising model object for studying the influence of pollinating birds on pollination mechanisms and the evolution of floral traits. The biology of *C. radicans* pollination, namely the causes and consequences of the effect of heterospecific pollen on stigma behaviour, is also discussed in the work of T.-T. Zou *et al.* (2022).

C. radicans plants have attracted the attention of researchers as a source of biologically active substances. In the work of M. Islam *et al.* (2020), the biochemical composition of the green mass of *C. radicans* was studied in terms of its pharmacological potential. The authors isolated five triterpene compounds, pharmacologically valuable secondary metabolites. M. Ramtin *et al.* (2022) investigated the active ingredient of *C. radicans* bark essential oils and evaluated its antimicrobial activity against resistant strains of some pathogenic bacteria and fungi. Studies by S. Tufail *et al.* (2022) and K. Bharadwaj *et al.* (2022) showed that the flowers and leaves of *C. radicans* have significant potential for the synthesis of silver nanoparticles with pronounced antibacterial and antioxidant activity, which has promising applications in biomedicine and biotechnology. T. Karaduman Yesildal & C. Soylukan (2024), while studying the potential therapeutic properties of *C. radicans* extracts, found that the plant has cytotoxic properties against human colon adenocarcinoma cells, as well as high antioxidant capacity. In a review study by K.U. Killi *et al.* (2024), dedicated to revealing the biomedical potential of *C. radicans*, an overview of the therapeutic use of this plant in inflammatory processes, in the treatment of cancer and prospects for use in neurology and cardiology is presented. It was also noted that similar approaches to the study of chlorophyll synthesis processes and the influence of agrotechnical factors on their dynamics are presented in the work of L.M. Burko (2020). Thus, given the antimicrobial, antiproliferative and antioxidant effects established by a number of authors, herbal medicines based on *C. radicans* can be considered as an alternative to chemical preparations, and the plant itself can be cultivated for use in official medicine in the future.

Information on the biological characteristics of *C. radicans* under introduction conditions is limited. In the monograph by L.I. Boiko *et al.* (2024), the successful introduction of *C. radicans* and its widespread use in vertical greening of Ukrainian cities among other species of woody vines was reported. The authors indicated that *C. radicans* belongs to thermophilic, fairly drought-resistant vines with highly decorative leaves and flowers that cling to supports with their roots, and is fully acclimatised to the conditions of the Kryvyi Rih Botanical Garden. As shown by the Lady Bird Johnson Wildflower Centre (2024), *C. radicans* demonstrates vigorous and rapid, even aggressive growth in its natural habitat, destroying stones, wood and bricks. According to the Global Invasive

Species Database (n.d.), the plant does not have invasive status, but given the above, the species has pronounced invasive properties. The aim of the study was to investigate the biological characteristics of *C. radicans* plants, in particular their growth, development, and seed sowing qualities in laboratory and field conditions in terms of their acclimatisation in the Northern Black Sea region.

Materials and Methods

The materials used in the study were plants of various ages, ripe fruits and seeds of *C. radicans*. Field studies were conducted during 2023-2025 at the experimental site of the Department of Plant Growing and Landscape Gardening of Mykolaiv National Agrarian University (observation of 1-2-year-old plants), as well as in 12 localities in the city of Mykolaiv (observation of virginal and generative age plants). The surveyed collection sites included residential areas and park zones in the Zavodskyi, Tsentralnyi, Ingulskyi and Korabelnyi districts of Mykolaiv; the degree of anthropogenic impact on the studied habitats was moderate. The fruits were collected from generative individuals of *C. radicans* in the specified locations in October-November 2023 and 2024, after their natural ripening. Laboratory studies were carried out at the Educational and Scientific Laboratory of Microbiology, Virology and Immunology of Petro Mohyla Black Sea National University.

To determine the developmental characteristics of *C. radicans*, plants were studied in the latent (seeds), pre-generative (30 plants; criterion for classification into the period – from the moment of seed germination) and generative (10 plants; criterion for classification into the period – from the moment of the beginning of the formation of generative shoots) ontogenetic periods. In the latent period of ontogenesis, *C. radicans* seeds were studied; in the pregenerative period, *C. radicans* plants were studied in the seedling, juvenile, immature, and virginal age states; in the generative period, they were studied in the young generative, middle generative, and old generative stages. Anatomical and morphological studies were conducted using light microscopy with the preparation of temporary micro-preparations. A total of 40 *C. radicans* individuals of different ages at various stages of ontogenesis were examined. The following biological parameters of plants characterising the generative development of *C. radicans* were analysed: morphometric parameters of fruits and seeds, weight of 1,000 seeds, germination and seed germination energy.

The fruits of *C. radicans* were collected at the stage of their natural ripeness, by random sampling of 20 fruits per plant, for a total of 200 fruits. The length and width of the fruits were measured using a ruler, and the weight of the fruits was measured using electronic scales with an accuracy of 0.01 g. To study the morphobiological characteristics of the seeds, 2,500 seeds were processed. The seeds were manually removed from the fruits and air-dried; a ruler was used to measure the linear dimensions of the seeds, and electronic scales with an accuracy of 0.01 g were used to measure the weight of 1,000 seeds. Mathematical calculations were performed using Statistics 17 software. The work uses generally accepted methods for determining seed quality, in particular the weight of 1,000 seeds is determined in accordance with DSTU 5036:2008 (2008), and the sowing quality of seeds was determined in accordance with V.M. Maurer & A.I. Kushnir (2008) and DSTU 8558:2015 (2015).

The weight of 1,000 seeds was used as an indicator characterising the viability, size and uniformity of the seeds. The sowing qualities of the seeds – germination and germination energy – were studied in laboratory conditions and in open ground; the number of seeds selected for each procedure was 100. Germination and germination energy were determined in accordance with the technical conditions of standard DSTU 8558:2015 (2015). In laboratory conditions, the seeds were germinated in a thermostat at a temperature of 25°C with a 12-hour photoperiod. To study the growth characteristics and sowing qualities of *C. radicans* seeds in field conditions, the seeds were planted in open ground in the third decade of April using the tape method; the distance between rows was 45 cm, the length of rows was 100 cm, the number of seeds per row was 20, and the number of rows was 5. The degree of acclimatisation of *C. radicans* in the study area was evaluated based on growth and generative development indicators using the acclimatisation number method according to the scale of M.A. Kochna and O.M. Kurdyuk (Shlapak *et al.*, 2019). The study was conducted in accordance with the Convention on Biological Diversity (1992).

Results and Discussion

This study found that reproductive individuals of *C. radicans* successfully pass through all stages of development and age in the conditions of introduction in the Northern Black Sea region. During the latent period of ontogenesis of *C. radicans*, morphometric indicators and sowing qualities of seeds were studied. *C. radicans* seeds are round-triangular, flat, with a thin seed coat and two winged wings. The morphometric parameters of the seed are 0.4-0.8 cm in length (average value 0.5±0.04 cm) and 0.6-0.9 cm in width (average value 0.8±0.03 cm). The weight of 1,000 seeds is 3.4±0.04 g. The established carpopological characteristics of *C. radicans* correspond to the species norm. Laboratory germination and seed germination energy are high, amounting to 94% and 90%, respectively, while field germination and seed germination energy are 86% and 77%. The germination phase begins immediately after sowing and lasts for 4-7 days until the cotyledon leaves appear. Germination is characterised by the appearance of cotyledon leaves on the soil surface, followed by juvenile leaves after the cotyledon leaves die off. Cotyledon leaves appear on average 6 days after sowing the seeds.

Juvenile leaves appear on average 11 days after the cotyledon leaves open. Juvenile leaves are simple, with an average length of 2.0-2.5 cm and a width of 2.0 cm. During this period, the plant has leaves with a shadow anatomical structure, weak mesophyll development, no differentiation into columnar and palisade parenchyma, weak venation development, and a small number of stomata per unit area. The transition of *C. radicans* plants to the immature state is evidenced by the formation of 8 or more true leaves, the presence of opposite leaf arrangement, and intensive growth of the main shoot. The formation and growth of the root system is intensified (the length of the main root averaged 20 cm), lateral roots are formed (on average, there were 20 of them). The average length of the leaves of virgin plants is 4-5 cm, and the width is 2.7 cm.

The virginal state in the ontogenesis of C. radicans lasts until the onset of the budding phase. Virginal plants are characterised by typical leaves in shape and size and the absence of generative shoots. The root system of *C. radicans* is of the allorizic type, taproot with well-developed main and lateral roots. Under the conditions studied, the root system of young plants is of the superficial-anchor type with roots concentrated in the soil horizon up to 42 cm. In the absence of support, the plant actively takes root. Certain features were found in the anatomical structure of the stem. The non-lignified shoots of *C. radicans* have a primary structure. The epidermis of *C. radicans* consists of a single layer of cells that are slightly elongated, with relatively thick straight walls. There are juvenile hairs on the surface of the stem. Under the epidermis, the primary cortex is differentiated, consisting of thin-walled parenchyma chlorophyll-bearing cells in which photosynthesis occurs. The peripheral layers of cells of this tissue are represented by collenchyma, which is located in a uniform layer or separate zones. The endoderm of *C. radicans* is represented by a starch-bearing sheath – it consists of a single layer of cells containing starch grains. Behind the endoderm, towards the centre of the stem, is the central cylinder, the main structural elements of which are the pericycle, the vascular tissue zone and the pitha.

The pericycle is the outer boundary of the axial cylinder and is located directly beneath the endoderm. Behind the pericycle is the conductive tissue of the central cylinder, which in *C. radicans* is represented by open collateral vascular-fibrous bundles. In their primary structure, they consist of primary xylem (closer to the centre) and primary and secondary phloem (closer to the periphery). The pith in the primary structure of the *C. radicans* stem is well developed and occupies its central part. It consists of large parenchyma cells with intercellular spaces. The cells of the pith are cylindrical with very thin cellulose walls. The central cylinder also includes primary pith rays, which are located between the vascular-fibrous bundles and separate them. In addition, the pith rays connect the pith with the primary cortex. The formation of the secondary structure of the stem in *C. radicans* begins in early summer with the laying of the cambium and the formation of secondary conductive tissues in the central cylinder of 1-year-old shoots. The formation of the periderm in Mykolaiv occurs later, in October-November, so the green shoots of the first year have primary covering tissue, a typical structure of the primary cortex, but already formed cambium from the procambium and secondary xylem and phloem. Parenchymatic rays in *C. radicans* are well developed in both phloem and xylem and heartwood. As indicated by J.C. Raulston & G. Grant (1994) and K.S. Rajput *et al.* (2018), in further development in perennial stems, the heartwood is completely replaced by secondary xylem and intrasaxillary secondary phloem.

Anatomical and morphological studies of the leaf blade of virginal plants *C. radicans* showed that the studied plants have a dorsoventral leaf structure with a single-layer upper and lower epidermis. The epidermal cells are relatively large, with thin walls. The central vein is more or less rounded, with a developed keel on the abaxial side and a groove on the adaxial side. The epidermis is single-layered, with collenchyma underneath. The mesophyll consists of parenchyma cells, weakly differentiated into multilayered columnar and spongy parenchyma. The leaf's conducting bundles are collateral, with well-developed xylem and phloem. The leaf of *C. radicans* is flat, and the veins on the abaxial side protrude strongly above the surface of the leaf blade. In large veins, the cells of the main parenchyma are large, with thin walls and intercellular spaces; the conducting bundles of the leaf are collateral; the collenchyma is well developed on the side of the veins. There is weak pubescence on the leaf: trichomes are few, simple, hook-shaped with a broad base, located singly along the edges of the leaf and on the veins on the underside of the leaf. Thus, the leaf of *C. radicans* has xerophytic structural features. According to S. Wennerberg (2004), the transition to the generative period in *C. radicans* occurs 4-6 years after sowing the seeds, or 2-3 years in the case of rooting cuttings. Plants in the generative period were studied in natural conditions at the research site. The generative period is characterised by the formation of flowers, the formation and ripening of seeds and fruits, and in the phenological spectrum includes the phases of budding, flowering, and fruiting (Table 1). The duration of the period from the end of flowering to fruit ripening averaged 51 days over 2 years of observation.

Table 1. *Phenological range of C. radicans in the Northern Black Sea region in 2023-2025*

Phenological phase	April	May	June	July	August	September	October	November	December
Shoot growth	■	■	■	■	■	■	■		
Budding		■	■	■	■				
Flowering			■	■	■	■			
Fruiting				■	■	■	■	■	
Relative dormancy									■

Source: compiled by the author

The flowering phase in generative individuals of *C. radicans* begins when the effective temperature exceeds +25°C and the average daily temperature is +21°C-+26°C, which in Mykolaiv occurs in the second ten days of June and lasts until the autumn frosts and a decrease in the average daily temperature. Flowering in *C. radicans* is gradual and abundant, which gives the plants high decorative value and expands the possibilities of its use in green construction. The fruiting phase in generative individuals of *C. radicans* begins in the third decade of July and lasts until the end of November. The fruit of *C. radicans* is solitary, dehiscent, pod-like with a partition, leathery walls, and greyish-brown in colour when ripe. By measuring the morphometric parameters of the fruits, it was established that in the studied area, *C. radicans* forms fruits ranging in size from 8 to 20 cm in length (average value 14.3±0.1 cm), from 2.0 to 3.3 cm in width (average value 2.5±0.1 cm), and up to 5 cm in diameter. The average fruit weight is 9.0±0.2 g. The smallest number of seeds in a fruit is 39, and the largest is 388. Ripe fruits open along the side seams, and seeds are dispersed by anemochory.

Observation of the natural seed renewal of *C. radicans* in the studied localities showed that the plant forms self-seeding, which germinates in the spring of the year following fruiting. The spread of self-seeding has certain peculiarities – seedlings were found both directly near the parent plants and beyond their boundaries. Studying the peculiarities of the seasonal rhythm of development and the duration of the phenological phases of the plant under conditions of introduction is of great importance for assessing the success of its acclimatisation. The studied species belongs to the group of spring-summer-autumn green plants with a late start and late end of vegetation. The beginning of plant vegetation is observed in the second decade of April at an average daily temperature of over +13°C. The end of vegetation is observed at the end of November. The duration of the growing season of *C. radicans* in the conditions of the Northern Black Sea region is 240 days. The acclimatisation index, calculated on the basis of four indicators, is 90 points, which indicates the complete acclimatisation of *C. radicans* in the conditions of the Northern Black Sea region. The plant goes through all ontogenetic periods and age stages (growth indicator – 5 points), produces completely similar seeds (generative development indicator – 5 points), has good winter hardiness with possible partial freezing of annual shoots (winter hardiness index – 4 points), and has excellent drought resistance (5 points).

Given the established ontogenetic characteristics, plant development throughout the year, and degree of acclimatisation, *C. radicans* can be considered successfully introduced in the Northern Black Sea region. The high potential for naturalisation in the Northern Black Sea region is primarily indicated by the fact that the plants are capable of successfully reproducing independently, both by seed and vegetatively. The quantitative parameters of seed quality obtained differ slightly from the indicators given in the available information sources. Thus, the fruit length established in this study varies significantly from 8 to 20 cm, while according to S. Wennerberg (2004) in the natural range it is 8-13 cm. The weight of 1,000 seeds in the studied plants was slightly lower than according to D. Chachalis & K.N. Reddy (2000) – 3.4 g and 4 g, respectively; the same applies to the average number of seeds in the fruit – 388 and 696, respectively. However, despite the formation of relatively smaller seeds, high field germination and germination energy rates were observed – both in comparison with our own laboratory data and in comparison with data from other researchers. Thus, D. Chachalis & K.N. Reddy indicate a maximum laboratory germination rate of 74%. Therefore, it can be assumed that *C. radicans* plants in the studied climatic and geographical conditions produce reproducible, high-quality and germinable seeds.

As S. Wennerberg (2004) points out, in its natural region, *C. radicans* is found in thickets, dry forests, wastelands, railway tracks, disturbed areas, clearings, and along roadsides and fences, i.e. in a wide range of habitats, preferring well-lit areas on sandy, loamy or clayey soils with varying moisture levels and pH ranging from 3.7 to 6.8. A study by X. Jiang-bao *et al*. (2011) on the photosynthetic efficiency of three-year-old leaves in relation to soil moisture and light intensity showed that *C. radicans* is also highly adaptable to light conditions. According to the results of observations, if *C. radicans* plants do not have vertical support, they switch to horizontal growth, spread across the soil surface and take root. The growth characteristics described above illustrate the species' significant ecological plasticity in terms of many growth conditions, which in turn indicates the significant adaptive potential of *C. radicans* in new areas of its distribution.

Under introduction conditions, *C. radicans* has been observed to spread beyond the boundaries of the crop. Thus, according to S. Wennerberg (2004) and J.A. Hurrell *et al*. (2012), throughout the United States, Canada and Argentina, the species grows as a weed, which is why S. Wennerberg (2004) recommends controlling its growth when using the vine in landscaping. In Europe, J. Blanco Salas (2014) reported the first discovery of a wild population of *C. radicans* in the natural environment in the west of the Iberian Peninsula in Spain. E. Raab-Straube & Th. Raus (2019) report on the spontaneous local naturalisation of the species in urban areas of Algeria. In this study, seedlings were observed at a distance from the parent plant, where they are able to withstand competition and develop successfully. Given the anemochorous mode of seed dispersal and the active wind regime in the study area, it is quite possible that seeds are carried beyond the parent plant over significant areas. In urban ecotopes, additional factors may contribute to the spread of *C. radicans* seeds, such as dispersal by motor vehicles, human transport during the cleaning of park areas and streets, etc. Thus, in the conditions of the Northern Black Sea region, *C. radicans* plants of generative age bloom, form viable seeds, produce self-sown seedlings, and are capable of spreading naturally without human intervention. Overall, the established biological characteristics of *C. radicans* indicate the plant's high potential for naturalisation in the Northern Black Sea region.

Conclusions

C. radicans successfully passes through the latent, pregenerative and generative periods and the age stages of seedling, juvenile, immature, virginal, young generative, middle generative and old generative in ontogenesis. In the conditions of the Northern Black Sea region, the length of the growing season of generative individuals of *C. radicans* is 240 days. In terms of phenological development, *C. radicans* has a late start and late end of vegetation and belongs to spring-summer-autumn green plants. In the conditions of the Northern Black Sea region, *C. radicans* forms fruits ranging from 8 cm to 20 cm in length (average 14.3 cm) and from 2 cm to 3.3 cm in width (average 2.5 cm). The linear dimensions of the seeds vary from 0.4-0.8 cm in length (average 0.5 cm) to 0.6-0.9 cm in width (average 0.8 cm). The average weight of 1,000 seeds was 3.4 g.

Under the introduction conditions of the Northern Black Sea region, *C. radicans* showed effective natural seed reproduction, characterised by abundant and prolonged flowering and the formation of viable and similar seeds. The germination rate and germination energy of *C. radicans* seeds in laboratory conditions were 94% and 90%, respectively, while in field conditions these indicators were 86% and 77%, respectively. The seeds remain viable under natural conditions, thus, when introduced into the Northern Black Sea region, seed reproduction and maintenance of the stability of *C. radicans* populations is possible without vegetative reproduction. The obtained characteristics of growth and generative development of *C. radicans* illustrate the high adaptive capabilities of the species. The acclimatisation index (90 points) indicates the complete degree of acclimatisation of *C. radicans* in the conditions of the Northern Black Sea region. As the results show, *C. radicans* is not only successfully introduced but also has a high potential for naturalisation in the conditions of the

Northern Black Sea region. Given the significant length of the growing season throughout the year, the success of seed reproduction of the plant, as well as the high degree of acclimatisation, the species is potentially risky in terms of biosafety and requires constant monitoring of its spread. Further research prospects include continuing to study the reproductive biology of *C. radicans*.

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Особливості росту та генеративного розвитку *Campsis radicans* (L.) Seem. ex Bureau в умовах Північного Причорномор'я

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Анотація. Необхідність контролю поширення інтродукованих видів із високим адаптивним потенціалом у нових екологічних умовах зумовлює потребу у вивченні їх біологічних властивостей. Мета дослідження полягала у встановленні біологічних особливостей рослин *Campsis radicans* (L.) Seem. ex Bureau в умовах Північного Причорномор'я з можливістю визначення потенційної здатності натуралізуватися. Матеріалом дослідження стали збори плодів і насіння *C. radicans*, а також спостереження за 40 різновіковими особинами *C. radicans*, виконані протягом 2023-2025 рр. У результаті досліджень було встановлено, що у своєму розвитку особини *C. radicans* проходять 3 онтогенетичні періоди та 7 вікових станів. Вегетаційний період *C. radicans* на дослідженій території триває 240 діб. *C. radicans* характеризується пізнім початком та закінченням вегетації і відноситься до весняно-літньо-осінньозелених рослин. З'ясовано, що карпологічні ознаки *C. radicans* узгоджуються із видовою нормою. Плоди *C. radicans* мали довжину 8-20 см (14,3 см в середньому) та ширину 2,0-3,3 см (2,5 см в середньому). Лінійні параметри насінини склали 0,4-0,8 см завдовжки (0,5 см в середньому) та 0,6-0,9 см завширшки (0,8 см в середньому). Показник маси 1000 насінин дорівнює 3,4 г. Визначено, що досліджені рослини утворювали якісний посівний матеріал. Показники схожості та енергії проростання насіння в лабораторних умовах були вищими, ніж у польових умовах (94 та 90 %, 86 % та 77 % відповідно). Розраховане за 4 критеріями акліматизаційне число дорівнює 90 балам, що відповідає повному ступеню акліматизації *C. radicans* на території Північного Причорномор'я. Виявлені особливості росту та генеративного розвитку *C. radicans* вказують на значні пристосувальні можливості виду

Ключові слова: *Campsis radicans*; онтогенез; посівні якості насіння; ступінь акліматизації; насіннєве поновлення

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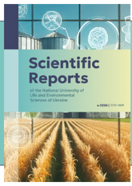

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Dynamics of the sanitary condition of Scots pine stands in the green zone of Kyiv (based on the example of the Sviatoshyn Communal Forest-Park Enterprise)

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Abstract. The relevance of the study is conditioned by the specifics of forest ecosystems in the green zone of Kyiv, which are located in a zone of intense anthropogenic stress and play a critical role in the urban environment. The purpose of the study was to analyse changes in the sanitary condition of green zone forests, identify key factors leading to their degradation, and develop recommendations for their improvement. The study used the analysis and generalisation of forest management materials, literature data, well-known methods of forestry and forest valuation (reconnaissance and detailed survey of plantings), and forest pathological methods for identifying and analysing the sanitary condition of pine plantations. During 2020-2024, a decrease in the overall stability of pine stands was found, since about 25% of them were mature and over-mature, which lose their environmental and aesthetic functions. The increase in dead wood volumes is the result of the colonisation of weakened plantings by stem pests, such as common pine shoot beetle (*Tomicus piniperda* L.), lesser pine shoot beetle (*T. minor* Hartig.), sharp-toothed bark beetle (*Ips acuminatus* Gyllenhal), six-toothed bark beetle (*Ips sexdentatus* Boerner), steelblue jewel beetle *(Phaenops cyanea* Fabricius), pine sawyer beetle (*Monochamus galloprovincialis* Ol.), and timberman beetle (*Acanthocinus aedilis* L.). The identified populations of xylophagous insects were characterised by a low to medium degree of infestation and were observed only on severely weakened trees. The largest area of pine stands (690.0 ha) covered by selective sanitary logging occurred in 2020, which indicates the impact of negative factors. Analysis of the typological structure showed that light pine forests were the most common (54.8% of the area), and fresh conditions predominate among hygrotopes (94.72% by area). High-performance stands of quality classes $1c^{-2}$ (99.1% of the area) and medium-aged stands (56.5% of the area) predominated. The total volume of accumulated dead wood was 285.4 thousand tonnes, of which 86.2% was concentrated in pine forests, with the largest carbon reservoir being the forest floor (65.1%). The average density of deadwood in pine stands was 2.61 $kg \cdot m^{-2}$. The results obtained can be used to develop effective measures to improve the sanitary condition of pine stands in the forests of green areas, increase their resistance to pests and diseases, and to optimise the recreational load

Keywords: recreational load; xylophagous insects; selective sanitary logging; deadwood; forest ecosystems

Introduction

The relevance of the study was conditioned by the need for a scientifically based assessment of the state of forests within the city of Kyiv, which were under the influence of intensive anthropogenic activity. Investigation of the productivity, composition, structure, and changes of forest stands will help to determine ways to optimise economic measures, ensure the stability of plantings, and increase their environmental efficiency. Research of the sanitary condition of forests in green areas of Kyiv is important for preserving valuable ecosystems, maximising their performance of ecosystem functions, and ensuring sustainable development of the city.

O. Tokarieva (2023) noted that the forests of urban green areas are functional natural objects that include the area outside the city, occupied by forests and other green spaces, the characteristic feature of which is manifested in the stabilising effect on the urban environment. They are important factors in the development and regulation of the urban and suburban environment, which is carried out by influencing the temperature, ionising regime of air, and its humidity and chemical composition, including the absorption of carbon dioxide with the subsequent release of oxygen, etc. The functions that the forests of green zones of cities perform can be grouped into the following groups: ecological (environment-forming or climate-regulating, sanitary and hygienic), social (recreational, health-improving, aesthetic), ecological (development of recreation, satisfaction of the population's needs for wood). Thus, urban forests are multifunctional elements of urban infrastructure that require special attention to their sanitary condition.

V. Levchenko & V. Gumeniuk (2024) found that intensive human economic activity leads to the violation of the mechanisms of self-healing and self-regulation of the ecosystem, which, accordingly, facilitates its degradation. The study showed that excessive stress on forest ecosystems disrupts their natural balance, causing them to be vulnerable to biotic and abiotic factors. The sanitary condition of forests, in particular pine stands, is deteriorating, and this may be conditioned by the occurrence of outbreaks of mass reproduction of harmful insects. N. Puzrina *et al.* (2022) found that under favourable conditions, insects can multiply rapidly and reach numbers of up to several tens of thousands of individuals per tree, which, if untimely detection and lack of effective control measures, causes massive damage to stands and disrupts the ecological balance in forest biocoenoses, significantly affecting the general biological stability of plantings.

M. O. Lakyda *et al.* (2022) noted that the determination of the sanitary condition of forest stands also allows assessing the patterns of buildup of deadwood reserves, which is of ecological importance as a habitat for biological species, and also performs the function of carbon deposition. A significant accumulation of deadwood, in particular, at the objects of the nature reserve fund and urban forests, creates prerequisites for the rapid spread of forest fires, which requires the development of an appropriate strategy for the management of dead wood in these forests. In the course of the study, O. Soshenskyi *et al.* (2021) found that such zones pose an increased risk of uncontrolled ignition, which was confirmed by examples of large-scale fires in protected areas. The revealed relationship between the amount of deadwood and the intensity of fire propagation justifies the need for regulated management of dead biomass. S. Zhang *et al.* (2025) noted that global warming increases the risk of forest fires and insect outbreaks, potentially reducing the carbon storage function of coarse wood debris. The researchers focused on the interaction of forest fires and insect damage on carbon deposition, but the effect of xylophagous insects on the flammability of dead wood remains unexplored. Excessive reserves of wood detritus can create conditions for the reproduction of pests, however, the direct impact on the spread of diseases and pests of the forest was not described in detail in scientific sources.

Thus, scientific assessment of the sanitary condition of urban forests becomes particularly important in the context of increasing anthropogenic stress, climate change, and disruption of natural regulation mechanisms. The purpose of the study was to identify spatial and temporal changes in the sanitary state of forest ecosystems, identify the main factors of their degradation, and develop practical recommendations for stabilising and improving the ecological efficiency of urban forests.

Materials and Methods

In the course of research, materials of basic forest management were analysed (Kyiv City State Administration, 2023) Sviatoshyn Communal Forest-Park Enterprise, the volume of selective sanitary logging for the period 2020-2024 was analysed with subsequent surveys in the foci of drying of pine stands. During the reconnaissance survey, a general inspection of the sites was carried out (Goychuk *et al.*, 2012), in the examined plantings, visual inspection revealed a significant weakening of them (yellowing of needles, falling bark, dryness).

Detailed surveys of plots on an area of 91.9 hectares were accompanied by the determination of the species composition of xylophagous insects. The species composition of xylophagous insects on dry and drying trees was determined by counting the population density: the average number of families of harmful insects per square decimetre of the trunk was calculated (Meshkova *et al*., 2020). When studying the species composition, each model tree was cleaned of knots. On the trunk, a 10 cm wide ribbon of bark was removed from the base to the top. Within the actual settlement areas of each species, accounting palettes were laid, on which the density of the infestation and real fertility were determined. The number of stem borer tunnels per 1 dm^2 on the barkless side of the stem was used to determine the areas and density of their settlement (Table 1).

Table 1. *Criteria for assessing the number of young generation or the production of stem pests*

Species	Number of the younger generation (p) per 1 dm^2		
	low	**average**	**high**
Monochamus galloprovincialis	0.2 or less	0.3-0.7	0.8 or more
Phaenops cyanea	0.2 or less	0.3-0.5	0.6 or more
Tomicus minor	4.9 or less	6.0-10.0	10.1 or more
Tomicus piniperda	2.9 or less	3.0-5.0	5.1 or more
Ips acuminatus	2.0 or less	2.1-5.0	5.1 or more
Acanthocinus aedilis	5.1 or less	6.0-10.0	10.1 or more

Source: developed by the authors based on V.L. Meshkova *et al*. (2020)

The relative density, i.e., the number of individuals of a certain pest species per unit of accounting (the number of trees examined (samples taken), was determined by the equation:

$$V_r = \frac{k}{n}, \quad (1)$$

where *Vr* – relative density; *k* – sum of all individuals of the species in all samples, units; *n* – number of samples taken (trees examined), units. Assessment of the volume of deadwood (or detritus) was carried out based on the materials of the specific taxation characteristics of forest fund plots (Kyiv City State Administration, 2023) using mathematical models of conversion coefficients (Bilous, 2018). Statistical processing of the obtained data was performed using the Microsoft Excel software suite. The study was conducted according to the Convention on Biological Diversity (1992).

Results and Discussion

In accordance with the systematic approach to forest management within the metropolitan area proposed by V.Yu. Yukhnovskyi *et al.* (2021), efficiency of forests in Kyiv should be evaluated primarily in terms of their ability to perform environmental functions. The state of green forests in the capital, in particular, on the territory of Sviatoshyn Communal Forest-Park Enterprise, should be considered through the prism of functional zoning and its impact on the environmental stability of plantings. According to the Ukrainian State Design Forestry Production Association (2022) and Resolution of the Cabinet of Ministers of Ukraine No. 733 (2007), the structure of green forests within this territory covers nature protection, scientific, historical and cultural, and recreational areas. Each of these categories has a specific functional load and usage mode, which is shown in Figure 1. The division of forests into functional categories allows for a more accurate assessment of the factors that affect their sanitary condition.

The largest share of the enterprise's territory is formed by national nature parks, the regulated recreation area is 38.1%, and green zone forests are 33.2%, respectively. The existing structure, where more than 70% of forests have conservation and recreational purposes, is aimed at preserving ecosystem functions and ensuring sustainable development of the city. The main task of these forests is to regulate and stabilise soil, climatic and hydrological conditions, and to perform environmental functions. However, intensive anthropogenic impact and climate changes lead to a deterioration in the sanitary condition of pine stands and an increase in the volume of dead wood.

Forests of Sviatoshyn Communal Forest-Park Enterprise by 52.7% in area and by 57.0% in trunk stock are represented by artificial stands of seed origin. Natural stands of seed origin account for 36.9% of the area of forest areas covered with forest vegetation, which is 35.8% of the stem stock. The rest, 10.4% by area and 7.1% by stock, respectively, falls on stands of vegetative origin. During the analysis of the data bank of specific taxation characteristics of forests, it was found that the most common forest-forming tree species on the territory of the enterprise was Scots pine, the share of plantings in the area of which was 86.3% (9,759.2 ha). Plantings with a predominance of common oak make up 9.8% (1,112.9 ha) (Fig. 2).

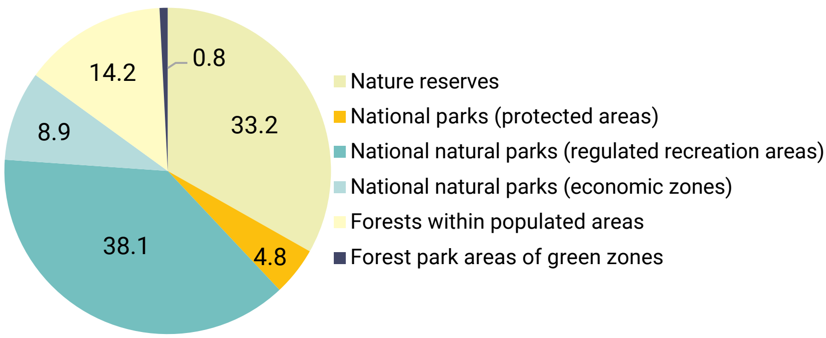

Figure 1. *Division of the forest area of Sviatoshyn Communal Forest-Park Enterprise into categories, %*

Source: developed by the authors based on materials of Kyiv City State Administration (2023)

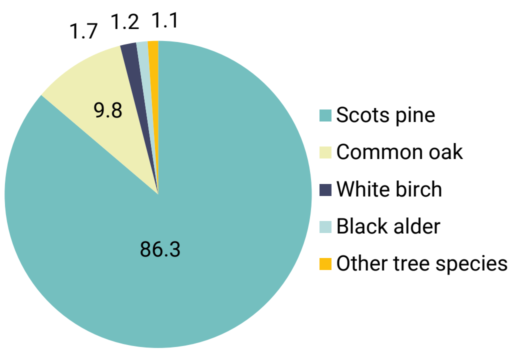

Figure 2. *Division of the area of forest areas covered with forest vegetation by dominant tree species, %*

Source: developed by the authors based on forest management materials (Kyiv City State Administration, 2023)

The data in Figure 2 indicate the dominance of Scots pine (86.3%) in the species composition of forests, which creates susceptibility to phytophagous insects, pathogens, and anthropogenic stress. Monospecific dominance of Scots pine reduces biodiversity and ecosystem sustainability, especially in the face of urban pollution and recreational stress, which exacerbate the weakening of trees and contribute to the spread of drying out. This creates a high need for continuous monitoring and adaptive forest management measures to maintain the viability of green area forests. Given that the bonus indicator reflects the influence of soil and climatic factors on the growth and development of tree species, Table 2 clearly shows the patterns of productivity of Scots pine plantings depending on the richness and humidity of the soil.

Source

Table 2. *Distribution of the area and stock of Scots pine stands by type of forest-growing conditions and bonus*

FST index	Quality class	Area		Stem stock	
		ha	%	thous. m³	%
		A			
A_1	2	1.1	0.01	0.26	0.008
	3	8.3	0.09	1.35	0.041
	4	4.6	0.05	0.58	0.018
	5	1.6	0.02	0.12	0.004
A_2	2	47.4	0.49	11.92	0.362
	3	39.1	0.40	8.33	0.253
	4	0.4	0.00	0.04	0.001
Total	-	102.5	1.05	22.6	0.686
		B			
B_1	2	23.7	0.24	1.41	0.043
	3	6.7	0.07	1.51	0.046
B_2	1^b	0.3	0.00	0.09	0.003
	1^a	1,641.7	16.82	630.59	19.148
	1	2,575.4	26.39	822.23	24.967
	2	788.2	8.08	232.68	7.065
	3	24.6	0.25	5.35	0.162
B_3	1^a	31.1	0.32	8.31	0.252
	1	204.4	2.09	70.56	2.143
	2	50.4	0.52	12.46	0.378
Total	-	5,346.5	54.78	1,785.19	54.208
		C			
C_2	1^c	1.3	0.01	0.33	0.010
	1^b	136.3	1.40	46.03	1.398
	1^a	1,797.6	18.42	696.80	21.158
	1	1,897.7	19.45	609.34	18.503
	2	292.3	3.00	80.04	2.430
	3	2.1	0.02	0.42	0.013
C_3	1^b	9.2	0.09	2.57	0.078
	1^a	82.4	0.84	23.23	0.705
	1	44.3	0.45	16.01	0.486
	2	46.6	0.48	10.64	0.323
	3	0.4	0.00	0.05	0.002
Total	-	4,310.2	44.17	1,485.46	45.106
Total	-	9,759.2	100.00	3,293.25	100.000

Note: A, B, C, D – soil fertility (from poor to fertile) and 0,1,2,3,4,5 – soil moisture (from very dry to very wet)
Source: developed by the authors based on forest management materials (Kyiv City State Administration, 2023)

In the course of the analysis of the typological structure of pine forests, it was found that the most common forest site type on the territory of Sviatoshyn Communal Forest-Park Enterprise are light pine forests, which occupy 54.8% of the area of forest areas covered with forest vegetation. There are no oak forest stands on the enterprise's territory. Among the hygrotopes, fresh conditions predominate – 94.72% by area and 95.47% by stock. There are no xerophilic, hygrophilic, or ultra-hygrophilic hygrotopes. Analysis of the distribution of areas of Scots pine stands by quality of locality shows that the enterprise is dominated by high-performance stands 1^c- 2 quality classes, which cover 99.1% of the area. Light pine forests, which occupy 54.78% of the area, are the most favourable for pine plantations, which is confirmed by high quality classes, however, it is in these conditions that intensive growth is observed, which can lead to the development of overgrown stands.

Pine plantations in spruce-fir forest conditions (44.17% of the area) are less adapted to heavier loamy soils, which can lead to stagnation of water after heavy precipitation, or, conversely, to excessive compaction during dry periods and makes plantings in spruce-fir forests vulnerable to root decay. After analysing the age structure of pine stands of Sviatoshyn Communal Forest-Park Enterprise, it can be concluded that the age distribution is dominated by middle-aged stands with a share of 56.5% of the area of forest areas covered with forest vegetation and 62.2% of the total stem stock of tree stands. The area of young stock is only 5.8% (Table 3).

Table 3. *Distribution of the area and stock of Scots pine stands by age groups*

Age group	Area		Stem stock	
	ha	%	thous. m³	%
Young stock	568.9	5.8	10.5	0.3
Middle-aged	5,515.6	56.5	2,048.16	62.2
Maturing	1,305.3	13.4	516.52	15.7
Fully mature	1,164.7	11.9	378.64	11.5
Overmature	1,204.7	12.3	339.43	10.3
Total	9,759.2	100.0	3,293.25	100.0

Source: developed by the authors based on Kyiv City State Administration (2023)

The distribution by age group indicates a suboptimal forest structure of Sviatoshyn Communal Forest-Park Enterprise from the standpoint of environmental sustainability. The predominance of middle-aged and the presence of a significant proportion of overmature plantings in combination with a low proportion of young animals creates prerequisites for mass drying out and deterioration of the sanitary condition. The largest share of the area (56.5%) and stem stock (62.2%) is occupied by middle-aged stands. This age period is often critical for pine stands from the standpoint of sanitary condition, because there is an intense crown closure, competition for light, water, and nutrients increases. Trees that lag behind in growth or are weakened begin to die intensively, creating prerequisites for the development of pathological processes. In the urban environment under the influence of additional stress (air pollution, soil compaction, recreational load), middle-aged plantings are particularly vulnerable to colonisation by stem pests (bark beetles, barbels) and the development of wood-destroying fungi. Figure 3 shows the distribution of pine forests of the enterprise by relative density, which reflects the efficiency of using the occupied space by tree stands.

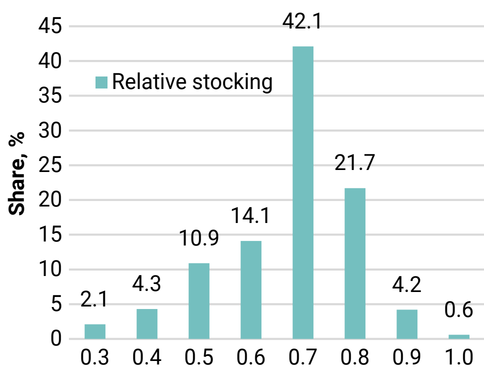

Figure 3. *Distribution of the area of Scots pine stands by relative density*

Source: developed by the authors based on Kyiv City State Administration (2023)

In general, Sviatoshyn Communal Forest-Park Enterprise is dominated by medium-sized stands with a relative density of 0.7 – more than 40% both in area and in stock. High-quality stands with a fullness index of more than 0.8-26.5% are also common. The high density of pine stands on 26.5% of the area can create favourable conditions for the development of fungal diseases and weakening of trees by reducing the intensity of sunlight and increasing humidity. For pine stands of green zone forests in conditions of intensive recreation, the optimal density is 0.6-0.7**.** Given the significant recreational load on the forest park economy and to assess the sanitary condition, the dynamics of carrying out a set of measures to improve the sanitary condition of forests for pine plantations to perform protective, water-regulating, aesthetic, and sanitary-hygienic functions, namely, sanitary selective logging for the period 2020-2024 (Fig. 4).

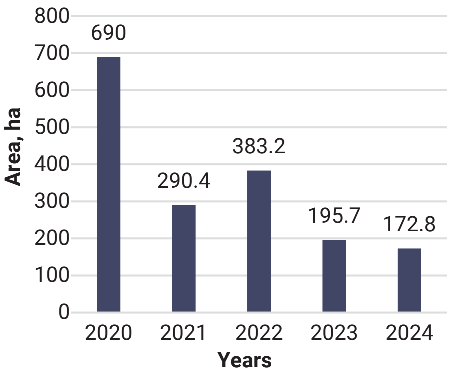

Figure 4. *Volumes of selective sanitary logging for the period 2020-2024*

Source: compiled by the authors

Analysis of logging volumes by year allows tracing the dynamics of the sanitary state of forests. For carrying out selective sanitary logging by removing dead trees and their groups, cleaning up clutter in those plantings where it is several times higher than the natural level, soil trophicity increases, conditions for root nutrition of plants and the general sanitary condition improve, the stability of the ecosystem's biological diversity and its balance are restored. It should be noted that the largest area of pine stands passed through selective sanitary logging (690.0 ha) was in 2020, which can be explained by the influence of negative factors of a reversible and irreversible nature (Fig. 5).

Figure 5. *Typical signs of colonisation by xylophagous insects*

Source: compiled by the authors

As a result, these processes have led to an increase in STEM pest populations, in particular, sharp-toothed bark beetle *Ips acuminatus*, six-toothed bark beetle *Ips sexdentatus*, common pine shoot beetle *Tomicus piniperda* and lesser pine shoot beetle *T. minor*, steelblue jewel beetle *Phaenops cyanea,* pine sawyer beetle *Monochamus galloprovincialis*, and timberman beetle

Acanthocinus aedilis. The damage of pine trees and an increase in the volume of dead wood is a consequence of the infestation of weakened plantings by stem pests with their subsequent spread to nearby stands. All trees inhabited by xylophagous insects belong to the 4-6 quality class. The involvement of the pests listed above in the drying and death of individual trees was confirmed by the bores found in nature under the bark, insect frass, shoots on the soil under the crown projections after passing additional nutrition to adults and their entrance and exit flight holes on tree trunks. Due to the intensive feeding of xylophages on weakened trees and the dynamic distribution of populations, the forest pathology situation in plantings has significantly worsened (Fig. 6). The surveyed areas with the established reasons for the deterioration of the sanitary condition are shown in Table 4.

a

b


Figure 6. *Foci of drying of Scots pine stands*

Note: a – 2022, b – 2024
Source: compiled by the authors

Table 4. *Summary of the surveyed stands (2024 survey)*

Compartment	Stratum	Area, ha	Stand composition	Pathological signs of weakening and drying out
Sviatoshyn Forestry				
89	3	11.6	100% Scots pine (95)+ Scots pine (165)	Dead wood from previous years, clutter
89	4	2.9	100% Scots pine	Drying of plantings (stem pest complex)
89	5	0.4	90% Scots pine (71)10% Witch elm + Scots pine (85)	Drying of plantings (stem pest complex)
101	1	0.5	100% Scots pine + Littleleaf Linden	Dead wood from previous years, clutter
101	2	0.3	100% Scots pine	Drying of plantings (stem pest complex)
101	3	0.4	100% Scots pine	Drying of plantings (stem pest complex)
101	5	3.3	100% Scots pine	Dead wood from previous years, clutter
101	6	1.0	100% Scots pine +Northern Red Oak	Drying of plantings (stem pest complex)
101	7	0.4	100% Scots pine + Witch elm + Common Oak + + Norway Maple	Drying of plantings (stem pest complex)
101	8	1.7	100% Scots pine	Drying of plantings (stem pest complex)
101	10	0.5	80% Scots pine 20% Witch elm+ Northern Red Oak	Drying of plantings (stem pest complex)
101	12	0.2	100% Scots pine	Dead wood from previous years, clutter
101	14	4.8	100% Scots pine + Norway Maple	Drying of plantings (stem pest complex)

***Table 4.** Continued*

Compartment	Stratum	Area, ha	Stand composition	Pathological signs of weakening and drying out
101	15	0.7	60% Scots pine 40% Witch elm	Dead wood from previous years, clutter
101	16	1.5	100% Scots pine + Scots pine +Norway Maple	Dead wood from previous years, clutter
115	2	0.9	60% Scots pine 20% Witch elm 20% Silver Maple + Norway Maple; 100% Scots pine – single trees	Dead wood from previous years, clutter
115	3	3.0	100% Scots pine	Dead wood from previous years, clutter
125	1	8.8	100% Scots pine 100% Norway Maple – of natural origin	Drying of plantings (stem pest complex)
125	2	2.7	100% Scots pine +Black Locust	Dead wood from previous years, clutter
125	3	1.0	30% Scots pine 30% Witch elm 30% Black Locust 10% Silver Maple +Sycamore Maple + + Common pear Black Locust – of natural origin	Dead wood from previous years, clutter
125	4	0.2	100% Scots pine + European Aspen	Drying of plantings (stem pest complex)
Total		**46.8**		
Kyiv Forestry				
114	2	2.4	90% Scots pine 10% Common Oak +Silver Birch Common Oak – of natural origin	Dead wood from previous years, clutter (planned selective sanitary cutting-2025)
114	4	1.0	90% Scots pine 10% Common Oak Common Oak – of natural origin	Dead wood from previous years, clutter (planned selective sanitary cutting -2025)
117	2	1.0	60% Scots pine 40% Common Oak	Dead wood from previous years, clutter (planned selective sanitary cutting -2025)
117	5	2.6	90% Scots pine 10% Common Oak	Dead wo od from previous years, clutter (planned selective sanitary cutting -2025)
117	6	3.6	80% Scots pine20% Common Oak	Dead wood from previous years, clutter (planned selective sanitary cutting -2025)
117	15	3.7	60% Scots pine 40% Common Oak	Dead wood from previous years, clutter (planned selective sanitary cutting-2025)
117	17	0.5	100% Scots pine	Drying of plantings (stem pest complex)
117	18	4.5	70% Scots pine 30% Common Oak	Dead wood from previous years, clutter (planned selective sanitary cutting-2025)
120	1	3.1	100% Scots pine	Drying of plantings (stem pest complex)
120	2	4.0	50% Scots pine 50% Common Oak	Drying of plantings (stem pest complex)
120	3	2.3	60% Scots pine 40% Common Oak 100% Scots pine – single trees	Drying of plantings (stem pest complex)
120	4	7.8	60% Scots pine 40% Common Oak	Drying of plantings (stem pest complex)
122	1	0.4	70% Scots pine 30% Common Oak + Black alder	Drying of plantings (stem pest complex)
122	2	1.2	60% Scots pine 40% Common Oak	Drying of plantings (stem pest complex)
122	4	0.8	100% Scots pine	Drying of plantings (stem pest complex)
122	8	2.4	100% Scots pine	Drying of plantings (stem pest complex)
122	9	1.0	100% Scots pine	Drying of plantings (stem pest complex)
122	14	1.2	100% Scots pine	Dead wood from previous years, clutter (planned selective sanitary cutting-2025)
122	15	1.2	100% Scots pine	Dead wood from previous years, clutter (planned selective sanitary cutting-2025)
122	16	0.4	100% Scots pine	Dead wood from previous years, clutter (planned selective sanitary cutting-2025)
Total		**45.1**		
Total, ha		**91.9**		

Source: compiled by the authors

Sites for conducting a detailed survey were selected based on reconnaissance survey and forest pathology surveys of previous years. To determine the species composition of xylophagous insects on dry and drying trees, the completeness of the settlement was recorded, that is, average number of families of different types of harmful insects per square decimetre of trunk surface was determined (Table 5). The identified populations of xylophagous insects were characterised by a low and medium degree of infestation, and they were also observed only on very weakened trees. Density of *Phaenops cyanea* indicates isolated cases or early stages of infestation. Average degree of infestation of *Monochamus galloprovincialis* and *Ips acuminatus* indicates an increase in numbers, which can cause significant damage to weakened trees. Despite the mostly low and average infestation rates, the presence of xylophagous populations on weakened trees confirms their role in the deterioration of the sanitary condition of forest stands, especially in conditions of intense anthropogenic pressure and climate changes that contribute to the weakening of trees. During the monitoring studies for the period 2020-2024, it was revealed, that pine stands have a reduced level of overall stability, since about 25% of plantings are mature and over-mature, which have practically lost or are losing their environmental and aesthetic functions (Table 6).

Table 5. *Degrees of tree infestation by xylophagous insects (2024 survey)*

Species	Settlement density, units · dm^{-2}/ average number of shoots per 1 m^2	Degree of infestation/number of beetles of the younger generation
Phaenops cyanea	0.1 ± 0.5	low
Monochamus galloprovincialis	0.5 ± 0.3	average
Tomicus minor Tomicus piniperda	5	average
Ips acuminatus	0.7 ± 0.4	average
Acanthocinus aedilis	4.5 ± 0.2	low

Source: compiled by the authors

Table 6. *Existing distribution of Scots pine forest stands by age group, %*

Species groups	Young stock	Middle-aged	Maturing	Fully mature
Regulated recreation area				
Coniferous	11.3	54.6	11.6	22.5
Economic zone				
Coniferous	3.2	61.2	11.4	24.2

Source: developed by the authors based on Kyiv City State Administration (2023)

The existing division of stands by age groups differs significantly from the optimal one. Overall, there are significantly fewer young trees than the optimal number, while the middle-aged trees are the most numerous and there is a certain shortage of maturing plantations. There is a significant shortage of young trees, especially in the economic zone of 3.2%, which indicates insufficient natural or artificial renewal of forests. A low proportion of young plantings may indicate a shortage of mature and over-mature stands in the future, which will lead to a suboptimal age structure of the forest fund. Forest ecosystems are degraded due to regular recreational loads, so intensive recreation leads to negative changes in biocoenoses. Despite the fact that tree stands are the most resistant component of forests to recreational loads, under certain conditions physiological processes become irreversible (Ukrainian State Design Forestry Production

Association, 2022). The volume of selective sanitary logging in various functional areas of the municipal enterprise Sviatoshyn Communal Forest-Park Enterprise is shown in Figure 7.

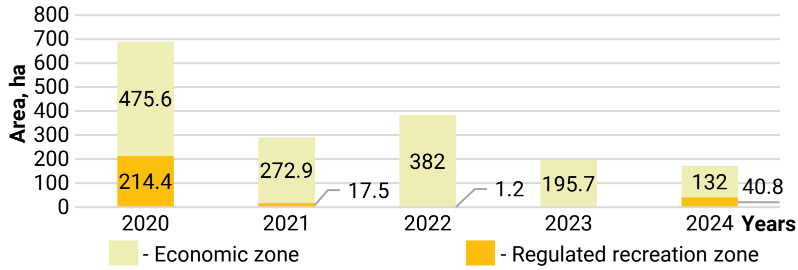

Figure 7. *Volumes of selective sanitary logging in various functional areas*
Source: compiled by the authors

Measures to improve the sanitary condition of forests were also carried out in areas that were damaged due to adverse anthropogenic factors, natural phenomena (snowstorms, windbreaks) of previous years, leading to drying of trees. Notably, middle-aged stands with high density are also significantly damaged. For the purpose of further research is to establish a pattern between the volumes of accumulated dead wood and the drying of Scots pine stands in Sviatoshyn Communal Forest-Park Enterprise, the volume of deadwood (or detritus) was estimated using mathematical models of conversion coefficients (Bilous, 2018) and specific taxation characteristics of forest fund plots. The total volume of dead organic wood accumulated in the forests of Sviatoshyn Communal Forest-Park Enterprise is 285.4 thousand tonnes, of which 86.2% of deadwood is concentrated in pine forests (Table 7).

Table 7. *Distribution of deadwood of forests of Sviatoshyn Communal Forest-Park Enterprise by components and groups of rocks*

Species group, tree type	Deadwood, thous. tonnes				
	drywood	clutter	dry branches	forest floor	total
Coniferous	24.5	7.4	55.1	159.4	246.4
including Scots pine	24.5	7.4	55.1	159.1	246.1
Hardwood	2.8	1.3	4.9	23.4	32.3
including common oak	2.6	1.2	4.6	22.0	30.6
Softwood	1.5	1.2	0.8	3.1	6.7
including silver birch	0.4	0.4	0.2	1.2	2.2
black alder	0.9	0.7	0.5	1.3	3.5
Total	28.8	9.9	60.8	185.9	285.4

Source: compiled by the authors

Analysing the data in Table 5, it was found that the largest reservoir of carbon storage in all tree groups is the forest floor. The participation of this component in the distribution of deadwood is 65.1%. The vast majority of deadwood (86.2% of the total volume) is concentrated in coniferous plantations dominated by Scots pine (246.1 thousand tonnes), which is consistent with data on the deterioration of the sanitary condition caused by anthropogenic load and exposure to stem pests.

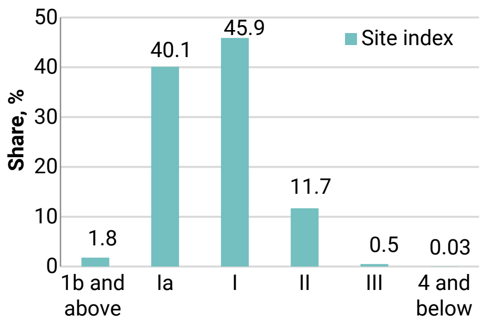

Figure 8. *Distribution of deadwood of pine forests by Sviatoshyn Communal Forest-Park Enterprise by quality classes*

Source: developed by the authors based on forest management materials

The largest volumes of deadwood in the forest stands of Scots pine were characteristic of both 1 and 1[a] site index, the total share of which was 86%. This distribution is explained by a similar distribution of areas covered with forest vegetation of forest areas by site index. Regarding the quality indicators of deadwood, it is worth noting that the average density per unit area in Scots pine stands was 2.61 kg$(m^2)^{-1}$. M.M. Kutia & O.A. Hirs (2012) noted the constant growth of the population of Kyiv, and therefore, the volume of recreation, which significantly affects the state of urban forests. The influence of the anthropogenic factor on woody phytocenoses is implemented through direct (mechanical damage, insect pests and phytopathogens) and indirect (soil degradation and depletion, atmospheric air pollution) mechanisms. Recreational load, in particular, causes significant changes in the forest floor and soil, which are expressed in compaction of the upper layer, changes in mechanical composition, and a decrease in humidity and aeration, which, in turn, negatively affects the root nutrition and overall sanitary condition of plantings. When studying pine stands, N. Puzrina *et al.* (2022) established the dependence of the increase in the index of sanitary condition of pine plantations and the deterioration of forests due to changes in weather conditions and climate aridity, and mass reproduction of stem pests after dry periods, which indicates the complex nature of the problem in the forests of green areas, where recreational load can increase the negative effects of climate change and pests. According to N. Puzrina *et al.*, the death of trees occurs in the stand as a result of natural selection mainly by the grassroots type, but in the case of adverse biotic, abiotic, or antrogenic factors, not only trees from the lower part of the canopy are lost, but also trees of the dominant (Kraft classes I-II) type. Low-top pine stands of artificial origin, clean in composition and simple in shape in all types of forest, dry up mainly in middle-aged and older age groups, which was confirmed by research. After logging and limiting the food supply, bark beetles can populate young stands. Initially, single and group foci of drying occur near the edges, in forest walls, narrow strips and low-density pine forest stands, and then expand and penetrate deep into woodlands.

F. Brovko *et al.* (2023) noted that intensive recreational loads lead to compaction of the soil, changes in its mechanical composition, a decrease in moisture and air, which negatively affects the root nutrition and general condition of trees, which was confirmed by studies in the area of intensive recreation. The reasons for the deterioration of the sanitary condition of the examined plantings are the weakening and drying of trees, a significant recreational load and unfavourable environmental factors, accompanied by the colonisation and damage of wood by xylophagous insects, which are carriers of other pathogenic microorganisms. According to the V.L. Meshkova & O.I. Borysenko (2018), the proportion of pine trees in the forest and the age of pine trees are the most important factors in predicting the threat of drying caused by bark beetles, which was confirmed by research, i.e., the relative density of the stand is less important as a risk factor than its sudden decline. Selective sanitary logging allows the extraction of freshly populated xylophages of dead trees and their groups. This was confirmed by a number of researchers, in particular, V. Melnyk (2019) noted that pine plantations where forest management measures were carried out in a timely and appropriate manner were more structurally sustainable. Faulty and wind-damaged trees, which are primarily removed during selective sanitary logging, are a substrate for the development of many microorganisms and fungi and a reservoir for forest pests.

The forests of the green zone of Kyiv, especially pine stands, play a key ecological role, but their sanitary condition is unsatisfactory. This is due to the predominance of artificial pine stands, suboptimal age structure (many middle-aged and over-mature trees, few young ones), high density, which makes them vulnerable to pests and diseases. A significant increase in deadwood and the presence of stem pests, such as the large and small pine bark beetle, the top bark beetle, and the impact of anthropogenic and recreational pressure, have been identified. The accumulation of deadwood (or detritus), which includes dead wood, wood breakage, rough branches, and forest floor, can change the living conditions of pests by affecting their numbers and distribution in plantings. It consists of organic matter from dead woody plants or isolated dead parts of living trees. The accumulation of deadwood (detritus) in forest stands is an important process that affects the ecosystem functions of forests, including their resistance to pests and diseases. The sanitary condition of plantings also determines the features of the development of stocks of deadwood, which serves as a habitat for numerous biological species (Pelyukh *et al.*, 2019). This confirms the importance of preserving different types of dead wood in forest ecosystems, as it creates microbiotopes for many rare and common species, which increases overall biodiversity. J. Sandström *et al.* (2019) noted that proper management of deadwood can help to maintain the stability of trophic connections in the forest, which is especially important for protected areas. It was considered as a reservoir of carbon, while P. Yavorovsky & S. Sendonin (2019) and M.O. Lakyda (2022) also emphasised that deadwood plays a role in nutrient accumulation and the development of a sustainable soil environment. Wood detritus is a long-term carbon storage and nitrogen source due to its long biodestruction period, which ensures a stable cycle of elements in forest biocoenoses and slows down their degradation. In the study by V.Y. Yarotskiy *et al.*, 2019), the spatial distribution of dead wood in the oak forests of the Left-Bank Forest-Steppe of Ukraine was estimated, which established the characteristic volumes of wood detritus accumulation depending on the type of plantings, age, and management regime. The researchers emphasised that dead wood is a critical component for maintaining ecosystem balance. Similar conclusions were obtained by L. Bujoczek *et al.* (2021), which shows that the amount of deadwood in non-exploited forests is six times higher than in forest ecosystems where active farming is carried out, indicating the need for a careful balance between forest management and natural recovery processes. In the Polish context, L. Bujoczek *et al.* systematised the types of dead wood according to morphological and stage signs of decomposition, and also revealed the spatial unevenness of its distribution, which was associated with forestry practices and the protected status of territories.

Thus, the presence of deadwood not only contributes to carbon accumulation, but also forms foci of biodiversity, especially for xylophages, fungi, and mosses, which was confirmed by many European studies. However, excessive detritus accumulation without a monitoring and regulatory system can create fire risks in climate change, which requires adaptive approaches to managing dead wood in forests of various functional categories.

Conclusions

In the forest fund, the predominance of high-quality (1c – 2 classes – 99.1%) and high-density (more than 0.8-26.5%) plantings in fresh forest conditions (94.72% of the area) with a monospecific dominance of Scots pine (86.3% of the area) in combination with a suboptimal age structure (the predominance of medium-aged plantings of

56.5% and a low proportion of young stands of 5.8%) creates prerequisites for deterioration of the sanitary condition. There was a deterioration in the sanitary condition and a decrease in the overall stability of pine stands during 2020-2024. About 25% of forests are mature and over-mature, which lose their conservation and aesthetic functions. The distribution of deadwood in pine forest stands showed that its largest volumes (86% of the total amount) fall on the 1 and 1a quality classes. This distribution directly correlates with a similar proportion of forest areas covered with forest vegetation for these quality classes.

The total volume of dead organic wood accumulated in the forests of Sviatoshyn Communal Forest-Park Enterprise is 285.4 thousand tonnes, of which 86.2% of the deadwood is concentrated in pine forests. According to qualitative indicators, the average density of deadwood per unit area in Scots pine stands was 2.61 kg/m². The increase in dead wood volumes is a direct result of the colonisation of weakened plantings by stem pests, such as *Tomicus piniperda, T. minor, Ips acuminatus, Ips sexdentatus, Phaenops cyanea, monochamus galloprovincialis and Acanthocinus Aedilis*. However, the identified populations of xylophagous insects were characterised mainly by a low and medium degree of infestation, they were observed on very weakened trees, which, in this case, indicates their role as secondary pests that complement the weakening caused by other factors. The results obtained confirmed the need to develop and implement effective measures to improve the sanitary condition of pine stands in the forests of green areas, increase their resistance to pests and diseases, and to optimise the recreational load by conducting systematic monitoring.

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Conflict of Interest

None.

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Анотація. Актуальність дослідження зумовлена специфікою лісових екосистем зеленої зони м. Київ, які перебувають у зоні інтенсивного антропогенного навантаження та відіграють критичну роль у міському середовищі. Мета дослідження полягала в аналізі змін санітарного стану лісів зеленої зони, визначенні ключових факторів, що призводять до їх деградації, та розробці рекомендацій щодо їх покращення. У дослідженні застосовано аналіз та узагальнення матеріалів лісовпорядкування, літературних даних, загальновідомі методи лісівництва та лісової таксації (рекогносцирувальне та детальне обстеження насаджень), а також лісопатологічні методи для виявлення та аналізу санітарного стану соснових насаджень. Протягом 2020-2024 рр. виявлено знижений рівень загальної стійкості соснових насаджень, оскільки близько 25 % з них відносяться до стиглих та перестійних, які втрачають свої природоохоронні та естетичні функції. Збільшення обсягів сухостою є результатом заселення ослаблених насаджень стовбуровими шкідниками, такими як великий сосновий лубоїд (*Tomicus piniperda* L.), малий сосновий лубоїд (*T. minor* Hartig.), верхівковий короїд (*Ips acuminatus* Gyllenhal), шестизубчастий короїд (*Ips sexdentatus* Boerner), синя соснова златка (*Phaenops cyanea* Fabricius), чорний сосновий вусач (*Monochamus galloprovincialis* Ol.) та сірий довговусий вусач (*Acanthocinus aedilis* L.). Виявлені популяції комах-ксилофагів характеризувалися низьким та середнім ступенем заселення і були відмічені лише на дуже ослаблених деревах. Найбільша площа соснових насаджень (690,0 га), охоплена вибірковими санітарними рубками, припала на 2020 рік, що свідчить про вплив негативних чинників. Аналіз типологічної структури показав, що найбільш поширеними є субори (54,8 % площі), а серед гігротопів переважають свіжі умови (94,72 % за площею). Переважають високопродуктивні деревостани Ів-ІІ класів бонітету (99,1 % площі) та середньовікові деревостани (56,5 % площі). Загальний обсяг накопиченої мертвої деревини становить 285,4 тис. т, з яких 86,2 % зосереджено у соснових лісах, причому найбільшим резервуаром вуглецю є лісова підстилка (65,1 %). Середній показник щільності мортмаси у соснових деревостанах становить 2,61 кг·м$^{-2}$. Отримані результати можуть бути використані для розробки ефективних заходів із покращення санітарного стану соснових насаджень у лісах зелених зон, підвищення їх стійкості до шкідників та хвороб, а також для оптимізації рекреаційного навантаження

Ключові слова: рекреаційне навантаження; комахи-ксилофаги; вибіркові санітарні рубки; мортмаса; лісові екосистеми

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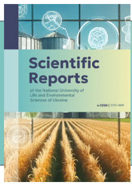

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Winter wheat productivity under conditions of uneven fertiliser distribution during application

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Abstract. The rational use of mineral fertilisers, given their uneven distribution, is an important factor in improving plant nutrition and achieving high yields of winter cereals. The aim of the study was to determine the effect of uneven distribution of mineral fertiliser granules during pre-sowing application on the productivity of winter wheat. The research was conducted in a four-fold field experiment on dark grey podzolised soil using nine fertiliser distribution options, including a control (100%) and deviations of ±10-25%. It was found that the rate of phosphorus and potassium fertilisers, which exceeded by 10-15% on dark grey podzolised soil, did not have a positive effect on the growth of the aboveground part and root system of winter wheat. It was found that increasing the uniformity of fertiliser distribution had a positive effect on the biometric indicators of plants, in particular height, mass of the aboveground and root parts, which contributed to higher yields and higher grain quality indicators. The maximum growth rates of the aboveground mass of plants were characteristic of the tillering phase. A deviation of 10-25% from the optimal fertiliser rate resulted in deviations in the indicators compared to the control by 10-72% in the tillering phase, 6.4-25% in the stem elongation phase, and 38-46% in the heading phase, respectively. The productivity analysis showed that only a 15% and 25% reduction in the fertiliser rate resulted in a significant decrease in winter wheat yield. The highest yield (10.4 t/ha) was obtained with the use of $N_{38}P_{98}K_{98}$ in pre-sowing

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application. Increasing the fertiliser rate to 110-120% resulted in an increase in protein content to 13.6-14.0%, which is 0.3-0.5% higher than the control. The results of the effect of fertiliser unevenness on crop yield formation can be used in precision farming

Keywords: yield; experimental plots; above-ground mass; root system; precision farming

Introduction

Winter wheat is one of the most important grain crops in global and national agricultural production, ensuring food security and accounting for a significant share of cultivated land. The high productivity of this crop is closely linked to the efficiency of the nutrition system, in particular the application of mineral fertilisers. In modern precision farming, increasing attention is being paid to the problem of spatial heterogeneity of soil agrophysical properties, which, in turn, causes uneven absorption of nutrients by plants and affects yield levels. The distribution of fertilisers across the field is a critical factor in ensuring uniform crop development, but in practice, there is often significant variability in their application due to both technical limitations and the characteristics of the terrain, granulometric composition and soil moisture. This requires a scientific analysis of the impact of such differences on crop productivity, taking into account modern approaches to nutrient management in the field.

As a leader among agricultural exporters, Ukraine has proven itself to be a country that is resilient to difficult circumstances and harsh conditions. The growth in the production of high-quality agricultural products, and for wheat in particular the harvesting of strong and valuable varieties, is in line with the main directions of state policy on food security and the country's export potential (Pustovit *et al.*, 2024). The productivity of winter wheat largely depends on effective plant nutrition management, which includes the rational use of mineral fertilisers. Effective fertiliser management is an important aspect that affects the range of wheat productivity. Applying fertilisers to the soil for subsequent uptake by plants is a method of increasing crop yields. The uniform distribution of fertiliser particles and the amount of fertiliser depend on the parameters of the pin and the speed of the operation. The uniformity of application (coefficient of variation) in both the transverse and longitudinal directions was in the range of 11.2-13.1% and 2.9-15.3%, respectively. The accuracy of the prototype was quantitatively determined as the percentile ratio of the collected amount of fertiliser to the desired amount per unit area. The application accuracy ranged from 81.9% to 97.4% in the working speed range (Sugirbay *et al.*, 2020).

According to the results of studies by Y. Wang *et al.* (2023), uneven distribution of fertilisers causes significant variations in wheat yields in different parts of the field. It has been proven that differential fertiliser application reduced the use of nitrogen (N), phosphorus (P) and potassium (K) fertilisers by 22.90-43.95%, 59.11-100% and 8.21-100%, respectively, and increased the efficiency of N, P and K use by 12.27-28.71, 89.64-176.85 and 5.48-266.89 kg/kg, respectively, without loss of yield. The results of the study indicate that fertiliser management has great potential for saving fertilisers, significantly increasing farmers' net income, reducing environmental pollution, and promoting sustainable resource use.

Studies by Z. Jiang *et al.* (2024) show that, in addition to the heterogeneity of fertiliser application, crop productivity is influenced by the combination of nutrient distribution in the study area and nutrient distribution in the meridional, mesmeridional and septentrional segments. A clear latitudinal dichotomy was also observed, delineating areas with excess and deficiency of nutrients in the soil. A. Aleminew *et al.* (2020) proved that the sensitivity of winter wheat to fertilisers varied depending on different areas of the map with stable intra-field heterogeneity. In the low fertility zone, increasing fertiliser application from 50 kg/ha^{-1} to 350 kg/ha^{-1} of ammonium nitrate (from 17.2 to 120.4 kg/ha^{-1}N) resulted in a 26% increase in wheat yield, compared to 50% in the optimal zone and 74% in the high fertility zone. A stable map of intra-field heterogeneity based on large satellite data can be used to intensify precision farming.

Uneven distribution of fertilisers at the time of application can have a significant impact on nutrient use efficiency, yield and economic benefits. The work of X. Wang *et al*. (2024) studied the biosynthesis of lignin in stems, which determines the level of resistance to lodging. Optimising fertiliser distribution improves the mechanical properties of stems by increasing the light exposure of the plant cover. This promotes the synthesis and accumulation of lignin in the stems and reduces wheat lodging. The use of precision farming and GPS positioning technologies significantly improves the uniformity of fertiliser distribution, which reduces fertilszer costs and increases their efficiency. Optimising fertiliser rates and application times significantly improves nutrient use efficiency.

The aim of the study was to assess the effect of artificially created heterogeneity in fertiliser application at ±10-25% of the standard DAFK rate (300 kg/ha), which occurs due to different granule sizes when spread by spreaders, on the intensity of above-ground mass and root system growth, the yield and quality of winter wheat.

Materials and Methods

The research was conducted in a field experiment by the Department of Agrochemistry and Plant Product Quality named after O.I. Dushechkin of the National University of Life and Environmental Sciences of Ukraine on the land of Biotech LTD (Boryspil district, Kyiv region) during 2023-2024. according to the developed experimental design with four replicates (Table 1; Fig. 1). The control was set at a rate of 300 kg/ha of diammonium phosphate (DAFK 10-26-26), which is widely used by agricultural producers. The heterogeneity of fertiliser distribution was created artificially using a 10*10 cm grid, and the fertiliser was applied manually to each cell according to the research variant.

Table 1. *Experimental design for determining the effect of uneven fertiliser application on winter wheat productivity*

No.	Fertilisation option	Percentage of uniformity of fertiliser distribution, %
1	$N_{30}P_{78}K_{78}$	100 % – control
2	$N_{27}P_{70}K_{70}$	90
3	$N_{34}P_{86}K_{86}$	110
4	$N_{26}P_{66}K_{66}$	85
5	$N_{35}P_{90}K_{90}$	115
6	$N_{24}P_{62}K_{62}$	80
7	$N_{36}P_{94}K_{94}$	120
8	$N_{23}P_{59}K_{59}$	75
9	$N_{38}P_{98}K_{98}$	125

Source: compiled by the authors

The area of the experimental plot was 250 m^2, and the area of the control plot was 180 m^2. The experiment was repeated four times, and the plots were arranged systematically. The experiments were set up and conducted in accordance with generally accepted methods (Ehrmantraut *et al.*, 2018). The study was conducted in accordance with the Convention on Biological Diversity (1992). The experimental field soil is dark grey podzolised light loam, formed on loess-like loam. The humus content is low – 2.12 ± 0.08%, the soil solution reaction is slightly acidic – pH 6.1±0.15, the level of mobile phosphorus compounds is average (167 mg/kg), and potassium (224 mg/kg) high, increased mobile magnesium (2.64 mg-eq/100 g), calcium (7.93 mg-eq/100 g) average, mobile sulphur (3.64 mg/kg) and mineral nitrogen (14.5 mg/kg) low. The Yulia winter wheat variety was selected for the study.

Figure 1. *Photos of the experimental plots*

Source: compiled by the authors

Soil preparation in the pre-sowing period was aimed at maximising moisture retention and accumulation in the soil and destroying weeds. The cultivation technology was generally accepted for the Kyiv region and included the following operations: application of mineral fertilisers in accordance with the research scheme, manually placing granules in cells; primary soil cultivation was performed with a HORSCH Tiger MT (Germany) deep loosener to a depth of 25-30 cm; sowing with the Amazone D9 6000 (USA) – TC sowing complex to a depth of 5 cm; nitrogen fertilisation during the tillering phase (CAS 150 kg/ha) and heading phase (CAS 100 kg/ha); to combat fungal diseases of the leaves during the tillering phase, the systemic fungicide Tebuconazole (250 g/l) was applied using a Tecnoma Lazar sprayer (France).

According to data from the Boryspil meteorological station, the average annual air temperature in 2023 was 0.9°C higher than the long-term average and amounted to 10.8°C. The temperature increase was 2.7°C in January, 2.1°C in February, 2.2°C in March, 4.9°C in September, 2.9°C in October, 1.5°C in November, and 2.7°C in December. Precipitation in 2023 was 15 mm higher than the long-term average and amounted to 636 mm. Precipitation distribution was uneven, with a maximum in June. The average annual air temperature in 2024 was 2.5°C higher than the long-term average and amounted to 11.4°C. The largest increase in temperature was observed in February (5.2°C) and September (6.4°C). In 2024, precipitation in Kyiv amounted to 642 mm, which is 4% higher than the climatic norm. The distribution of precipitation was uneven: in April and June, almost two months' worth of precipitation fell, while in May and September, precipitation amounted to only 23% and 36% of the long-term average, respectively.

Soil samples were selected and prepared in accordance with standard requirements for sample preparation and storage in laboratory conditions, in accordance with DSTU 4287:2004 (2004). Soil samples were examined in four replicates. The biometric indicators of winter wheat were determined by the weight method during the tillering, stem elongation and heading phases. The ratio of the root and above-ground parts was calculated as the ratio of the dry weight of the root system to the dry weight of the above-ground part of the plant at each stage of development. This indicator was determined to assess the balance of plant development under different nutritional conditions. The weight of wheat plant roots was determined by weighing after washing in tap water and drying at 100°C in a drying oven. Grain samples for quality analysis were pre-ground to a particle size of 1 mm using a laboratory mill. The quality indicators of winter wheat grain were determined in accordance with DSTU 4117:2007 (2007). Yield was determined for each research variant using the 1 m^2 test plot method, and threshing was carried out manually. Grain yield results were adjusted to standard moisture content in accordance with DSTU 3768:2019 (2019). Quality indicators were determined by infrared spectroscopy using an Infratec 1241 FOSS express analyser (Labimpex Ltd., Ukraine). Statistical processing of the results was carried out using standard methods with computer data processing via MS Excel and Statistica 8.0. To assess the reliability of the experimental data presented in the work, parametric criteria of normal distribution were used, calculating the arithmetic mean (Xavg.) and standard deviation (SXavg.) at a significance level of < 0.05.

Results and Discussion

The main indicator affecting the yield of vegetative mass is the height of the plant stem, which is a genetic trait of the variety and depends on the fertiliser rate (Gangur *et al.*, 2020). This was confirmed by the results of this study (Fig. 2). Under the conditions of the experiment, fairly high growth rates of winter wheat plants were established, and in the spring tillering phase, their height reached 34.1-38.0 cm, stem elongation 62.0-65.8 cm, and heading 99.1-109.0 cm.

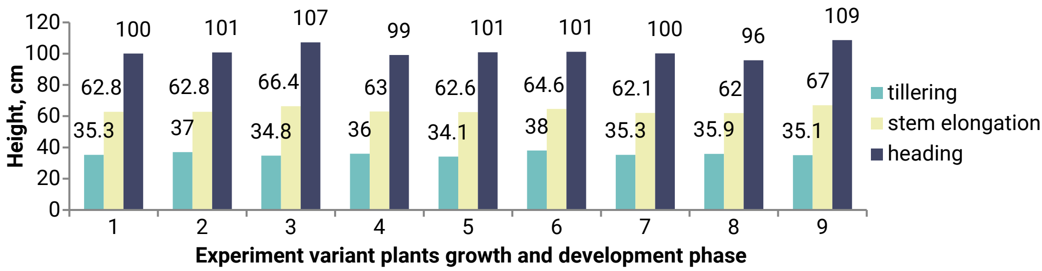

Figure 2. Dependence of winter wheat plant height on the uniformity of fertiliser distribution in pre-sowing application, average for 2023-2024

Note: 1. $N_{30}P_{78}K_{78}$ (DAFK 10-26-26) (100% uniformity of fertiliser distribution) – control; 2. $N_{27}P_{70}K_{70}$ (DAFK 10-26-26) (90% uniformity of fertiliser distribution); 3. $N_{34}P_{86}K_{86}$ (DAFK 10-26-26) (110% uniformity of fertiliser distribution); 4. $N_{26}P_{66}K_{66}$ (DAFK 10-26-26) (85% uniformity of fertiliser distribution); 5. $N_{35}P_{90}K_{90}$ (DAFK 10-26-26) (115% uniformity of fertiliser distribution); 6. $N_{24}P_{62}K_{62}$ (DAFK 10-26-26) (80% uniformity of fertiliser distribution); 7. $N_{36}P_{94}K_{94}$ (DAFK 10-26-26) (120% uniformity of fertiliser distribution); 8. $N_{23}P_{59}K_{59}$ (DAFK 10-26-26) (75% uniformity of fertiliser distribution); 9. $N_{38}P_{98}K_{98}$ (DAFK 10-26-26) (125% uniformity of fertiliser distribution)

Source: compiled by the authors

Analysis of the data obtained shows that growth processes in plants reflect the influence of external and internal conditions, including nutrition, with plant height being one of the key indicators characterising the intensity of these processes. An increase in the uniformity of fertiliser distribution (by 25%) led to an increase in this indicator during the stem elongation phase (by 6.6%) and heading phase (by 8.7%). Also, in the heading phase, a positive effect on plant height of 7% was noted from a 10% increase in the fertiliser rate due to its uneven distribution. Research by V.V. Gamayunova (2015) showed that winter wheat varieties differed in plant height, which is determined by their genetic basis, high heritability and sowing dates. The highest height was achieved by plants of the Kolchuga and Natalka varieties – 83.2 cm and 76.7 cm, respectively. Plants of the "Podolyanka" and "Blagodarka Odeska" varieties were slightly shorter – 74.5

and 71.4 cm, respectively, and the shortest were plants of the Kosovitsa variety – 66.6 cm. The height and growth of the above-ground part of plants are interrelated.

The above-ground mass of plants is one of the main components of the crop, on which the productivity of the crop largely depends. It reflects the impact of weather conditions, the level of agricultural technology, etc. on plants. It has been established that the doses of mineral fertilisers and winter wheat varieties significantly affected plant height and above-ground mass growth in all phases of plant development. Fertilisers increased plant height depending on the application rate and variety. This study found that different uniformity of mineral fertiliser distribution significantly affected the growth of above-ground plant biomass (Fig. 3).

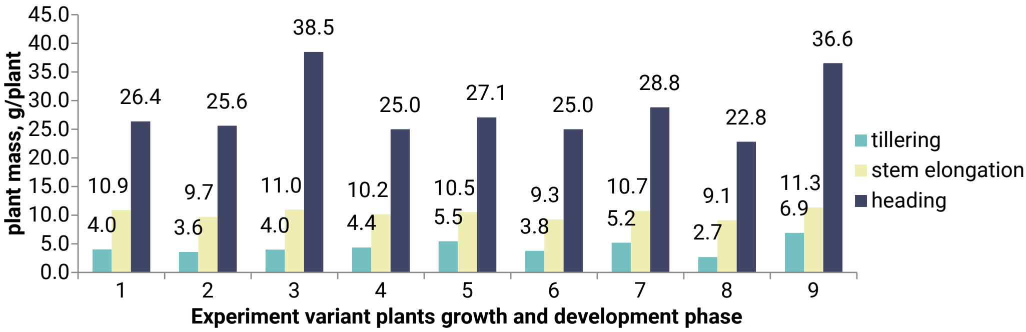

Figure 3. Dependence of the mass of the above-ground part of winter wheat plants on the uniformity of fertiliser distribution in pre-sowing application, average for 2023-2024, g/plant

Note: $N_{30}P_{78}K_{78}$ (DAFK 10-26-26) (100% uniformity of fertiliser distribution) – control; 2. $N_{27}P_{70}K_{70}$ (DAFK 10-26-26) (90% uniformity of fertiliser distribution); 3. $N_{34}P_{86}K_{86}$ (DAFK 10-26-26) (110% uniformity of fertiliser distribution); 4. $N_{26}P_{66}K_{66}$ (DAFK 10-26-26) (85% uniformity of fertiliser distribution); 5. $N_{35}P_{90}K_{90}$ (DAFK 10-26-26) (115% uniformity of fertiliser distribution); 6. $N_{24}P_{62}K_{62}$ (DAFK 10-26-26) (80% uniformity of fertiliser distribution); 7. $N_{36}P_{94}K_{94}$ (DAFK 10-26-26) (120% uniformity of fertiliser distribution); 8. $N_{23}P_{59}K_{59}$ (DAFK 10-26-26) (75% uniformity of fertiliser distribution); 9. $N_{38}P_{98}K_{98}$ (DAFK 10-26-26) (125% uniformity of fertiliser distribution). LSD 0.95 in the tillering phase 0.21 g/plant; stem elongation 0.29; heading 0.89 g/plant

Source: compiled by the authors

Thus, during the spring tillering phase, the plant mass was 2.7-6.9 g/plant, the stem elongation phase was 9.3-11.3 g/plant, and the heading phase was 22.8-38.5 g/plant. The highest rates of above-ground biomass growth with varying fertiliser distribution were obtained during the spring tillering phase. Thus, a 10-25% reduction in fertiliser rates resulted in a 10-46% decrease in plant growth rates, while a 25% increase resulted in more intensive biomass growth (72% compared to the control). In the booting phase, a significant difference between the variants was obtained with a reduction in the rate by 15-25%. The above-mentioned intensity was also characteristic of the heading phase. Increasing the fertiliser rate by 10-25% increased the growth rate of the above-ground part of plants by 38-46%. The most intensive growth of the raw above-ground mass of winter wheat plants occurs from the tillering phase to the heading phase. In the tillering phase, the increase occurred in variants 5, 7 and 9 with 115-125% heterogeneity. In the heading phase, the highest biomass growth was obtained using $N_{34}P_{86}K_{86}$ with 110% heterogeneity and amounted to 38.5 g/plant. Studies by V.V. Gamayunova *et al.* (2021) show that there is a close positive correlation between the amount of above-ground mass and wheat grain yield: the higher the yield of vegetative mass, the higher the grain yield should be, as a rule.

Starting from the first stages of development, the accumulation of significant vegetative mass of plants is an important condition for the formation of a high yield. The above-ground mass of plants plays a particularly important role in southern Ukraine, where a significant part of the leaf apparatus dies off before the wheat grain filling period. Over the years of research, in the control of raw biomass, plants of the Zamozhnist variety accumulated 1,595 g/m^2 in the stem elongation phase, 2,083 g/m^2 in the heading phase, and 2,276 g/m^2 during the milk ripeness phase, which is 84-107 g/m^2 or 3.8-5.3% more than the raw mass formed by plants of the Kolchuga variety. The same trend was observed in other variants of the experiment. In the work of M. Kazlauskas *et al.* (2022), results similar to this study were obtained and it was shown that the use of precision farming technologies on more productive land plots led to an increase in wheat biomass growth (up to 6.74%), grain yield (up to 14.5%), number of grains per ear (up to 6.2%) and protein content in grain (up to 12.56%), as well as a lower (up to 8.61%) average weight of 1,000 grains than with conventional fixed fertilisation. There was a direct relationship between the intensity of above-ground mass formation, the development of the root system of field crops and their productivity. Therefore, this should be given sufficient attention, as an increase in the proportion of the root system has the potential to increase yield (Fig. 4).

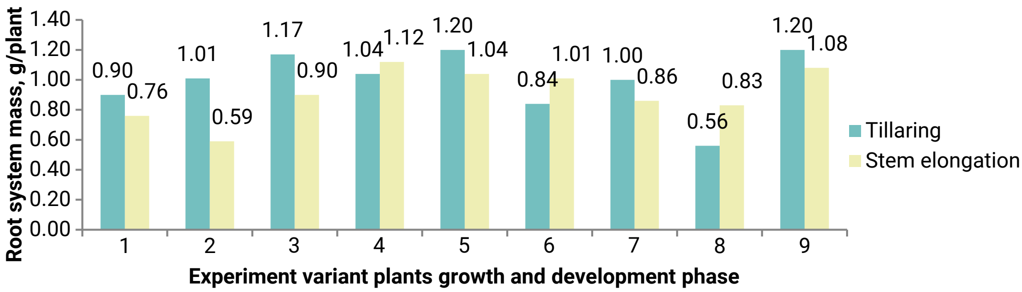

Figure 4. Dependence of the root system mass of winter wheat plants on the uniformity of fertiliser distribution in pre-sowing application (average for 2023-2024)

Note: 1. $N_{30}P_{78}K_{78}$ (DAFK 10-26-26) (100% uniformity of fertiliser distribution) – control; 2. $N_{27}P_{70}K_{70}$ (DAFK 10-26-26) (90% uniformity of fertiliser distribution); 3. $N_{34}P_{86}K_{86}$ (DAFK 10-26-26) (110% uniformity of fertiliser distribution); 4. $N_{26}P_{66}K_{66}$ (DAFK 10-26-26) (85% uniformity of fertiliser distribution); 5. $N_{35}P_{90}K_{90}$ (DAFK 10-26-26) (115% uniformity of fertiliser distribution); 6. $N_{24}P_{62}K_{62}$ (DAFK 10-26-26) (80% uniformity of fertiliser distribution); 7. $N_{36}P_{94}K_{94}$ (DAFK 10-26-26) (120% uniformity of fertiliser distribution); 8. $N_{23}P_{59}K_{59}$ (DAFK 10-26-26) (75% uniformity of fertiliser distribution); 9. $N_{38}P_{98}K_{98}$ (DAFK 10-26-26) (125% uniformity of fertiliser distribution)

Source: compiled by the authors

It was established that during the tillering phase, the root system weight was 0.9-1.2 g/plant, and the stem weight was 0.59-1.12 g/plant (Fig. 4). Deviations from the norm of fertilisers in the direction of an increase of 20 and 28 kg/ha of phosphorus and potassium caused an intensification of the growth of the root system of plants in the tillering phase by 33%, and, accordingly, a decrease of 28 kg/ha inhibited it (by 60%). In the stem elongation phase, the dependence on fertiliser unevenness was less pronounced (growth of the root system and central root). Only in variant 9 (125% uniformity of fertiliser distribution) did the root system weight increase by 45% compared to the control. Thus, uneven fertiliser distribution, with increases and decreases of 20 and 28 kg/ha of phosphorus and potassium, significantly affected the development of the root system of winter wheat.

An important condition for obtaining high yields of winter wheat is the good development of embryonic and nodal roots in plants. Studies by Yu. Tkalich (2015) show that the root system of wheat develops most intensively from the autumn vegetation period (2.4 cm/day) and in spring until the heading phase (1.1-1.4 cm). The central root, or taproot, plays an important role in the development of wheat, especially in the early stages. It is the first root to sprout from the seed and provides the initial anchoring of the plant in the soil and the absorption of water and nutrients. Although wheat has a fibrous root system (without a clearly defined main root), the central root still plays an important role in the formation of young plants (Kalenska, 2020). According to the data of this study, the length of the central root increased with an increase in the fertiliser rate (Fig. 5).

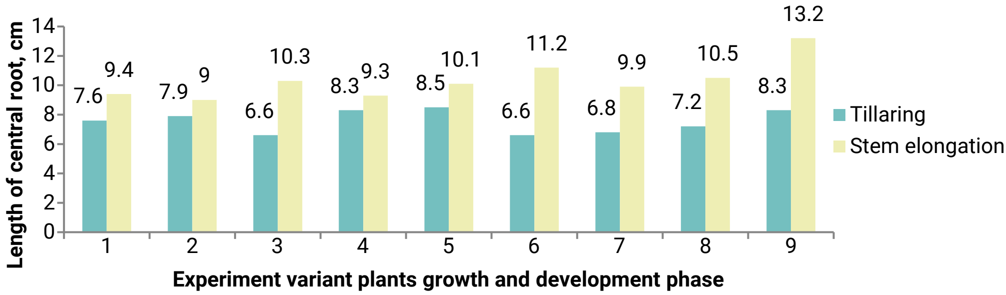

Figure 5. Dependence of the length of the central root of winter wheat plants on the uniformity of fertiliser distribution, average for 2023-2024

Note: 1. $N_{30}P_{78}K_{78}$ (DAFK 10-26-26) (100% uniformity of fertiliser distribution) – control; 2. $N_{27}P_{70}K_{70}$ (DAFK 10-26-26) (90% uniformity of fertiliser distribution); 3. $N_{34}P_{86}K_{86}$ (DAFK 10-26-26) (110% uniformity of fertiliser distribution); 4. $N_{26}P_{66}K_{66}$ (DAFK 10-26-26) (85% uniformity of fertiliser distribution); 5. $N_{35}P_{90}K_{90}$ (DAFK 10-26-26) (115% uniformity of fertiliser distribution); 6. $N_{24}P_{62}K_{62}$ (DAFK 10-26-26) (80% uniformity of fertiliser distribution); 7. $N_{36}P_{94}K_{94}$ (DAFK 10-26-26) (120% uniformity of fertiliser distribution); 8. $N_{23}P_{59}K_{59}$ (DAFK 10-26-26) (75% uniformity of fertiliser distribution); 9. $N_{38}P_{98}K_{98}$ (DAFK 10-26-26) (125% uniformity of fertiliser distribution)

Source: compiled by the authors

A 10% reduction in fertiliser rates compared to the control did not result in a significant difference compared to the control, while an increase in these rates during the tillering phase reduced the central root by 14% and increased it by 9.6% during the stem elongation phase. Accordingly, ±15% unevenness increased the indicator in the tillering phase by 9.6-12%, in the stem elongation phase by 7%, ±20% unevenness decreased in the tillering phase by 13.6-14%, increased in the stem elongation phase by 19%. The longest central root was obtained in variant 9 using $N_{38}P_{98}K_{98}$, which was 8.3 cm in the tillering phase and 7.6% longer than the control, and 13.2 cm in the stem elongation phase and 44% longer. The work of M. Hashimoto *et al.* (2024) shows that the growth of wheat shoots depends on the phosphorus content and its distribution in the soil. Among the root types, only the intensity of lateral roots increased significantly in areas with high phosphorus content and was lower in phosphorus-deficient soils, despite the absence of differences in the total root intensity per plant. The reaction of lateral roots after emergence was strongly dependent on the available phosphorus content in the soil.

The biometric indicators of winter wheat plants in the spring period until the onset of heading determine the rate of formation of the structural elements of its yield. However, according to G.M. Gospodarenko *et al*. (2020), only in the stem elongation and heading phases was there a strong (R = 0.77) and very strong (R = 0.97) correlation between phytomass and winter wheat yield. The unevenness of processes and different timing of plants entering individual phases cause a decrease in crop productivity as a whole. Under the conditions of the experiment, it was found that a significant increase in yield was characteristic only for variants with a 25% increase in dose. Its value reached 10.4 t/ha with an increase of 0.62 t/ha (Table 2).

Table 2. *Winter wheat productivity with varying unevenness of fertiliser distribution in pre-sowing application on dark grey podzolised soil, average for 2023-2024*

Experiment variant	Yield, t/ha	Yield increase		Grain content, %	
		t/ha	%	raw gluten	protein
$N_{30}P_{78}K_{78}$ (100 % uniformity of fertiliser distribution) - control	9.56	-	-	24.1	13.3
$N_{27}P_{70}K_{70}$ (90 % uniformity of fertiliser distribution)	9.19	-	-	22.4	12.3
$N_{26}P_{66}K_{66}$ (85 % uniformity of fertiliser distribution)	8.98	-0.58	-6.1	25.4	12.4
$N_{24}P_{62}K_{62}$ (80 % uniformity of fertiliser distribution)	9.60	+0.04	+0.4	22.3	12.8
$N_{23}P_{59}K_{59}$ (75 % uniformity of fertiliser distribution)	8.92	-0.64	-6.7	22.3	12.5
$N_{34}P_{86}K_{86}$ (110 % uniformity of fertiliser distribution)	9.31	-	-	25.4	13.7
$N_{35}P_{90}K_{90}$ (115 % uniformity of fertiliser distribution)	9.69	+0.13	+1.4	22.9	14.0
$N_{36}P_{94}K_{94}$ (120 % uniformity of fertiliser distribution)	9.39	-	-	24.5	13.6
$N_{38}P_{98}K_{98}$ (125 % uniformity of fertiliser distribution)	10.4	+0.84	+8.8	24.7	13.2
LSD 0.95	0.41	-	-	0.48	0.26

Source: compiled by the authors

It should be noted that, thanks to the high level of technological support for both winter wheat and its predecessor (table potatoes), high yields (8.92-10.4 t/ha) were achieved in the experiment. The uniformity of fertiliser distribution at 90%, 110% and 120% did not lead to a significant decrease or increase in wheat yield. Accordingly, 85 and 75% of fertilisers from the norm of 300 kg/ha of diammonium phosphate reduced the yield of winter wheat by 6.1-6.7%, while an increase of 15 and 25% increased the yield by 0.13-0.84 t/ha and 1.4-8.8%.

Similar results regarding the positive effect of fertilisers on winter wheat yield were obtained in studies by D. Litvinov *et al*. (2024). The work of Y. Chen *et al*. (2020) showed that nitrogen application significantly increased grain yield and protein concentration in grain due to an increase in residual nitrates in the soil during both growing seasons, at three phosphorus application rates. Phosphorus application alone did not affect these parameters. Significant interaction between nitrogen and phosphorus fertilisers was found for most of the parameters tested. The highest grain yield, nitrogen content and nitrate content in the soil, as well as the lowest residual nitrate content in the soil, were observed with N1P1 treatment. The recommended fertiliser rate was N 240 kg/ha^{-1} and P 150 kg/ha^{-1} as the optimal nitrogen-phosphorus regime in the North China Plain.

Uneven fertiliser application can lead to excess or deficiency of nutrients and reduce their efficiency. For example, under dry conditions during the growing season, the application of 70 and 90 kg/ha of nitrogen had the same effect on yield, which varied depending on the amount and distribution of precipitation (Basso *et al*., 2013). Research by Z. Li *et al*. (2022) has shown that irrigation and nitrogen use increased the average yield of winter wheat by 40% and 15%, respectively, compared to control variants without irrigation or fertiliser application. The state of nutrients in the soil and the organic carbon content in the soil had a more significant impact on wheat yield than climatic factors (average annual temperature) or water and nitrogen management methods.

This could be the basis for offsetting the negative impact of uneven fertiliser distribution on this indicator. Regardless of the yield obtained (9-10 t/ha) and the probable possibility of a decrease in grain quality under the conditions of the experiment, regardless of the degree of uneven distribution of fertilisers, grain of class 2 was obtained in accordance with DSTU 3768:2019 (2019), with the exception of the variant where DAFK was applied at a reduced dose of 10-15% (protein content 12.3-12.4%). In all other variants, the protein content ranged from 12.5 to 14.0%. In terms of "raw" gluten content, all variants provided grain of at least grade 2. It should be noted that with an increase in the DAFK dose, the grain quality improved. A number of authors show that with an increase in the rate of fertiliser, the protein content increases and its content was higher when wheat was grown after a nitrogen-fixing crop (Ali *et al.*, 2019; Novak *et al.*, 2019). Research by A. Shuvar *et al.* (2024) has shown that the use of differentiated nitrogen fertiliser application when feeding winter wheat not only increases yield but also has a positive effect on the quality indicators of the grown crop. In the control variant of the experiment, a fourth (feed) class wheat grain yield was obtained, while in the experimental variant with differentiated nitrogen application using the Yara N-Sensor device, a third (food) class yield was obtained. Thus, the results of numerous studies indicate the importance of optimising the rates and methods of nitrogen fertiliser application, taking into account soil and climatic conditions and technological solutions, in order to achieve stable yields and high grain quality.

Conclusions

Critical limits of uneven fertiliser distribution for winter wheat on dark grey podzolised soil have been established, at which significant changes in crop productivity occur. The possibility of compensating for the negative impact of uneven fertiliser application has been proven, provided that high technological support for cultivation is available. Artificially created heterogeneity of fertiliser application at ±10-25% of the standard DAFK rate (300 kg/ha) for winter wheat cultivation on dark grey podzolised soil showed a significant effect on plant height, above-ground mass and root system growth, yield and quality of the crop under study. The difference in plant height during the tillering and stem elongation phases of wheat did not exceed 5%. In the heading phase, the highest indicators were obtained with the application of $N_{34}P_{86}K_{86}$ and $N_{38}P_{98}K_{98}$ (variants 3 and 9) and amounted to 107 and 109 cm, which is 7 and 9% more than the control variant. Also, in these variants, with an increase in the fertiliser rate by 10 and 25%, the highest mass of the aboveground part of winter wheat plants was obtained in the ear emergence phase. The indicators were 46% (110% fertiliser unevenness) and 38% (125% fertiliser unevenness) higher than the control variant. Moreover, the difference in the last variant (9) is evident from the tillering phase, when the excess of the indicators compared to the control was 73%. A 10-25% higher fertiliser rate contributed to the intensification of wheat root system growth in the tillering phase by 30-33% and tillering by 29-32%.

When the dose was reduced (by 10-25%), the ratio between the root system of plants and their aboveground part was not significantly affected (during the tillering phase, it ranged from 0.016 to 0.029, and during the stem elongation phase, from 0.009 to 0.018) . When the dose was increased (by 10-25%), this indicator was significantly optimised (during the tillering phase, it ranged from 0.028 to 0.036, and during the stem elongation phase, from 0.014 to 0.017). With high technological support for the cultivation of winter wheat and its predecessor (table potatoes), it is possible to offset the negative impact of uneven fertiliser distribution on yield, which reached 8.92-10.4 t/ha, and grain quality, which was classified as grade 2 (protein content within 12.5-14.0%, and "raw" gluten – 22.3-24.7%). Further research prospects include studying the artificially created heterogeneity of fertiliser application on the yield and quality of winter wheat after other predecessors (peas, silage corn, etc.), studying heterogeneity that is ±20-35% greater than the standard DAFK rate (300 kg/ha).

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Conflict of Interest

None.

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Продуктивність пшениці озимої в умовах неоднорідного розподілу добрив при внесенні

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Анотація. Раціональне використання мінеральних добрив за умови їх нерівномірного розподілу є важливим чинником підвищення ефективності живлення рослин і формування високого врожаю озимих зернових. Метою дослідження було встановлення впливу неоднорідного розподілу гранул мінеральних добрив за передпосівного внесення на формування продуктивності пшениці озимої. Дослідження проводилися у польовому чотирикратному досліді на темно-сірому опідзоленому ґрунті з використанням 9 варіантів розподілу добрив, що включали контроль (100 %) та відхилення ±10-25 %. Встановлено, що норма фосфорних і калійних добрив, яка перевищувала на 10-15 % на темно-сірому опідзоленому ґрунті не має позитивного впливу на наростання надземної частини і кореневої системи пшениці озимої. Встановлено, що збільшення рівномірності розподілу добрив позитивно впливало на біометричні показники рослин, зокрема висоту, масу надземної та кореневої частини, що сприяло формуванню більшої врожайності та вищих якісних показників зерна. Максимальні темпи наростання надземної маси рослин були характерні для фази кущення. Відхилення норми добрив на 10-25 % від оптимальної обумовило у фазу кущення відхилення у показниках порівняно з контролем на 10-72 %, у фазу виходу в трубку – 6,4-25 %, колосіння, відповідно, на 38-46 %. Аналіз продуктивності показав, що тільки за зниження норми добрив на 15 % і 25 % встановлено достовірне зменшення урожайності пшениці озимої. Найбільшу урожайність (10,4 т/га) отримано за використання у передпосівне внесення $N_{38}P_{98}K_{98}$. Збільшення норми добрив до 110-120 % обумовило підвищення вмісту білку до рівня 13,6-14,0 %, що на 0,3-0,5 % більше порівняно з контролем. Результати з впливу нерівномірності добрив на формування врожаю культур можуть бути використані в точному землеробстві

Ключові слова: урожайність; посівні ділянки; надземна маса; коренева система; точне землеробство

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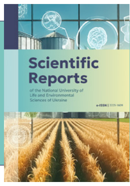

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Correlation between spring barley performance constituents under arid conditions

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Abstract. Barley possesses unique dietary properties and is among the richest sources of phenolic compounds among cereal crops, which explains the growing interest in barley grain as a raw material for functional food production. The purpose of the study was to identify valuable starting material for the breeding of naked spring barley with pigmented grains. To achieve this, the level of productivity and its relationship with structural elements (spike length, number of grains per spike) and plant height were determined. The study involved seven accessions of naked barley with pigmented grains and the standard, hulled barley cultivar 'Avhur'. The naked barley accessions included yellow-grained cultivars 'CDC(Crop Development Centre) Hilose', 'CDC Alamo', and 'Mebere' (var. *nudum*); collection accession UA 0800645 (var. *nudimelanocrithum*, black grain), UA 0800663 (var. *viride*, green grain), and UA 0805462 (var. *daghestanicum*, gray-green grain); and the breeding line Violet 18-1207 (var. *nudidubium*, purple grain) developed at the Plant Breeding and Genetics Institute, NAAS. Statistical analysis was performed using ANOVA with post-hoc Fisher's LSD test and correlation analysis. A wide variability of productivity was demonstrated (V = 26-47%), and a strong correlation was established between the productivity of the main spike and its structural elements (r = 0.65-0.96). As a result, a correlation cluster was identified: productivity → number of grains per spike → spike length. Considering the low variability of the trait "number of grains per spike" and its strong correlation with spike length, these traits were determined

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to be key indicators for selection aimed at high productivity. A source of long spikes was identified ('CDC Alamo', 10.6 cm), including sources of a large number of grains per spike ('CDC Alamo' and the breeding line Violet 18-1207, 26-28 grains). The identification of sources of valuable traits is essential for breeding aimed at increasing the yield of naked barley and ensuring food security, particularly under conditions of climate change

Keywords: naked barley; variability; primary spike; number of grains; plant height; weight of grains per spike; correlation cluster

Introduction

Resolution of the Cabinet of Ministers of Ukraine No. 684-r (2024) states that the main problems in nutrition that need to be solved have been identified at the global level, in particular: the availability of foods in sufficient quantities, their accessibility for all segments of the population, safety of foods for health, and rational nutrition. Barleys with pigmented caryopses are little spread in Ukraine, but it has long been a traditional food crop in countries of North Africa, the Middle East, China, and Tibet. Research by S. Iwatani & N. Yamamoto (2019) indicates that the concept of functional foods (FOSHU, Food of Specific Health Use), referring to foods with specific therapeutic effects on the human body, was introduced in Japan in 1991. Subsequent programmes in other countries have expanded barley diversity through breeding, resulting in new accessions and cultivars better suited for food production. For example, the study by M. Yirgu *et al.* (2022) concluded that in Ethiopia, there are many landraces with coloured grains and their dispersal depends on environmental conditions. Barleys with white caryopses are most widespread followed by accessions with purple, black, and grey grains. In terms of altitude, the dispersal of white-grained barleys tends to increase from low to high altitudes, while the dispersal of brown-grained accessions, vice versa, tends to increase from high to low altitudes.

Global food demand is predicted to grow, so it is necessary to increase agricultural production to ensure food security while minimising environmental impacts, especially in the context of possible climate change. Understanding agronomic and biological characteristics of crops under water deficit is crucial to increase performance and yield potentials. K. Sato (2025) determined that agronomically important traits are often controlled by several interacting genes, requiring in-depth knowledge of genetics. To better understand contributions of genomic sequence variations to different traits, standardised phenotyping and systematic gene modification through genome editing have become widely used. This provides new strategies for improving traits through gene sequence-based barley breeding. M. Jayakodi *et al.* (2021) stated that Haplotype (haploid genotype)-based characterisation of Single Nucleotide Polymorphism copies from gene banks and breeding germplasm is a state-of-the-art approach to plant breeding. High-quality genome sequences are essential for haplotype analysis and association of barley sequence variations with phenotypic variations. The haploid genotype, as a region of DNA that is inherited as a single unit from parent to offspring, cannot always be determined by genotype. Haplotype determination is only possible through sequencing. Combined information gained from genomic sequences and systematic functional gene analysis provides new strategies for trait improvement through sequence-based barley breeding.

J.H. Czembor (2023) investigated that agromorphological characteristics of collection naked barley accessions as starting materials are crucial for the development of targeted breeding strategies that respond to changing environmental conditions and demand for agricultural products, and are thus valuable resources for breeding programmes. This is all the more important given that the use of elite materials in breeding has led to cultivars becoming genetically homogeneous and more vulnerable to stresses such as droughts and elevated temperatures. In particular, narrowing and homogeneity of the barley gene pool are a challenge for breeders of stress-tolerant cultivars. It has been shown by S. Sakuma & T. Schnurbusch (2020) that over the past decades, breeders have raised the yield of barley grain mainly by increasing the number of grains per spike, a trait determined by the number of spikelets per spike and the number of fertile flowers, which emphasises the significance of spike architecture in improving yield potential.

The purpose of this study was to create starting materials for the breeding of naked barleys with pigmented caryopses and other valuable traits.

Materials and Methods

The experiments with barley plants were carried out in compliance with the requirements of the International Plant Protection Convention (2006) and in accordance with the Law of Ukraine No 4147-IX (2024). Based on the findings of other researchers, the Yuriev Plant production Institute of the National Academy of Agrarian Sciences of Ukraine (YPPI NAAS) determined the performance of the naked spring barley accessions and relationship between performance and its constituents (spike length, number of grains per spike) and plant height. Since naked barley yields little in breeding nurseries under arid conditions, assessment of genotypes by this trait would be incorrect; therefore the accessions were characterised by primary spike performance. Seven naked barley accessions with pigmented caryopses and the check cultivar (chaffy barley 'Avhur' (var. *nutans*) bred at the YPPI NAAS) were studied. The naked cultivars with yellow caryopses were 'CDC Hilose', 'CDC Alamo' and 'Mebere' (var. *nudum*); collection accession UA 0800645 (var. *nudimelanocrithum*) has black caryopses; collection accession UA 0800663 (var. *viride*) has green caryopses; collection accession UA 0805462 (var. *daghestanicum*) has grey-green caryopses; and YPPI-bred line Violet 18-1207 (var. *nudidubium*) has purple caryopses.

The cultivars and collection accessions were grown in the YPPI NAAS scientific crop rotation fields in 2022-2024. The sowing was carried out with a cassette seeder SKS-6A (USSR) within optimal timeframes in 2023 and 2024; in 2022, the sowing was two weeks later than the optimal time because the Institute's fields were in the combat zone. The barley accessions were sown according to the breeding nursery scheme; each plot was 2 m^2, without replications; the check cultivar was placed after every 10 accessions. Plants with roots were harvested manually. To analyse performance constituents, 15-20 typical plants of each accession were selected. Data were statistically processed in STATISTICA-6: one-way analysis of variance (ANOVA) for pairwise comparison and post-hoc comparison of homogeneous groups using Fisher's LSD test. Different letters (a, b, c, d) indicate statistically significant differences among years and barley accessions. Boxplots (box-and-whisker plots) were used to visualise the original data. Such diagrams are convenient to show the median, mean, lower and upper quartiles, minimum and maximum, and outliers. Distances between different parts of the box allowed evaluating of dispersion degrees and data asymmetry and identifying outliers. The weather in the study years varied, enabling the comprehensive evaluation of the naked barley accessions (Fig. 1).

Data for April and 20 days of May 2022 are missing, since meteorological observations were impossible because the Russian invasion. Barley was sown later than usual, so the available meteorological data for 2022 fully correspond to the growing period of spring barley in this study. The April air temperature in the study years was 1.3-3.7°C higher than the long-term mean value; the May temperature was 0.5-0.3°C lower in 2022 and 2023 and 0.4 °C higher in 2024 than the long-term mean value. In May, barley went through one of the critical phases – tillering; therefore it was especially demanding on growing conditions. In June, when barley went through the next critical phases, earing and filling, the air temperature was similar to the long-term mean value in 2023, but it exceeded the long-term mean value by 1.4-2.1°C in the other years. The July temperature was 1.5-4.6°C higher than the long-term mean value. Elevated air temperatures during this period are dangerous because they cause grain scorching, thereby significantly reducing yield. The amount of productive precipitation also had a negative impact on the naked barley performance at elevated temperatures (Fig. 2).

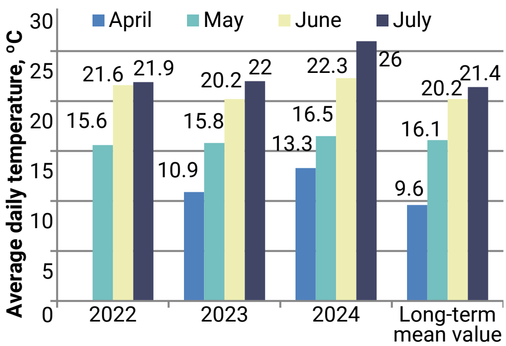


***Figure 1.** Mean daily air temperature in the study years compared to the long-term mean daily air temperature*

Source: constructed by the authors based on data from the Kharkiv Regional Hydrometeorological Centre

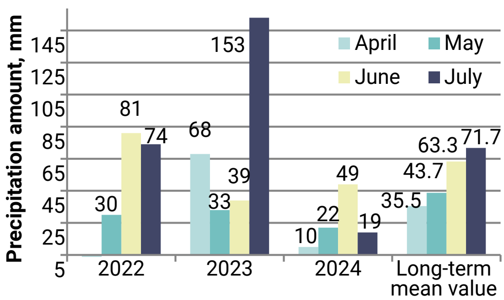


***Figure 2.** Monthly precipitation in the study years compared to the long-term mean value*

Source: constructed by the authors based on data from the Kharkiv Regional Hydrometeorological Centre

Thus, in May (in all years of the study), the precipitation amount was smaller than the long-term mean value by 21.7-10.7 mm, which did not help productive tillering of barley. The June precipitation amount was bigger than the long-term mean value only in 2022, while it was 14.3-2.3 mm smaller in the other years. The July precipitation in 2022 and 2023 was more abundant than the long-term mean value, but the rains were torrential and unproductive, that is, a large amount of precipitation fell within several days and the moisture quickly evaporated at elevated temperatures. 2024 had particularly harsh conditions: high temperatures and continuous drought throughout the entire growing period of barley. This had a severely negative impact on the performance and yield, but simultaneously allowed assessing the accessions for drought tolerance.

Results and Discussion

It was found that the primary spike performance was significantly lower in 2024[b] (1.42 g) than in 2022 and 2023 (1.81-1.86 g, group [a]), which was explained by an abnormally harsh weather (a prolonged drought combined with high temperatures: the mean daily temperature in June-August reached 32°C). These observations are consistent with data by S.G. Thabet *et al.* (2020) where 121 accessions of the world collection were tested under arid conditions, the outcome was a significant decline in levels of agronomic traits related to barley yield, i.e., spike length, awn length, the numbers of spikelets and grains per spike, and thousand-grain weight. M.A.E.-H. Attia *et al.* (2022) noted that the negative impact of water deficit during the earing and filling phases of naked 'Giza 129', 'Giza 130', and 'Giza 131' on the barley yield and performance and the numbers of spikelets and grains per spike and thousand-grain weight made the greatest contributions to yield. In this study, ANOVA revealed significant differences in all elements of the plant structure depending on growing conditions. The post-hoc comparison showed that the plant height in 2023[b] (63 cm) was significantly different from that in 2022[a] (55 cm) and 2024[a] (54 cm) (Fig. 3).

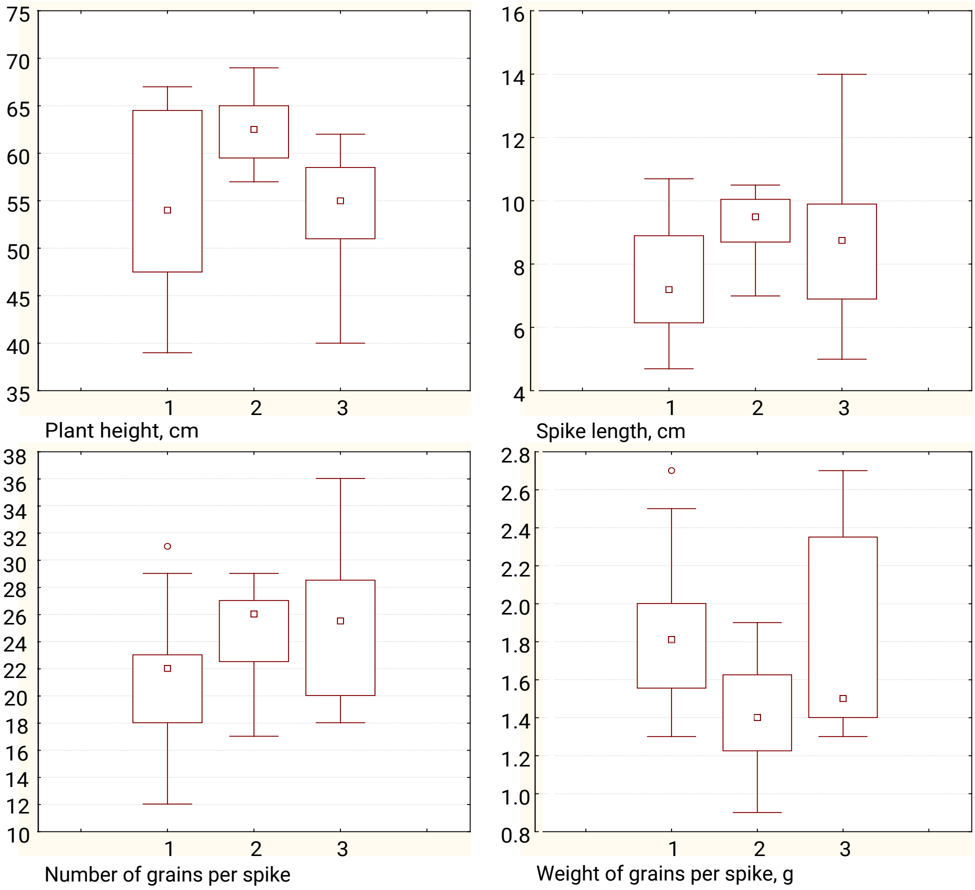


Figure 3. *Inter-year variability of the elements of barley plants structure, 2022-2024*

Note: study years: 1 – 2022, 2 – 2023, 3 – 2024

Source: constructed by the authors

The spike length in 2022[a] (7.5 cm) was significantly different from that in 2024[b] (9.3 cm), while the 2023[ab] value was intermediate (8.7 cm). The number of grains was fewer in 2022[b] (21 grains) compared to 2023[a] and 2024[a] (25 grains). Thus, 2022 was the worst year for the expression of the "spike length" and "number of grains" traits in naked spring barley, which is attributed to the late sowing because of hostilities at the scientific crop rotation site in the 2022 spring. However, this allowed assessing the responses of different naked barley accessions to late sowing. The coefficient of variation of the weight of grains from the primary ear (CV) was 26% in 'Avhur', 29% in line Violet 18-1207, 30% in accession UA 0805462, 34% in accession UA 0800663 and 'Mebere', 36% in 'CDC Hilose', 44% in 'CDC Alamo', and 47% in accession UA 0800645. That is, the variability of the primary spike performance was high, as the coefficients of variation exceeded 20% in all accessions. This is consistent with the data by C. Massman *et al.* (2022) that genotype made a greater contribution to thousand-grain weight and plant height than "genotype x environment" interaction, but the "genotype x environment" factor had a five-fold stronger effect on performance variance than genotype. The naked cultivars turned out to be less adaptable to changes of growing conditions than the chaffy check cultivar ('Avhur'); they responded with greater trait variability to such changes. A trait variability range can be estimated by "whiskers" length on a "box", where the "whiskers" ends are the limits of a statistically representative sample (without outliers). There were also significant inter-genotype differences in all elements of the plant structure (Fig. 4).

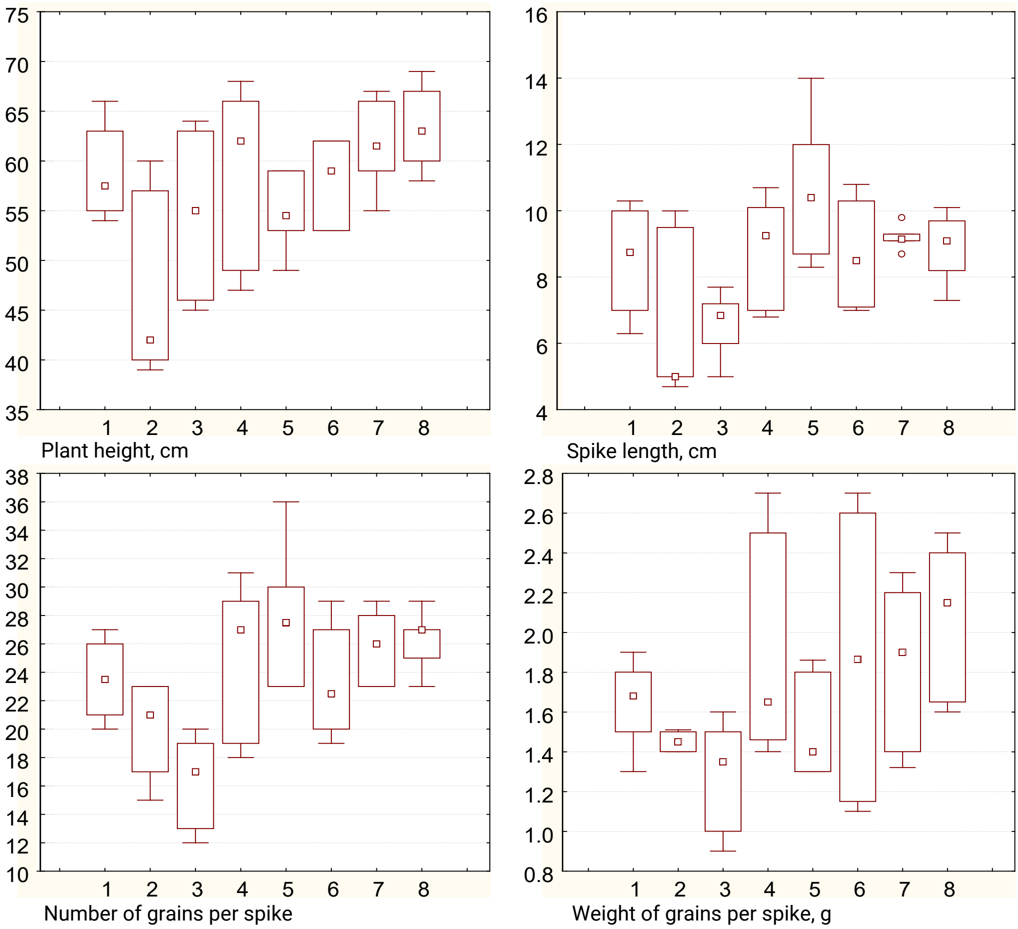
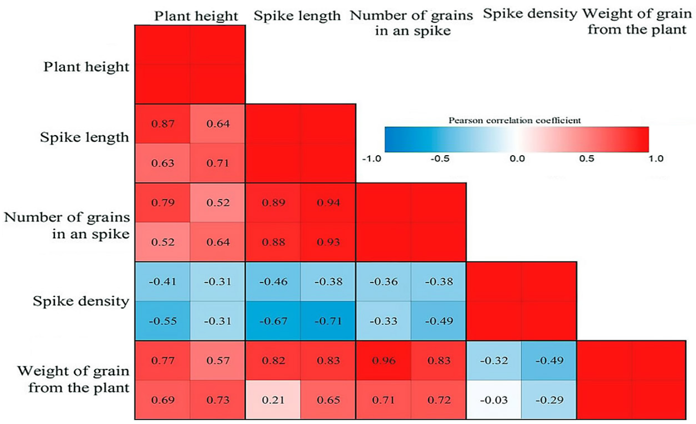


Figure 4. *Inter-genotype variability of the elements of barley plants structure, 2022-2024*
Note: barley accessions: 1 – Avhur, 2 – UA 0800645, 3 – UA 0800663, 4 – CDC Hilose, 5 – CDC Alamo, 6 – Mebere, 7 – UA 0805462, 8 – Violet 18-1207
Source: constructed by the authors

The post-hoc comparison showed that the plant height in UA 0800645[c] (47 cm) was significantly different for from that in all other accessions, this is explained by the fact that accession UA 0800645 is erectoid and belongs to var. *nudimelanocrithum*. Line Violet 18-1207[b] (63 cm) was also taller than accession 'UA 0800663'[a] and 'CDC Alamo'[a] (55 cm). Other accessions were classified as group [ab] with a plant height of 58–62 cm. The spikes in accessions UA 0800645[c] and UA 0800663[c] (6.5-6.6 cm) were significantly shorter than those in the other accessions, and 'CDC Alamo'[b] (10.6 cm) also had longer spikes than 'Avhur'[a] and 'Mebere'[a] (8.5-8.7 cm). The other accessions were classified as group [ab] with a spike length of 8.9–9.2 cm.

The number of grains per spike was the maximum in 'CDC Alamo'[b] (28 grains); 'Avhur'[ac], 'Mebere'[ac] (23–24 grains), and 'CDC Hilose'[ab], accession UA 0805462[ab], and line Violet 18-1207[ab] (25–26 grains) had similar numbers of grains in their primary spikes. Accession UA 0800663[d] (16 grains) was significantly different from all accessions; accessions UA 0800645[cd] was at the level of 'Avhur'[ac], 'Mebere'[ac]. As to weight of grains from the primary spike, there were only significant differences between line Violet 18-1207[b] (2.08 g) and accessions UA 0800663[c] (1.28 g) and UA 0800645[ac] (1.45 g). The other accessions were classified as groups [ab, ac] and [abc] (1.45-1.89 g).

Thus, in terms of the primary spike performance, 'CDC Alamo' (var. *nudum*) and line Violet 18-1207 (var. *nudidubium*) were the best accessions, while accessions UA 0800645 (var. *nudimelanocrithum*) and UA 0800663 (var. *viride*) showed the lowest performance. Based on the results of ANOVA and boxplot comparison, it was concluded that spike length and the number of grains per spike are the determinants of the performance of naked barley plants. Spike density is a trait that little depends on the weather during cultivation. In this study, this parameter did not significantly change over the years. Among the studied accessions, erectoid accession UA 080064 with a dense spike (14 segments per 4 cm) stood out conspicuously, while the other accessions were classified as loose (10-12 segments per 4 cm). There was a strong correlation between the primary spike performance and the number of grains per spike in all years of the study: the coefficient of correlation was from 0.71 in 2024 to 0.96 in 2022 (Fig. 5).



Pearson correlation coefficient

Correlation coefficients for different years and mean values

2022	2023
2024	Mean

Figure 5. *Correlations between the performance constituents in the naked barley accessions*
Source: constructed by the authors

The primary spike performance also depended on spike length (r = 0.65-0.83) and plant height (r = 0.69-0.77). The number of grains per spike was significantly correlated with spike length and the latter was closely correlated with plant height. Of all the studied traits, only spike density was negatively correlated with other traits, including weight of grains per plant. It is worth noting that there was a strong negative correlation between spike density and spike length (r = 0.69-0.77). This is explained by the fact that there was accession UA 0800645 (var. *nudimelanocrithum*), which is erectoid, i.e., has shortened internodes and very dense short spikes, in the sample analysed in this study.

A similar conclusion regarding negative correlation between performance and spike density was drawn by C. Fan *et al.* (2024), who reported about a significant positive correlation between the number of nodes per rachis and spike length and a significant negative correlation between spike density and spike length. A genome-wide association study of agronomic traits in 431 spring barley accessions, including landraces and old cultivars from the Polish Gene Bank, failed to find a positive correlation between spike density and other agronomic traits (Karabach & Berezhniak, 2021; Czembor & Czembor, 2022). The following correlation cluster was established: performance → number of grains per spike → spike length. However, spike length was closely correlated with plant height; therefore, plant height also significantly, though indirectly, affects performance through spike length (Fig. 6).

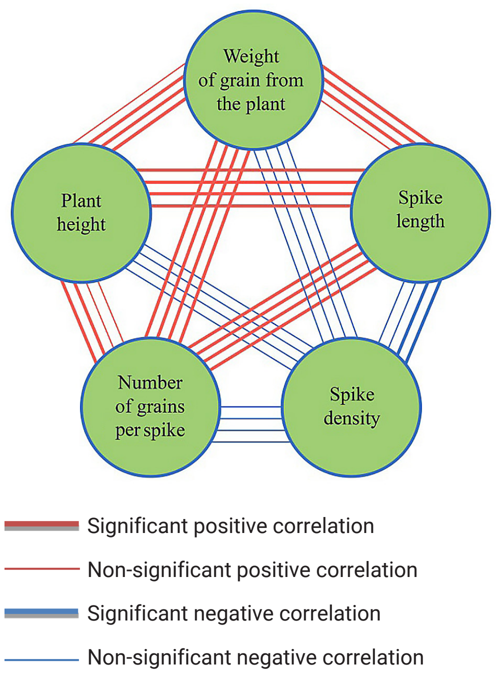


Figure 6. *Correlation clusters of the performance constituents in the naked barley accessions*
Source: constructed by the authors

Since such a correlation was unchanged for several years, one can affirm that performance-oriented selection can be driven by the "spike length" and "the number of grains per spike" traits. This enables pre-harvest culling, facilitating and accelerating breeding algorithms. However, it should be noted that these conclusions are correct for the naked barley sample under study and specific growing conditions. In studies on other cultivars/accessions or/and in other environments, differing results can be obtained due to various compensatory effects of plants of different barley cultivars.

This data on the significant contribution of the number of grains in the primary spike to barley performance are consistent with R.A. Serrago *et al.* (2025). Thus, in order to create a database of barley yield and its constituents, in particular, the number of grains per spike and thousand-grain weight, scientific studies on barley in four journals (Field Crop Research, European Journal of Agronomy, Crop and Pasture Science) over 25 years were reviewed. It was found that the number of grains was more closely correlated with yield (86% of yield variability) than thousand-grain weight (13%).

According to V. Thirulogachandar & T. Schnurbusch (2021), determination of yield potential by the number of grains is a step towards increasing yields of cereals, including barley. To achieve this goal, it is extremely important to establish the maximum yield potential, which is determined by the number of spikelet buds per spike in. The number of and weight grains of per spike was also defined as the major constituents of barley performance. The researchers found that the inter-environmental factor and inter-genotype variability of performance were usually attributed to variations in the number of grains. Therefore, the performance potential fulfilment depends on how optimal environmental conditions are in the critical phase, when the number of grains per spike is determined.

Aarushi *et al.* (2023) investigated the impact of drought on barley and found that plant height and spike length varied greatly (40-60%) under stress, while the number of grains per spike changed little (about 11%). They also reported a negative effect of drought on chlorophyll content, flag leaf area, plant height, and grain weight from the primary spike, whereas the trait "spike length" remained comparatively stable. T. He *et al.* (2023) noted that plant height and performance are complex traits and are influenced by numerous genes; therefore, the pleiotropic effects of these genes contribute to the positive correlation between these two traits. It was reported about correlations between spike length and the number of grains per spike, between spike length and weight of grains per spike, and between the number of grains per spike and weight grains per spike. Based on a positive regression, it was concluded that the number of grains per spike meant a larger weight of grains per spike. According to a study by N. Vasko e*t al.* (2023), performance was strongly correlated with productive tillering capacity, weight of grains per spike, and spike length and moderately correlated with the number of grains per spike. Weight of grains per spike was significantly strongly correlated with spike length and the number of grains per spike; spike length was correlated with plant height.

Similar findings were obtained by G. Akdogan *et al.* (2025), who claimed that the number of grains per spike was one of the three major components that determine barley yield, along with the number of spikes per 1 m^2 and thousand-grain weight. According to their data, there was a strong positive correlation between the number of grains and weight of grains per spike (r = 0.85). Plant height was significantly positively correlated with all yield indicators, and as a result of predicting the effectiveness of breeding for increased harvest index, the number and weight of grains per spike turned out to be the most promising traits.

According to V. Kaur *et al.* (2022), plant height is an important trait for barley yield because shorter plants with stronger stems are less prone to lodging, while taller plants contribute to greater photosynthetic capacity. Their study showed a strong positive correlation of plant height with spike length, number of grains per spike, and number of spikelet triplets per spike. Together with spike traits, plant height explained up to 78% of the total yield variance, highlighting its central role in determining performance. Data of K.T. Desta *et al.* (2024) are somewhat different, stating positive correlations between plant height and the number of grains per spike, between spike length and plant height and between spike length and awn length but a negative correlation between spike length and the number of grains per spike. Given the stability of spike length and number of stems per plant (bushiness) in environments with different degrees of drought, one can assume their potential as reliable selection criteria in breeding for drought tolerance. The analysis confirmed clear variability in plant structure elements among the studied naked barley accessions. Grain number and spike traits proved to be the main factors influencing differences in their performance.

Conclusions

The study of naked spring barley variability and performance correlations under arid conditions revealed significant relationships between performance and spike length (r = 0.65-0.83), between performance and grain number (r = 0.71-0.96), and between performance and grain weight per spike (r = 0.73). Performance was also indirectly related to plant height. The correlation pattern "performance → number of grains per spike → spike length" was established, with plant height and other performance constituents being closely positively correlated regardless of environmental conditions. The exception was spike density, which showed negative correlations with all other parameters under study. Considering the low variability of grain number per spike and the strong relationship between grain number and spike length (r = 0.93), these traits were determined as essential for high performance selection in naked spring barley. Sources of long spikes were identified: 'CDC Alamo' (10.6 cm); sources of high grain numbers were detected: 'CDC Alamo' (28 grains) and 'CDC Hilose', accession UA 0805462, and line Violet 18-1207 (25-26 grains).

Line Violet 18-1207 was also distinguished by grain weight per spike (2.08 g).

The revealed patterns provide a foundation for further research and breeding programmes. Statistical analysis identified valuable accessions suitable for use as starting materials in hybridisation. The stability of correlations across different environmental conditions confirmed the reliability of these traits as selection criteria. Identifying sources of valuable traits was found to be crucial for enhancing naked barley yield and addressing food security needs, particularly under climate change conditions. The introduction of naked barleys with pigmented caryopses was determined to be promising for sustainable agricultural development in medium and small enterprises.

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Conflict of Interest

None.

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Кореляція елементів продуктивності ярого ячменю в посушливих умовах

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Анотація. Ячмінь має унікальні дієтичні властивості та є одним з найбагатших джерел фенолових сполук серед зернових культур, тому зростає зацікавленість зерном ячменю як сировиною для продукції функціонального харчування. Метою дослідження було виділення цінного вихідного матеріалу для селекції голозерного ярого ячменю з кольоровим зерном. Для цього було визначено рівень продуктивності та її зв'язок із структурними елементами (довжиною колоса, кількістю зерен у колосі) і висотою рослини. Вихідним матеріалом були сім зразків голозерного ячменю з кольоровим зерном та стандарт – плівчастий ячмінь сорту 'Avhur'. Серед голозерних сорти з жовтим зерном 'CDC(Crop Development Centre) Hilose', 'CDC Alamo' та 'Mebere' (var. nudum), колекційні зразки UA 0800645 var. nudimelanocrithum (чорне зерно), UA 0800663 var. viride (зелене зерно), UA 0805462 var. daghestanicum (сіро-зелене зерно), лінія селекції ІР НААН Violet 18-1207 var. nudidubium (фіолетове зерно). Статистичну обробку здійснено за дисперсійним аналізом ANOVA з апостеріорним порівнянням за Fisher LSD та кореляційним аналізом. Показано широку мінливість продуктивності (V = 26-47 %), встановлено тісну сильну кореляцію між продуктивністю головного колоса та елементами її структури (r = 0,65-0,96). У результаті виділено кореляційний кластер продуктивність → кількість зерен у колосі → довжина колоса. Враховуючи низьку мінливість ознаки кількість зерен у колосі та сильну кореляцію між кількістю зерен та довжиною колоса, встановлено, що ці ознаки є ключовими для добору на високу продуктивність. Визначено джерело довгоколосості сорт 'CDC Alamo' (10,6 см) та великої кількості зерен у колосі – сорт 'CDC Alamo') і лінія Violet 18-1207 (28-26 зерен). Виділення джерел цінних ознак є важливим для селекції на підвищення врожайності голозерного ячменю та задоволення потреб у продовольстві, особливо в умовах зміни клімату

Ключові слова: голозерний ячмінь; мінливість; головний колос; кількість зерен; висота рослини; маса зерна з колоса; кореляційний кластер

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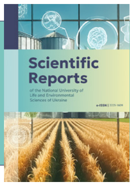

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Optimisation of the operating parameters of the vibration cleaning machine to improve the quality of seed cleaning

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Abstract. The relevance of the study was determined by the need to improve the efficiency of grain material purification in the conditions of energy-limited agro-processing enterprises of Ukraine. The purpose of the study was to determine the optimal kinematic parameters of the oscillatory mode of operation of the machine, considering the specifics of cleaning wheat, barley, and millet seeds. To achieve this goal, a series of experimental studies was conducted using high-speed video recording, digital image processing, variance analysis, and energy audit. As a result, it was found that the optimal parameters of the oscillatory mode – a frequency of 11 Hz, an amplitude of 4.5-6.0 millimetres and an angle of inclination of 10-13 degrees – provided the highest cleaning efficiency indicators for three crops. Under these conditions, an average level of purification efficiency was achieved at the level of 98.2% for wheat, 97.3% for barley, and 98.4% for millet, while reducing specific seed losses to 1.2%, 1.3%, and 0.9%, respectively. A decrease in residual impurities to 0.6-1.7%, stabilisation of the technological process (the coefficient of variation did not exceed 3.3%), and an increase in the efficiency to 87-89%

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were recorded. Specific electricity costs decreased to 0.88-1.05 W·h/kg, which led to savings of UAH 12.4-15.8 per tonne of purified material. The overall economic effect due to the combined impact on energy consumption, seed loss, and increase in the commodity fraction amounted to UAH 66.8-81.2 per tonne, which confirmed the practical effectiveness of applying new parameters in the conditions of serial grain cleaning. The results obtained can be used by engineers, technologists, and designers to optimise the operating modes of vibration cleaning systems in the grain processing industry

Keywords: energy consumption; efficiency; load uniformity; oscillatory mode; economic effect; oscillation amplitude

Introduction

The growing requirements for energy efficiency and quality of grain cleaning processes have led to the need for scientific substantiation of the operating modes of vibrating equipment for seed cleaning. In production conditions, cases of operation of machines with fixed parameters without considering the specifics of grain material remain common, which leads to overspending of electricity, increased seed losses, and a decrease in the share of the commodity fraction. The optimisation problem is to ensure high quality of cleaning with minimal energy consumption, considering the physical and mechanical properties of wheat, barley, and millet seeds.

P. Palamarchuk *et al*. (2021) substantiated the amplitude-frequency characteristics and design parameters of a vibrational exciter for a volume oscillation separator. The researchers established optimal conditions for the transfer of vibrational energy to the working chamber by varying the mass of the eccentrics and the shaft geometry, which ensured the stability of the particle trajectory over a wide range of loads. The proposed design of the vibrator helped to reduce resonant loads and coordinate the kinematics of grain mass movement with separation modes, increasing the overall efficiency of the process. F. Dai *et al*. (2023) determined the efficiency of optimised parameters of the cleaning device as part of a flax harvester, where a decrease in the frequency of vibrations caused a reduction in losses by up to 1.7%. The study also established the dependence of the separation efficiency on a combination of oscillation parameters and feed rate, which justified the need to adapt the modes to a specific crop. S. Chen *et al*. (2024) proved that the combination of air flow with a vibrating mechanism improves the quality of cleaning by 15% compared to standard solutions. Additionally, it was shown that the stability of the aerodynamic mode under the influence of vibrations reduces background dust and increases the service life of filtration systems.

Researchers L.B. Jaques *et al*. (2022) focused on the relationship between seed moisture and post-harvest processing efficiency, which helped to substantiate the need to adapt cleaning parameters depending on the technological state of raw materials. It was found that even a slight excess of critical humidity leads to an increase in specific losses and uneven distribution along the sieve plane. X. Gao *et al*. (2021) based on the application of the discrete element method, seed movement was modelled in a high-speed metering device, which helped to identify the zones of the greatest energy load. The study also proposed ways to compensate for peak loads by changing the shape of guide elements. O. Bazaluk *et al*. (2022) found that increasing the efficiency of grain cleaning is achieved through the introduction of systems with synchronised vibrators, which ensure an even distribution of material over the sieve and reduce unit costs by 0.28 kW·h/t. The study also highlighted the importance of synchronising vibrational elements to minimise material backflow. Z. Xu *et al*. (2023) found that the use of symmetrical designs of sieve elements in combination with the discrete element method provided an improvement in the sorting capacity of machines by up to 92%, which was confirmed experimentally. In addition, a reduction in the load on the edge zones of the sieve was found, which reduced its wear and increased the service life of the system.

Scientists W. Liu *et al.* (2021) established the dependence of the uniformity of seeding of mini-potato tubers on the amplitude of vibrations in the seed drill, confirming the effectiveness of using controlled vibrations to reduce the variability of seeding. It was also found that oscillatory modes help to improve the stability of the material feed even under conditions of uneven preload. C. Jin *et al.* (2021) described an automated seed cleaning system using pneumatic and vibrating mechanisms, which helped to achieve high dosing accuracy and increase the efficiency of sowing equipment. The study focused on the importance of integrating sensor systems to stabilise sorting processes with variable seed mass composition.

The effectiveness of multiparametric online monitoring in stabilising cleaning modes under variable load conditions was substantiated in the study by T. Jiang *et al.* (2025), where the collaborative optimisation method for combine harvesters was implemented. Development of a combined unit for harvesting *Astragalus sinicus* L. seeds, carried out by Z. You *et al.* (2022), showed the effectiveness of integrating the vibration component with pneumatic separation, which helped to achieve high efficiency indicators with minimal losses. Both models worked with a complex interaction of technological parameters, which emphasised the importance of digital modelling in determining optimal operating conditions. This approach demonstrated an example of effective synergy between engineering design and dynamic adaptation to environmental properties.

Despite significant progress in the study of vibration cleaning processes, the analysed sources did not provide a comprehensive assessment of the interdependencies between the frequency, amplitude, and angle of inclination of the working surface plane in relation to energy efficiency, effectiveness, and technological losses. Most of the research focused on the analysis of individual components of the technological process or was limited to highly specific cultures. In addition, there is an insufficient level of testing of results in industrial conditions, which reduces the possibility of their practical application in agricultural production. The purpose of the study was to substantiate the rational parameters of the oscillatory mode of a vibration cleaning machine, considering their impact on the quality of cleaning and the efficiency of the technological process. To achieve this goal, the following tasks were defined: to characterise the influence of the frequency, amplitude of vibrations, and the angle of inclination of the sieve plane on the kinematics of grain mass movement; to establish relationships between the parameters of the oscillatory mode and technological indicators of purification, including purity, specific losses and energy consumption; to determine the optimal operating modes that ensure technological stability, energy efficiency and economic feasibility of cleaning wheat, barley, and millet seeds.

Materials and Methods

The study belonged to the experimental type with elements of empirical verification of results in production conditions. The timing of the research procedures covered one full agricultural season – from March 2024 to March 2025. Within this period, the stages of experimental determination of the parameters of the oscillatory regime, statistical generalisation of technological results of purification, and testing of the established parameters in production conditions at three agro-industrial enterprises of Ukraine were consistently implemented. The experiments were carried out considering the seasonal availability of agricultural crops, which ensured full representativeness of empirical observations for wheat, barley, and millet.

The empirical base of the study was formed using the actual production data of the three largest agricultural companies in Ukraine – Kernel joint-stock company, Nibulon limited liability company, and MHP joint-stock company. The information basis of the analysis was the report on the sustainable development of MHP (n.d.), Integrated Report on the activities of the Kernel (2025) for the 2024/2025 marketing year, and analytical material in the section "Sustainable development" on the official website of the Nibulon limited liability company (2025). Additionally, the statistical collection "Agriculture of Ukraine" by State Statistics Service of Ukraine (n.d.) was used. The expediency of including these structures and sources was substantiated by the possibility of scaling the results to the vast majority of enterprises with medium and large production volumes in the agro-processing sector of Ukraine. These enterprises were characterised by automated production processes, a stable volume of seed processing and openness of production documentation, which ensured the reliability and comparability of experimental data.

To substantiate the choice of optimal frequency-amplitude modes, the method of full factor experimental planning was used, which provided for variations in frequency (9, 11, 13 Hz), amplitude (from 3 to 7 mm) and tilt angle (5°, 10°, 15°, 20°) with fixing the effect on cleaning efficiency, specific seed losses, energy consumption, and kinematic movement parameters. Recording of grain mass movement was carried out using a high-speed Photron FASTCAM Mini Ux100 video camera (Japan) and Tracker Video Analysis Software (USA), which provided spatiotemporal accuracy of analysis. Measurements of cleaning efficiency and seed losses were carried out using the Pfeuffer HE 60 electronic analyser (Germany) and Kern PCB scales (Germany), and energy consumption parameters were recorded through the Testo 435-4 device (Germany) with recording of instantaneous and total power values. Statistical analysis of the collected data was implemented using variational analysis and correlation-regression estimation, which helped to quantify the effect of variable mode parameters on the effective cleaning indicators. The mean values ($\bar{x}$) were defined as the arithmetic mean of the results of three repeated measurements for each combination of modes. Standard deviations (σ) were calculated using the formula of the root of the mean square deviation, and the coefficients of variation (V, %) were calculated as the ratio σ to $\bar{x}$ multiplied by 100. Technological stability was evaluated by deviations in the cleaning efficiency within homogeneous series of experiments, and the ranking of modes was carried out by a cumulative summary score, which considered the weight sum of normalised values of specific energy consumption, seed losses, and the level of purification.

The technical and economic assessment was based on the method of comparing before and after the implementation of the recommended regimes, considering specific energy consumption, the volume of loss reduction, and the growth of the commodity fraction. The conditional economic effect was calculated using a direct estimate of the difference in the cost of losses and the increase in commercial mass. Data in monetary terms were expressed in UAH per tonne of refined grain. Additionally, concomitant effects were taken into consideration, in particular, reducing the load on the ventilation system and reducing the wear of working bodies.

Interpretation of the results was based on comparing indicators in different experimental combinations of parameters, followed by determining the optimal modes for each crop separately. When evaluating the effectiveness, not only the absolute efficiency of the regime was considered, but also its stability in serial implementation, adaptability to industrial conditions, energy feasibility, and scaling potential. Generalisation was carried out by constructing generalising tables and graphs that helped to identify trends, patterns, and optimal parameter intervals.

Results

Influence of the frequency and amplitude of vibrations on the efficiency of cleaning wheat, barley, and millet seeds. As a result of the study, it was found that the combination of frequency and amplitude of the oscillatory mode is crucial for achieving high quality of grain mass purification. For each of the three crops – wheat, barley, and millet – characteristic ranges of parameters were determined that ensure effective separation of impurities with minimal losses of the main seed. These parameters proved to be sensitive to the morphophysical properties of grain, which necessitates their individual selection in the technological process. The nature of changes in technological indicators depending on the parameters of fluctuations is summarised in Table 1.

Table 1. *Influence of the frequency and amplitude of the oscillatory mode on the efficiency of grain cleaning*

Crop	Frequency, Hz	Amplitude, mm	Average cleaning efficiency, %	Main seed losses, %	Residual impurities, %
Wheat	9	4	95.2	1.8	3
	11	5	98.1	1.3	1.9
	13	6	96.4	1.5	2.1
Barley	9	4	94.6	2	3.8
	11	6	97.5	1.2	2.5
	13	7	95.3	1.7	3.2
Millet	9	3	90.3	3.4	6.1
	11	4.5	98.3	0.9	1.7
	13	6	92.1	2.6	3.8

Note: average cleaning efficiency – percentage of seeds that meet the standards of marketability; losses of the main seed – mass fraction of the target material lost during cleaning due to knocking out or attribution to impurities
Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

Analysis of the presented Table 1 indicates the presence of a pronounced dependence of the cleaning efficiency on the oscillatory mode settings. For wheat, the maximum efficiency was achieved at a frequency of 11 Hz and an amplitude of 5 mm, which helped to keep losses at 1.3% and reduce the proportion of residual impurities to 1.9%, while a further increase in frequency led to a decrease in the stability of the grain movement trajectory and an increase in impurities to 2.1%. In the case of barley, the best result was observed at a slightly higher amplitude (6 mm), which is due to a more massive grain structure capable of active separation from small inclusions; residual impurities in this mode were 2.5%, which was lower compared to other modes (3.2-3.8%). For millet, the highest sensitivity to parameter changes was observed: only at precisely set values (11 Hz and 4.5 mm), a high level of purification (98.3%) was achieved with minimal losses (0.9%) and the lowest impurity content (1.7%). Under other regimes, millet was characterised by an increased level of impurity – up to 6.1% – and losses, which is associated with its low density and microfractional nature. Thus, the results of Table 1 confirm the feasibility of an individual approach to setting the operating modes of the vibration cleaning machine depending on the morphophysical characteristics of the crop.

To assess the stability of the technological process of grain mass purification, the coefficient of variation was used, which reflects the relative variability of cleaning quality indicators when kinematic parameters change. This helped to determine how stable the vibration cleaning machine works in different modes for each individual crop. The results obtained are shown in Table 2.

Table 2. *Coefficients of variation in the efficiency of seed cleaning by a set of tested modes*

Crop	Average cleaning efficiency (x̄), %	Standard deviation (σ), %	Coefficient of variation (V), %
Wheat	96.6	1.2	1.2
Barley	95.8	1.5	1.6
Millet	93.6	3.1	3.3

Note: coefficient of variation is calculated as the ratio of the standard deviation to the average value of cleaning efficiency, expressed as a percentage; standard deviation – absolute measure of dispersion around the average value; cleaning efficiency – proportion of seeds that meet the conditions of commercial condition
Source: developed by the authors based on data from MHP (n.d.), Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.)

Analysis of Table 2 shows that wheat is characterised by the lowest coefficient of variation (1.2%), which indicates a high stability of purification indicators regardless of changes in the parameters of the oscillatory regime. Barley showed a slightly higher sensitivity to changes in amplitude, as evidenced by a change of 1.6%, although it still remains within acceptable technological stability. The lowest stability was recorded for millet, where the coefficient of variation was 3.3%, which was explained by both the low grain weight and an increased response to minor changes in the dynamics of the process. This indicates the need for fine-tuning of the equipment when working with millet, and the feasibility of automated monitoring of parameter stability. In general, the coefficient of variation can be used as an auxiliary indicator of the technological reliability of modes for various grain crops.

The results obtained confirm that the efficiency and stability of vibration cleaning directly depend on carefully selected frequency-amplitude parameters adapted to the physical and mechanical properties of grain crops. Generalised indicators and indicators of variation allow not only to assess the quality of cleaning, but also to develop a methodological basis for optimising operating modes in production conditions. This approach creates prerequisites for improving technological reliability and minimising losses of agricultural raw materials.

Determination of the optimal angle of inclination of the oscillatory plane to improve the dynamics of grain mass separation. One of the key factors in the efficiency of the vibration cleaning machine is the nature of the movement of grain mass along the sieve plane, depending on the angle of its inclination. The main criteria for evaluating this process are the average speed of movement of particles and the duration of their contact with the sieve, because these indicators determine the intensity of stratification and the efficiency of separation of impurities. Changing the angle of inclination affects both the dynamics of seed movement and the duration of its interaction with the separation surface, which together forms the basis for optimising the technological regime.

To quantify these parameters, a series of measurements was performed at different values of the plane tilt angle: 5°, 10°, 15°, and 20°. Indicators were recorded for three crops – wheat, barley, and millet – using high-speed video recording and subsequent processing of grain trajectories. Based on the obtained data, Table 3 is formed, which allows comparing the effect of angle changes on the kinematic characteristics of the cleaning process and highlight the features of each crop. The analysis of Table 3 shows a clear trend towards an increase in the seed movement rate with an increase in the angle of inclination of the oscillation plane. The lowest velocities were recorded at 5° for all crops, which was accompanied by the longest duration of contact with the sieve – up to 4.1 seconds for millet. At angles of 10-15°, an optimal ratio between the speed and duration of contact was observed, which ensured effective separation without the appearance of stagnation zones or excessive acceleration of the flow. An increase in the angle to 20° led to a decrease in the interaction time with the sieve to critical values (1.1-1.4 s), which could complicate the complete separation of impurities, especially in cultures with a fine fraction. Millet showed the greatest sensitivity to angle changes, which confirms the need for strict control of parameters to ensure stable cleaning quality. One of the important areas of evaluating the parameters of the oscillatory regime is to determine their influence on the integral indicators of cleaning efficiency, in particular, the purity of the final product, specific seed losses, and the mass fraction of residual impurities. Based on the results of observations, it was found that the nature of changes in these indicators depends on the angle of inclination of the oscillation plane. The change in this parameter significantly affected the duration of grain contact with the sieve surface and the intensity of its stratification. Comparison of the obtained data for wheat, barley and millet allowed summarising the average values and presenting them in Table 4.

Table 4 shows the features of cleaning three grain crops at tilt angles of 5°, 10°, 15°, and 20°, which allowed identifying the ranges of parameters with the highest efficiency indicators. All values are given as the average results of several homogeneous experiments.

***Table 3.** Average seed movement speed and duration of contact with the sieve plane at different angles of inclination*

Crop	Angle of inclination, °	Average travel speed, cm/s	Duration of contact with the sieve, s
Wheat	5	6.1	3.4
	10	9.4	2.6
	15	12.7	1.9
	20	15.2	1.4
Barley	5	5.8	3.6
	10	10.1	2.3
	15	13.5	1.7
	20	16	1.2
Millet	5	4.3	4.1
	10	7.9	2.8
	15	11.4	1.6
	20	14.8	1.1

Note: contact with the sieve means the time during which the seed remained on the surface of the sieve within one cleaning cycle

Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

***Table 4.** Efficiency of cleaning grain crops at different angles of inclination of the oscillation plane*

Crop	Angle of inclination, °	Cleaning efficiency, %	Seed loss, %	Residual impurities, %
Wheat	5	94.7	2.3	3
	10	98.2	1.2	0.6
	15	96.5	1.4	2.1
	20	93.1	2.5	4.4
Barley	5	93.5	2.7	3.8
	10	97.3	1.3	1.4
	15	95.2	1.6	3.2
	20	91.7	2.8	5.5

Table 4. *Continued*

Crop	Angle of inclination, °	Cleaning efficiency, %	Seed loss, %	Residual impurities, %
Millet	5	90.1	3.8	6.1
	10	98.4	0.9	0.7
	15	94.3	1.9	3.8
	20	89.5	3.5	7

Note: cleaning efficiency – mass fraction of seeds that meet commodity standards; seed losses – proportion of suitable grain that was removed together with impurities; residual impurities – mass fraction of undivided impurities after the cleaning cycle is completed

Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

Analysis of Table 4 shows a clear dependence of the cleaning efficiency on the angle of inclination of the oscillation plane. In all crops, the maximum values of cleaning efficiency were recorded at an angle of 10°, which was accompanied by the lowest seed losses and the minimum proportion of residual impurities. For wheat, the efficiency was 98.2%, for barley – 97.3%, and for millet – 98.4%, which indicates a high stability of the process in this range. When the angle was increased to 15° and 20°, the cleaning quality decreased due to a reduction in the duration of grain contact with the sieve, which worsened the stratification efficiency. A particularly pronounced deterioration was observed in millet, where at 20° the residual impurity reached 7%, and the losses increased to 3.5%, which confirms the high sensitivity of this culture to kinematic equilibrium disorders. The results obtained confirm the possibility of limiting the range of the slope angle to ensure stable cleaning.

Energy expediency of choosing the operating modes of a vibration cleaning machine when cleaning seeds of various crops. To substantiate energy-efficient modes of operation of a vibrating cleaning machine in the conditions of agro-processing production, it is advisable to analyse the specific costs of electricity and energy efficiency at various kinematic parameters. The relationship between frequency, amplitude, tilt angle, and indicators of specific costs and efficiency allows identifying critical points where the ratio between qualitative cleaning indicators and energy consumption is the most optimal. The studies were conducted considering the constant productivity of the machine and a fixed processing time for each of the experimental modes, which makes it possible to ensure correct comparison between crops.

The experimental data presented below are based on a series of studies with a gradual change in frequency (10-12 Hz), amplitude (4-7 mm) and tilt angle (8-15°) in accordance with the technological specifics of wheat, barley, and millet purification. Table 5 shows exactly how energy consumption changes and the efficiency of its conversion into a useful action depending on the culture. Identification of optimal combinations of parameters makes it possible to establish not only technically, but also economically justified modes of operation of the machine.

Table 5. *Specific power consumption and efficiency in different cleaning modes*

Crop	Frequency, Hz	Amplitude, mm	Angle of inclination, °	Unit consumption, W·h/kg	Efficiency factor, %	Cleaning efficiency, %	Seed loss, %
Wheat	10	4	8	1.12	82	96.4	1.7
	11	5	10	0.92	87	98.2	1.2
	12	6	12	1.27	78	96	1.6
Barley	10	5	10	1.18	80	95.1	1.8
	11	6	13	1.05	84	97.3	1.3
	12	7	15	1.3	76	94.7	2

Table 4. *Continued*

Crop	Frequency, Hz	Amplitude, mm	Angle of inclination, °	Unit consumption, W·h/kg	Efficiency factor, %	Cleaning efficiency, %	Seed loss, %
Millet	10	4	8	1.06	81	92	2.9
	11	4.5	10	0.88	89	98.4	0.9
	12	5	12	1.22	77	93.1	2.3

Note: the efficiency factor reflects the percentage ratio between usefully used and total energy consumed; W·H/kg – specific energy consumption per 1 kg of purified seeds

Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

Analysis of Table 5 shows that there is a clear relationship between the mode parameters and the level of power consumption. In the case of wheat, the most effective mode was with a frequency of 11 Hz, an amplitude of 5 mm and an angle of inclination of 10°, at which the specific consumption was 0.92 W·h/kg, the efficiency was 87%, the cleaning efficiency was 98.2%, and seed losses did not exceed 1.2%. For barley and millet, a similar mode also provided minimal flow, but required an amplitude and angle adjustment of 6 mm/13° for barley and 4.5 mm/10° for millet. The optimal result for barley was achieved at an amplitude of 6 mm and an angle of 13°, which provided an efficiency of 84%, a cleaning efficiency of 97.3%, and a loss of 1.3%. In the case of millet, the highest energy efficiency (efficiency – 89%) and the lowest specific consumption (0.88 W·h/kg) were recorded at an amplitude of 4.5 mm and an angle of 10°, at which the cleaning efficiency reached 98.4%, and the losses were only 0.9%. Exceeding these parameters led to a rapid decrease in energy efficiency, in particular, a decrease in efficiency by 5-10%. In addition, there was an increase in unit costs and a deterioration in the quality of cleaning, which was reflected in an increase in seed losses. Thus, these values should be considered as an indicative basis for establishing regulations for the operation of vibration cleaning equipment in a particular production environment.

Optimisation of energy consumption in the process of vibration cleaning of seeds allowed quantifying the feasibility of adapting the operating modes of equipment to the morphophysical properties of the crop. The analysis of specific costs and efficiency factors revealed the most energy-efficient parameters of frequency, amplitude, and tilt angle for wheat, barley, and millet. The generalised values provided not only minimal electricity consumption, but also a high level of purification with permissible seed losses, which confirms their practical suitability. The obtained dependencies form a reasonable basis for regulating the operational modes of vibration cleaning equipment in industrial conditions of agro-processing.

Testing of optimised cleaning modes in the conditions of Ukrainian enterprises and technical and economic assessment of the results. In the process of implementing optimised oscillatory mode parameters at the production facilities of Kernel (2025), Nibulon (2025), and MHP (n.d.) a quantitative assessment of the effectiveness of changes in key qualitative indicators of grain mass purification was carried out. In particular, the effect of new settings on the specific losses of the main seed and the level of residual impurities in the finished product was investigated. The comparison was based on aggregated average daily data recorded in production logs and technical reports of enterprises, which ensures the objectivity of the presented results. Comparative values of losses and efficiency of grain mass purification before and after the introduction of optimised modes are shown in Table 6. The data cover three crops – wheat, barley, and millet – and reflect changes in quality indicators as a result of adaptation of vibration effects to the morphophysical properties of seeds.

Table 6. Comparison of cleaning losses and efficiency before and after implementing optimised modes

Crop	Pre-implementation losses, %	Post-implementation losses, %	Efficiency before implementation, %	Efficiency after implementation, %
Wheat	1.9	1.2	96.1	98.2
Barley	2.1	1.3	95.4	97.3
Millet	1.8	0.9	96.7	98.4

Note: losses – proportion of the main seed lost during the cleaning process, as a percentage of the mass of the initial material; cleaning efficiency – mass fraction of the main fraction after the extraction of impurities, as a percentage. All values are presented as average indicators based on the results of testing for 30 days

Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

Analysis of Table 6 shows a significant improvement in both key indicators in all three cultures. The reduction in specific losses ranged from 0.7% for wheat to 0.9% for millet, which is critical for ensuring the preservation of commercial mass during mass processing. There was an increase in the cleaning efficiency, in particular for millet – by 1.7%, which indicates the effective selection of light impurities under the new vibration regime. Indicators for barley were also consistently improved, despite its increased brittleness and uneven flowability. The overall dynamics of the results confirms both the technological efficiency of the implemented parameters and their adaptability to the conditions of different regions and cultures.

In order to substantiate the economic feasibility of introducing optimised oscillatory mode parameters, the integral technical and economic effect was calculated for each of the crops under study. The assessment was based on specific indicators of energy consumption, losses of basic seeds, and growth of the commodity fraction, converted into monetary equivalent in accordance with the average purchase prices on the Ukrainian market. The calculations considered typical electricity tariffs for agro-industrial enterprises, and the average cost of seeds by type. This approach helped to form a practical basis for assessing the profitability of the process of implementing optimised operating modes of vibration cleaning equipment (Table 7).

Table 7. Cost-effectiveness of implementing optimised modes

Crop	Energy savings, UAH/t	Reduction of losses, UAH/t	Increase in the commodity fraction, UAH/t	Overall economic effect, UAH/t
Wheat	12.4	21.6	32.8	66.8
Barley	15.8	23.3	35.2	74.3
Millet	13.6	25.1	42.5	81.2

Note: reduction of losses – savings resulting from the preservation of the main fraction; increase in the commodity fraction – additional income from increasing the share of grain suitable for sale. The data is calculated based on average production and market indicators

Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

The analysis of the data shown in Table 7 shows a significant economic effect achieved as a result of the introduction of optimised operating modes of the vibration cleaning machine. The greatest overall effect was recorded for millet – 81.2 UAH/tonne, which is explained not only by a significant reduction in losses, but also by a significant increase in the commodity fraction, which traditionally has a higher market value. Indicators for barley and wheat also indicate the profitability of technical changes, providing overall savings of 74.3 UAH/tonne and 66.8 UAH/tonne, respectively. It is worth emphasising that specific electricity costs decreased in the range of 12.4-15.8 UAH/tonne, which is a significant factor in the structure of the cost of processing. Thus, Table 7 confirmed the relationship between technical optimisation parameters and direct financial benefits for agricultural entities. Optimisation of the operation parameters of the vibration cleaning machine helped to establish a clear relationship between the kinematic characteristics of the equipment and the efficiency of cleaning grain material. It was established that wheat, barley, and millet are characterised by different sensitivity to changes in the frequency and amplitude of vibrations, and to the angle of inclination of the working plane. The highest cleaning rates were observed at a frequency of 11 Hz and an amplitude of 4.5-6 mm with an angle of inclination of 10-13°, which provided an optimal balance between the speed of mass movement and the separation of fractions according to aerodynamic properties. Especially significant changes were recorded for millet, where improved movement dynamics led to a decrease in re-mixing and an increase in product efficiency. An additional analytical unit devoted to the energy feasibility of implementing optimised modes demonstrated a reduction in specific electricity costs while maintaining or increasing the level of purification. The calculation results showed an increase in the efficiency in the range of 5-7% depending on the crop, and a reduction in energy consumption to 1.9 W·h/kg in the case of millet. A direct relationship was recorded between the stability of the purification mode (determined by the coefficient of variation) and economic efficiency, which was manifested in an increase in the share of the commodity fraction. This dependence confirmed the validity of the technological model based on a combination of several motion parameters.

Testing of new modes in production conditions confirmed the possibility of their implementation in serial production lines without reducing overall productivity. Comparative analysis showed a decrease in seed loss to 0.8% and an increase in efficiency to 98.2% on average for all crops. Under the conditions of standard tariffs and processing volumes, the overall economic effect was obtained in the range of 66.8-81.2 UAH/tonne, which indicates the feasibility of large-scale implementation. Based on the results of the study, it is recommended: to use the frequency of 11 Hz as the base for vibration cleaning, to adapt the amplitude within 4.5-6 mm depending on the crop, to set the angle of inclination of the screen in the range of 10-13°, and to introduce modular adjustment of parameters depending on the morphophysical characteristics of the grain material. Consideration of the specifics of the regional agricultural infrastructure regarded these recommendations as adapted to practical implementation in the conditions of medium-sized enterprises in Ukraine.

Discussion

Optimisation of the frequency-amplitude characteristics of the vibration effect helped to quantify stable relationships between the parameters of the oscillatory mode and the efficiency of cleaning seed material, which turned out to be critical for improving the quality of agricultural products. The implementation of optimal modes contributed not only to reducing losses and increasing the selectivity of separation, but also to reducing specific energy costs, which corresponds to the principles of energy efficiency. The formalised relationships between the frequency, amplitude and quality indicators of purification allowed forming reasonable technological recommendations for adapting vibration modes to the morphophysical properties of grain, and to determine the potential for scaling parameters in high-performance systems.

The significance of the established dependencies was consistent with the provisions presented in the study by Z. Zhao *et al*. (2022), where the feasibility of optimising the vibration effect on seed material in corn purification processes was proved. The results of this study confirmed the importance of achieving stable particle excitation to ensure efficient separation of flow components, which is consistent with the recorded dynamic differentiation effect in this study. The established resonant correspondence of the parameters had a similar interpretation in their experimental model, which confirmed the consistency of the observed phenomena. Similar conclusions were obtained in the paper by D. Xiong *et al.* (2021), where the efficiency of a combined pneumatic-mechanical dispenser capable of compensating for seed supply instability using controlled vibration pulses was analysed. The results of this study focused on the importance of the parameters of the oscillatory effect for stabilising grain mass flows, which correlated with the identified features of the transportation mode in the machine under study. In addition, the expediency of regulating the oscillation parameters considering the granulometric composition of the mixture confirmed the relevance of the proposed multi-factor approach to optimising the cleaning process.

The study analysed the efficiency of implementing vibration excitation in purification processes, which helped to establish a close relationship between the stability of the vibration mode and the effectiveness of separation. Matching the vibration parameters with the physical and mechanical properties of the material provided a resonant correspondence, according to which the intensification of impurity separation occurred. Similar conclusions were presented in the study by J. Zhou *et al.* (2022), where effective excitation during the ginkgo harvesting process was provided by adjusting the frequency and strength of the vibration according to the characteristics of the object. The dynamic consistency of the parameters revealed in the framework of the performed study confirmed the relevance of the chosen approach, in particular, when achieving stable purification under resonant influence conditions. During the implementation of the study, the influence of the dynamic balance of the drive on the efficiency of seed transportation and the effectiveness of its separation was also confirmed. Determining the optimal eccentricity and stable vibration mode ensured the uniformity of the load on the screen surface and reduced material losses. According to the conclusions given by C. Popa *et al.* (2021), even minor deviations in the configuration of the drive mechanism led to a decrease in the quality of cleaning, which is fully consistent with the relationships found in the study between dynamic unbalance and a decrease in the uniformity of separation.

During experimental tests, instability of the movement of seed material was recorded when the direction of vibrations changes, which required clarification of the conditions for spatial movement of particles. Analysis of the dynamics of mini-tuber transport performed by Q. Niu *et al.* (2025), demonstrated the presence of amplitude-frequency fluctuations affecting the stability of the material feed in the vibrating feeder. These conclusions were directly confirmed in the results of the study, where similar violations were recorded in the case of deviations from the optimal oscillation mode, which led to a complication of the purification process. An important aspect of empirical verification of the efficiency of the system was the assessment of the process of filling bounded cells under variable conditions of spatial interaction of particles. Y. Cai *et al.* (2022) presented a multi-factor model that considered the limitation of the working volume of metering elements and the dynamic interaction of particles during seeding. The generalised conclusions coincided with the results obtained in the course of the study, which established a relationship between the cleaning efficiency, the degree of filling, and the characteristics of the vibration mode, which determined the feasibility of considering the volume-spatial parameters in the design of vibration cleaning systems.

As part of the study, it was found that the lack of coordination between the frequency of vibrations and the inertial characteristics of the system leads to an increase in specific energy consumption. This aspect was confirmed by the analytical conclusions of K. Tang *et al*. (2022), which summarised approaches to adaptive regulation of energy consumption in systems with vibrational components on the example of bioreactor processes. The presented recommendations for multiparametric optimisation of vibration effects aimed at reducing power consumption were consistent with the recorded results, where dynamic inconsistency led to overspending and reduced technological efficiency. Analysis of energy consumption dynamics confirmed that the use of adaptive mechanisms for controlling oscillation parameters allows achieving a balance between technological efficiency and energy saving. F. Matsunaga *et al*. (2022) substantiated the use of cyberphysical systems to optimise energy consumption in intelligent manufacturing. The approaches to adaptive control of technical modes proposed by the authors helped to reduce energy consumption without reducing productivity, which was consistent with the conclusions of the study, where the adjustment of vibration parameters in accordance with the properties of seed material provided rational energy consumption with stable cleaning quality.

As an experimental part of the study, the expediency of adjusting the oscillation frequency and geometric characteristics of working units to reduce specific energy costs was established. Confirmation of the effectiveness of such approaches was contained in the paper by S. Sivakumar *et al*. (2024), which present a model for energy optimisation in Industry 4.0 sensor node systems, based on the principle of balancing functional performance and minimising power consumption. The relationship between the technical parameters of the vibration mode and energy efficiency revealed in the study corresponded to the modelling logic implemented in the mentioned source. The results of the study confirmed that the lack of regulation of the oscillatory mode leads to irrational energy use and a decrease in the stability of operation under prolonged load. Similar patterns were described in the paper by D.J. Sun *et al*. (2021), where modelling of energy consumption by electric vehicles under variable urban load conditions was carried out. It was proved that only optimisation of technical parameters allows ensuring economic efficiency without loss of operational reliability, which was consistent with the conclusions of the study on the importance of regulating the vibration effect against the background of variable mass and density of seed flow.

One of the significant factors affecting the level of separation was the contact relationship between the grain material and the elements of the vibration cleaning unit. The study by M. Sohail *et al*. (2022) analysed the prospects for introducing seed coating technologies as a means of improving their interaction with technical systems. It was found that surface modification helps to reduce the friction resistance and reduce the probability of sticking together, which corresponded to the results of the study, in which the stabilisation of the movement of fine seeds was noted when using the adapted geometry of working elements. The analysis of the aerodynamic support of the cleaning process showed the need for a comprehensive approach to regulating air and oscillatory effects. The study by J. Wang *et al*. (2021) demonstrated the effectiveness of an internal filling pneumatic mechanism for precise seeding, in which the consistency of air flow with design parameters determined the effectiveness of operation. Similar patterns were established in the study: a change in the force of the air flow in the vibration-aspiration unit caused variability in the quality of cleaning, which required simultaneous adjustment of the fan power and vibration parameters to achieve a stable mode. As part of the study, special attention was paid to the influence of the biophysical characteristics of seed material on the constancy and uniformity of its transportation in the working chamber. As evidenced by K. Zhang *et al*. (2022), the use of a BioCarbon coating has contributed to improving the dynamic properties of grain, reducing energy losses during movement, and improving processing efficiency. A similar trend was recorded in the implemented experiment, where grain particles with a uniform surface structure showed a more stable trajectory of movement. This ensured a uniform load on the screen surface and reduced the risk of undivided fractions forming. Similar patterns correlated with the findings of H. Tang *et al*. (2022), which presented an optimised design of a precision metering device with a long belt gripper, which guarantees uniform feeding of corn seeds and stable operation under various conditions. The researchers also emphasised the effectiveness of the built-in monitoring system, which helped to adjust the seed supply in real time, improving the accuracy and uniformity of dosing.

Improving the functional properties of the vibration system through digital technologies was analysed in the context of improving the stability of cleaning processes. As demonstrated by R. Reddy (2022), the use of innovative solutions in the field of precision farming provides a significant reduction in the impact of the human factor on the accuracy of equipment tuning. The results obtained as part of the study confirmed that the integration of sensor systems and frequency regulators helps to stabilise the separation parameters under conditions of variable impurity composition. Combined with this, W. Ma *et al*. (2023) proved that the use of adaptive technology in agricultural production allows achieving increased environmental efficiency due to optimal adjustment of technical parameters. Thus, the results of the experiment confirmed that the reduction of energy consumption and emissions is possible if the correspondence between the oscillatory regime and the characteristics of the grain mass is ensured. The problem of losses in the post-harvest period has become particularly relevant in the context of improving primary cleaning. A critical review by B.J. Olorunfemi & S.E. Kayode (2022) found that a significant proportion of losses are caused by high levels of residual humidity and insufficient efficiency of primary cleaning mechanisms. The empirical data obtained as part of the study indicated a decrease in the volume of fine impurities after the first separation cycle, which potentially minimises the need for re-cleaning and reduces storage losses. An additional perspective in this context is opened up by works on the relationship between the parameters of purification and the quality of grain preservation, which requires further research based on the results obtained.

In the study, modelling of the dynamics of seed movement was implemented on the basis of a discrete element method, which made it possible to track the trajectories of particle movement and form an adaptive oscillation profile. The feasibility of this approach was consistent with the conclusions of D. Yan *et al*. (2022), who demonstrated the effectiveness of using the discrete element method to predict the behaviour of soybean particles in agricultural systems. Similar provisions are reflected in the study by L. Wang *et al*. (2021), which described the introduction of a bioinspired oscillation principle based on the movement of earthworms. Both approaches confirmed that the adaptation of structural elements of vibration cleaning equipment to the physical characteristics of grain is a key prerequisite for ensuring uniform feed and reducing stagnant zones in the working chamber. The study also confirmed the possibility of reducing post-harvest losses by improving the efficiency of primary cleaning. In particular, E.E. Tiguh *et al*. (2024) proved that insufficient purification at the initial stages of teff processing is one of the main reasons for the loss of quality and volume of finished products. This logic was confirmed by the results of the experiment, where improving the screen geometry and adjusting the oscillatory mode helped to minimise the amount of impurities without the need for a second cleaning cycle. Thus, the results obtained not only confirmed the relevance of modern approaches to engineering modelling, but also allowed proposing optimisation solutions adapted to different types of seed material.

Generalisation of the results showed that the research corresponds to current scientific and applied areas in agricultural engineering. The ratio between the frequency-amplitude parameters of vibration exposure, the characteristics of grain mass and the dynamics of its transportation allowed formulating basic technical and technological provisions for the design of new-generation cleaning systems. The synergistic combination of digital, biophysical and engineering components provided a comprehensive effect of stabilising the workflow while reducing energy consumption. Thus, the results of the study can be used for further modernisation of vibration technologies in the agro-industrial sector, considering the principles of energy efficiency, technological adaptability, and functional reliability.

Conclusions

As part of the study, a differentiated method for optimising the kinematic parameters of the oscillatory mode for cleaning wheat, barley, and millet seeds was developed and tested. Based on multivariate analysis, it was found that the frequency of 11 Hz, the amplitude of 4.5-6 millimetres and the angle of inclination of 10-13 degrees are optimal for ensuring high quality of cleaning without exceeding the permissible grain losses. For each crop, clear parameters were set that allowed achieving a cleaning efficiency of 98.2% for wheat, 97.3% for barley, and 98.4% for millet with a loss of the main seed not exceeding 1.3%. The results of the energy analysis confirmed the effectiveness of the optimised modes. Specific electricity consumption for wheat was reduced to 0.92 W·h/kg, for barley – to 1.05 W·h/kg, for millet – to 0.88 W·h/kg, which was accompanied by an increase in efficiency to 87-89%. According to the results of testing in real production conditions, the decrease in specific losses reached 0.7-0.9%, while the increase in the commodity fraction was 1.6-2.5%. In monetary terms, the overall effect of implementing optimised regimes ranged from UAH 66.8 to UAH 81.2 per tonne of purified material, which confirmed the economic feasibility of the recommendations. Additionally, it was found that the coefficients of variation of the cleaning quality did not exceed 3.3%, which showed the stability of the process with repeated modes.

The key advantage of the developed methodology was the combination of analytical assessment of grain mass movement with validation through field tests. It was established that a crop-specific approach to tuning the frequency-amplitude mode allows adapting equipment to specific characteristics of raw materials without changing the design of machines. The obtained data allow formalising the approach to the rules for setting up vibration cleaning equipment, considering the target indicators of cleaning efficiency of more than 97%, losses of less than 1.5%, unit costs of no more than 1.1 W·h/kg. It is recommended to introduce optimised frequency-amplitude modes in production with preliminary adaptation to the physical properties of a particular batch of seeds. Promising areas of further research are the development of an automated system for regulating the vibration mode with sensory diagnostics of grain mass movement, and the analysis of the influence of sieve structures and guide elements on the efficiency of breeding small organic impurities. It is also advisable to investigate the long-term effects of optimised modes, considering the wear of machine elements, and develop an integral criterion for energy-quality efficiency for comparing cross-cultural settings.

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Conflict of Interest

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Оптимізація робочих параметрів віброочистної машини для підвищення якості очищення насіння

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Анотація. Актуальність дослідження зумовлювалася необхідністю підвищення ефективності очищення зернового матеріалу в умовах енергообмежених агропереробних підприємств України. Метою дослідження було визначення оптимальних кінематичних параметрів вібраційного режиму роботи машини з урахуванням специфіки очищення насіння пшениці, ячменю та проса. Для досягнення поставленої мети було проведено серію експериментальних досліджень із використанням високошвидкісного відеозапису, цифрової обробки зображень, дисперсійного аналізу та енергоаудиту. У результаті встановлено, що оптимальні параметри вібраційного режиму – частота 11 герц, амплітуда 4,5-6,0 міліметрів та кут нахилу 10-13 градусів – забезпечували найвищі показники ефективності очищення для трьох культур. За цих умов досягнуто середнього рівня ефективності очищення на рівні 98,2 % для пшениці, 97,3 % для ячменю та 98,4 % для проса, при зниженні питомих втрат насіння до 1,2 %, 1,3 % та 0,9 % відповідно. Одночасно зафіксовано зменшення залишкових домішок до 0,6-1,7 %, стабілізацію технологічного процесу (коефіцієнт варіації не перевищував 3,3%) та підвищення коефіцієнта корисної дії до 87-89 %. Питомі витрати електроенергії зменшилися до 0,88-1,05 ват-години на кілограм, що зумовило економію на рівні 12,4-15,8 гривень на тонну очищеного матеріалу. Загальний економічний ефект за рахунок сукупного впливу на енерговитрати, втрати насіння та приріст товарної фракції склав 66,8-81,2 гривень на тонну, що підтвердило практичну ефективність застосування нових параметрів в умовах серійного очищення зерна. Отримані результати можуть бути використані інженерами, технологами та проєктувальниками для оптимізації режимів функціонування віброочистних систем у зернопереробній галузі

Ключові слова: енерговитрати; коефіцієнт корисної дії; рівномірність навантаження; коливальний режим; економічний ефект; амплітуда коливань

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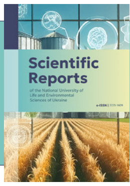

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Dynamics of biometric indicators of maize plants under the influence of sowing rates and field productivity zones

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Abstract. Biometric indicators of maize are an important indicator of the effectiveness of agricultural technologies and reflect the adaptive response of crops to spatial heterogeneity of growing conditions. The aim of the study was to determine the effect of zonal productivity and sowing rates on the height and dry matter formation of maize in the early stages of organogenesis. Field studies were conducted in 2023-2024 within three field productivity zones: high, medium and low. Five sowing rates were varied, ranging from 65 to 85 thousand seeds/ha. The results of the studies show that the productivity zone had the main influence on the biometric parameters of plants, while the sowing rate had an additional but less significant effect. At the V2-V3 stage of corn development, the maximum dry matter content (up to 23.5%) was observed in the high-yield zone at a sowing rate of 70 thousand seeds/ha. In low-productivity zones, the indicators decreased to 15.5%. Plant height in this phase ranged from 22.5 cm in the high zone to 16.6 cm in the low productivity zone. In the early flowering phase (R1), a decrease in dry matter content was observed towards less productive zones: from 31.7% (high zone, 70 thousand/ha) to 25.3% (low zone, 85 thousand/ha) in 2023. Plant height varied from 252 cm in high-yielding areas to 143 cm in low-yielding areas. The biometric parameters of maize can be used as a reliable criterion for assessing the response of crops to differentiated

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technological techniques, which is a promising direction in precision farming systems. The use of zonally differentiated sowing rates allows for more efficient use of resources and optimisation of agricultural technologies for growing maize in fields with varying productivity

Keywords: *Zea mays* L.; plant height; differentiated sowing; plant density; dry matter

Introduction

In the current conditions of climate change and increasing spatial variability in the productivity of agrocenoses, it is particularly important to improve the technologies used to grow maize, a crop that plays a key role in the global grain and feed system. The use of intensive hybrids with high genetic potential requires precise selection of sowing rates and a differentiated approach to fertilisation depending on growing conditions, which is the basic principle of precision farming technologies. Taking into account field productivity zones allows for the optimisation of resource use and increased efficiency of agrotechnical measures.

Recent studies emphasise that spatial management of sowing rates allows for the optimisation of corn photosynthetic activity by adapting the sowing structure to environmental conditions. In particular, according to research by N. Saleem *et al*. (2025), the use of differentiated sowing rates in combination with consideration of leaf orientation (phyllotaxis) improves light use efficiency in dense crops. Similarly, the results of studies by K. Djaman *et al*. (2022) in North America showed that optimal densities (approximately 80-90 thousand/ha) contribute to increased moisture efficiency and yield under conditions of limited moisture supply, which is relevant in the context of adapting corn crops to climate change. Research by G. Lacolla *et al*. (2023) in Mediterranean conditions indicates that optimising corn planting density has a positive effect not only on yield, but also on root system formation and soil water balance, which is critically important for regions with seasonal droughts. In addition, recent developments by K. Bűdi *et al*. (2025) in the field of precision farming demonstrate that the use of Variable Rate Seeding technology in combination with adaptive hybrid selection reduces seedling heterogeneity and ensures more uniform biometric indicators within a heterogeneous field.

The work of E. Sarauskis *et al*. (2022) analyses modern approaches to variable seeding rates based on the use of yield maps, remote sensing data and sensor systems. The results show that combining different sources of information for field zoning makes it possible to increase the accuracy of determining the optimal plant density and reduce spatial variability in yield. According to the results of Z. Du *et al*. (2022), the use of spatial gradient analysis for decision-making on VRS allows for a 5-10% increase in maize yield while reducing seed costs. The researchers emphasise that this approach is effective in fields with heterogeneous soil and climatic conditions, where traditional fixed sowing rates do not ensure optimal productivity.

The study by K. Bakó *et al*. (2025) summarises current approaches to modelling the leaf area index (LAI) of maize using remote sensing and models such as CERES-Maize, AquaCrop, WOFOST, APSIM and RZWQM2. The authors point out that a decrease in LAI under conditions of insufficient moisture directly correlates with a decrease in CO_2 absorption and plant productivity, while accurate LAI prediction allows for the optimisation of seeding rates to improve adaptation to stressful conditions. The work of D. Li *et al*. (2022) demonstrates the potential of integrating machine learning and active sensor monitoring to predict the nitrogen status of maize crops. This allows the optimisation of plant density to be combined with nitrogen nutrition regulation, which together contributes to increased grain yield and quality.

Field experiments by M. Videgain *et al.* (2024), conducted under commercial farming conditions, showed that optimising plant density in the range of 350-450 grains/m² while taking into account microzone productivity resulted in improved yield and agrophysiological characteristics of the crop without additional resource costs. In addition, the use of VRS improved the uniformity of emergence and reduced intraspecific competition between plants. Thus, a modern corn cultivation strategy must take into account the interaction of planting density, zonal productivity, and nutritional conditions to achieve the maximum genetic potential of the crop. In this context, studying changes in maize biometric indicators depending on field spatial conditions and sowing rates is extremely relevant.

The aim of the study was to analyse the effect of seed sowing rates and zonal field productivity on changes in morphometric indicators and dry matter accumulation in maize during different phases of its growth and development.

Materials and Methods

Field studies were conducted in 2023-2024 on the territory of "Chernihiv Industrial Dairy Company" LLC, located within the Chernihiv district of the Chernihiv region, in the transition zone between Polissia and Forest-Steppe. The agricultural landscape of this territory is characterised by high spatial heterogeneity in terms of relief, granulometric composition and agrochemical condition of soils, which creates optimal conditions for studying changes in the biometric parameters of maize depending on field productivity zones.

The field experiment was two-factor. Factor A – field productivity zones (high, medium, low), determined on the basis of long-term yield, relief, agrochemical maps and cluster analysis in the QGIS environment (Havlin *et al.*, 2013). Factor B was the corn sowing rate (65, 70, 75, 80, and 85 thousand seeds/ha). The object of the study was the DKS 3939 maize hybrid of the medium-early maturity group. The experiment was set up in four replicates on three experimental plots with an area of 6.6 ha. The predecessor crop was winter wheat. Plant density at the time of harvesting was ensured by controlling sowing rates and the quality of seedling formation. The boundaries of the zones were determined using digital yield maps and spatial analysis modules, and the agrochemical status of the zones was detailed using the analysis of soil samples taken from a depth of 0-30 cm with a density of 10-20 points per zone. The samples were mixed, processed and analysed in accordance with the requirements of DSTU ISO 11260:2001 (2001). Biometric indicators of maize were determined at the initial stages of maize development (V2-V3) and flowering (R1). The following were measured: plant height (from the soil surface to the growing point), dry matter content (drying at 105°C to constant weight). Data collection was based on a sample of 10 typical plants in each variant. Mathematical statistics methods were used to analyse the impact of factors on biometric parameters. In particular, mean values and standard deviations were calculated. Correlations between sowing rates, productivity zones and dry matter accumulation were also identified. The study was conducted in accordance with the Convention on Biological Diversity (1992).

Meteorological conditions during the experiment were monitored using an automatic weather station installed directly on the experimental site, recording air temperature, precipitation, relative air humidity and wind speed at 1-hour intervals. To assess the statistical significance of the differences between the variants, a two-factor analysis of variance (ANOVA) was used, followed by a comparison of the means using the least significant difference (LSD_{05}) criterion in the R software environment, version 4.3.0. Correlation analysis was performed to establish relationships between agrochemical soil indicators (humus content, mobile forms of phosphorus and potassium, pH) and biometric parameters of plants at different sowing rates. Plant samples for determining biometric indicators were selected in the morning (7:00-9:00) to minimise the impact of daily fluctuations in turgor and photosynthetic activity on the measurement results.

Results

Despite differences in weather conditions between years, similar patterns in changes in biometric indicators were observed. The highest plant height and dry matter indicators were observed in high-yield areas with sowing rates of 70-75 thousand/ha, while in medium and low areas, the effectiveness of factors increased with increasing sowing rates. The results of the studies show that the level of biometric parameters of maize in the early stages of vegetation was determined by the influence of the zonal productivity of the field. The sowing rate in the early stages of development (V2-V3 emergence phase) had a negligible effect on plant growth intensity, which is explained by insufficient competition among plants for resources in dense crops. The dry matter content and plant height showed a clear gradation in accordance with the productive potential of the zones. The actual plant density reflected a high level of maize field emergence, but at the same time indicated the presence of plant losses at certain stages of seedling establishment (Table 1).

Table 1. *Actual plant density of maize and its deviation from planned values at the seedling stage*

Zone	Sowing rate, thousand/ha	Actual plant density, thousand/ha			Deviation from planned sowing rate, %		
		1	2	Avg.	1	2	Avg.
High	65	63.8	62.7	63.3	1.8	3.5	2.7
	70	68.4	67.6	68.0	2.2	3.4	2.9
	75	73.4	72.4	72.9	2.1	3.4	2.8
	80	78.1	77.2	77.7	2.3	3.5	2.9
	85	83.2	82.1	82.7	2.1	3.4	2.8
Average deviation for high-productivity zone, %:					2.1	3.4	2.8
Medium	65	63.1	62.1	62.6	2.9	4.4	3.7
	70	68.2	66.7	67.5	2.5	4.7	3.6
	75	73.1	71.7	72.4	2.5	4.4	3.5
	80	78	76.7	77.4	2.5	4.1	3.3
	85	82.9	81.6	82.3	2.4	4.0	3.2
Average deviation for medium-productivity zone, %:					2.6	4.3	3.5
Low	65	61.8	61.3	60.7	4.9	6.6	5.8
	70	66.5	66.0	65.4	5.0	6.5	5.8
	75	71.3	70.7	70.1	4.9	6.5	5.7
	80	76	75.4	74.8	5.0	6.5	5.7
	85	80.8	80.2	79.5	4.9	6.4	5.7
Average deviation for low-productivity zone, %:					4.9	6.5	5.7

Note: 1 – 2023; 2 – 2024

Source: developed by the authors

In the high-yield zone, with a sowing rate of 65-85 thousand plants per hectare, the actual density in 2023 was 63.8-83.2 thousand plants per hectare, and in 2024 – 62.7-82.1 thousand pcs/ha, which indicates a deviation from the planned indicators at the level of 1.8-2.4% in 2023 and 3.4-3.5% in 2024. The average deviation for this zone over two years was 2.8%, indicating relatively stable conditions for crop growth and effective seedling formation. In the medium productivity zone, there was a slightly greater deviation from the planned density: 2.5-2.9% in 2023 and 4.0-4.7% in 2024. This is explained by less favourable conditions. The average deviation in this zone was 3.5%, which is acceptable for field conditions but indicates the need to adjust agronomic measures in less favourable microzones. The largest deviations were observed in the low-productivity zone: 4.9-5.0% in 2023 and 6.4-6.6% in 2024. The average deviation from the planned density was 5.7%, which indicates a significant impact of unfavourable environmental conditions on seed germination processes.

In general, the results show a steady trend towards a decrease in actual density as we move from high-yield to low-yield zones, indicating spatial heterogeneity in the conditions for the formation of initial plant cover density. The data obtained are important for optimising maize cultivation technology, in particular for the application of precision farming and differentiated seed sowing technologies. Studies of the influence of spatial variability and variable sowing rates on plant height and dry matter content at the V2-V3 stage of maize development showed that these parameters varied significantly depending on the productivity zone of the field and, to a lesser extent, on the sowing rate (Table 2).

Table 2. *Effect of spatial variability and variable sowing rates on dry matter content and plant height of maize at the V2-V3 stage of development*

Zone	Sowing rate, thousand/ha	Dry matter content in plants, %,			Plant height, cm		
		1	2	Avg,%	1	2	Avg,%
High	65	22.3	17.6	20.0	21.7	19.9	20.8
	70	23.5	19.4	21.5	22.5	19.2	20.9
	75	22.6	18.3	20.5	21.2	18.3	19.8
	80	20.5	19.7	20.1	21	19.7	20.4
	85	21.4	18.6	20.0	22.2	19.4	20.8
Average for high zone:		22.1	18.7	20.4	21.7	19.3	20.5
Medium	65	19.8	16.2	18.0	19	17.8	18.4
	70	18.8	16.6	17.7	20.7	16.5	18.6
	75	17.2	15.1	16.2	19.4	16.5	18.0
	80	19.4	15.1	17.3	19.6	17	18.3
	85	17.5	16.3	16.9	19.9	16.6	18.3
Average for medium zone:		18.5	15.9	17.2	19.7	16.9	18.3
Low	65	15.7	10.9	13.3	17.2	13.5	15.4
	70	15.5	12	13.8	16.6	13.8	15.2
	75	14.6	10.7	12.7	16.9	14.4	15.7
	80	14.6	10.6	12.6	16.5	14	15.3
	85	15.6	11.8	13.7	17.2	13.4	15.3
Average for low zone:		15.2	11.2	13.2	16.9	13.8	15.4

Note: 1 – 2023; 2 – 2024
Source: developed by the authors

The highest dry matter content values were observed in the high-yield zone, where the average values for two years were 20.1-21.5%, and the average value for the zone was 20.4%. In the middle zone, this indicator ranged from 16.2 to 18.0%, with an average value of 17.2%, and in the low-productivity zone, it was only 12.6-13.8%, with an average level of 13.2%. This confirms the close relationship between the level of environmental productivity and the intensity of biomass accumulation in the early stages of organogenesis. Plant height in the early stages of development (at the V2-V3 stage), as one of the key morphometric indicators, differed significantly between productivity zones. In the highly productive zone, the average height was 20.5 cm, in the medium zone – 18.3 cm, and in the low-productive zone – 15.4 cm. Within each zone, the sowing rate had a less significant effect on plant height, although a slight decrease in height was observed with an increase in sowing density. This pattern can be explained by the initial competition for moisture. Thus, the results show that in the early stages of maize vegetation, the main determining factor of biometric indicators was the productivity of the zone, while the differentiation of sowing rates had only a slight effect. At the beginning of maize flowering (R1), biometric indicators showed significant variability depending on spatial productivity zones and sowing rates, reflecting the interaction of the genetic potential of plants with environmental conditions (Table 3).

Table 3. *Effect of spatial variability and variable sowing rates on dry matter content and plant height at the beginning of maize flowering (R1)*

Zone	Sowing rate, thousand/ha	Dry matter content in plants, %,			Plant height, cm		
		1	2	Avg,%	1	2	Avg,%
High	65	32.2	30.6	31.4	225	178	201.5
	70	31.7	30.1	30.9	235	185	210.0
	75	31.2	29.5	30.4	245	192	218.5
	80	30.7	29.1	29.9	252	196	224.0
	85	30.1	28.5	29.3	250	194	222.0
Average for high zone:		31.2	29.6	30.4	241.4	189.0	215.2
Medium	65	30.1	28.4	29.3	200	164	182.0
	70	29.6	27.9	28.8	210	171	190.5
	75	29.1	27.3	28.2	220	178	199.0
	80	28.6	26.8	27.7	218	176	197.0
	85	28.1	26.2	27.2	215	175	195.0
Average for medium zone:		29.1	27.3	28.2	213	173	192.7
Low	65	27.2	25.6	26.4	160	147	153.5
	70	26.8	25.1	26.0	170	154	162.0
	75	26.3	24.5	25.4	168	153	160.5
	80	25.8	24.0	24.9	165	150	157.5
	85	25.3	23.4	24.4	155	143	149.0
Average for low zone:		26.3	24.5	25.4	163.6	149.4	156.5

Note: 1 – 2023; 2 – 2024
Source: developed by the authors

The general trend showed an increase in dry matter content and plant height in more productive areas under optimal density conditions. The highly productive zone provided the highest dry matter accumulation rates, averaging 30.4%, with a variation from 29.3 to 31.4% depending on sowing rates and weather conditions during the year. In the medium zone, dry matter content decreased to 28.2%, and in the low-yield zone to 25.4%, indicating the limiting effect of less favourable soil and microclimatic conditions. The decrease in dry matter content from high-yielding to low-potential zones confirms the dependence of maize growth and development intensity on resource availability.

Plant height in the R1 phase proved to be the most sensitive indicator to growing conditions. In the high-yield zone, the average height was 215.2 cm, ranging from 201.5 to 224 cm depending on the sowing rate and year. In the medium zone, the average plant height was 192.7 cm, and in the low zone, it was 156.5 cm. The decrease in plant height from high to low productivity zones is due to a reduction in the amount of available nutrients and moisture and less favourable conditions for photosynthetic activity. Optimal height indicators were observed at a density of 80 thousand/ha in highly productive zones, indicating a balance between resource availability and the intensity of competition between plants. In less productive areas, increasing density did not result in further height growth, indicating limited environmental resources. Thus, at the flowering stage, the main factors influencing the biometric indicators of maize were the productivity zone and weather conditions of the year, while the sowing rate had an additional but less pronounced effect. The results indicate the feasibility of a spatially differentiated approach to managing sowing rates and fertiliser application to optimise maize growth and development in heterogeneous field conditions.

Discussion

The results of the study indicate a significant influence of sowing rates and productivity zones on the formation of biometric indicators of maize and dry matter accumulation during vegetation. Similar patterns are described in the work of W. Liu *et al.* (2023), where it was found that spatial differences in soil fertility and moisture supply determine the rate of dry matter accumulation in different phases of maize growth. A. Shatkovskyi *et al.* (2020) note that under favourable conditions, dry matter accumulation is linearly increasing until the beginning of the milk ripeness phase, while under moisture deficit, there is an early decrease in photosynthesis intensity and premature leaf senescence, which reduces potential yield. Compared to the results of this study, in highly productive areas, the rate of dry matter accumulation corresponded to global trends, indicating the effectiveness of adapting plant density to spatial conditions.

A study by Z. Zhu *et al.* (2022), which used the Richards model to describe the growth dynamics of maize, showed that optimising agronomic parameters, in particular plant density, affects not only the final amount of dry matter accumulated, but also the duration of the active growth phase. The authors emphasise that prolonging the period of maximum absorption of photosynthetically active radiation directly correlates with an increase in yield and energy use efficiency. In the same study, increasing the duration of active vegetation in high-yield areas also resulted in higher yields, confirming the importance of regulating sowing density to optimise plant photosynthetic activity. A.A. Anselmi *et al.* (2021) note that under conditions of high productivity, thickening is advisable, while in low-productivity areas, moderate density is more effective. The results of this study confirm this pattern: in a high-yielding area, a density of 70-75 thousand/ha proved to be optimal, while in medium and low-yielding areas, increasing the sowing rate did not result in an increase in biometric indicators. A.F. Silva *et al.* (2021) showed that spatially differentiated sowing rates increase resource efficiency and reduce stress risks for plants. This is consistent with the data from this study: the actual density and dry matter content differed significantly between productivity zones, confirming the need to adapt density to local field conditions.

A study by M. Zhang *et al.* (2025) showed that optimising corn seeding density significantly affects both yield and resource use efficiency. Based on a meta-analysis of 1951 data sets, it was found that increasing seeding density increases leaf area by 23.4%, plant height by 1.8%, dry biomass accumulation by 15.9%, water use efficiency by 3.8%, nitrogen use efficiency by 34.2% and yield by 10-11%. At the same time, a decrease in the weight of 1,000 grains by 7.2% and the collection coefficient by 2.4% was found, indicating a compromise between the structural components of yield. The authors emphasise that the optimal plant density should take into account hybrid characteristics and moisture levels in order to avoid the negative effects of excessive crop compaction.

Field trials by J. Cui *et al.* (2022) of modern maize hybrids at three density levels, where stem strength indicators were measured: stem breaking strength (SBS), dry weight per unit length, stem cross-section, lignin and cellulose content showed that at high densities, modern hybrids exhibited lower SBS, lower stem weight and reduced structural biomass content, which correlated with an increased likelihood of lodging. These findings are consistent with the observations in this study: the highest resistance to lodging was achieved at a density adapted to the resource potential of the productivity zone. The interaction between sowing rate and nitrogen nutrition level, according to the results of a study by P. Tian *et al*. (2022), indicates a significant increase in photosynthetically active radiation (PAR) absorption, yield and nitrogen use efficiency in maize. Thus, an increase in density, together with optimal N application, stimulated better light absorption due to a change in the structure of the crop.

The results of the study showed that the correct allocation of productivity zones significantly enhances the effect of sowing rate differentiation: in highly productive zones, the potential of density is better realised, while in low-productive zones, the risk of seed overspending and increased intraspecific competition is reduced. A similar pattern is demonstrated by the study by M.A. Munnaf *et al*. (2022). The authors formed productivity zones by merging data from proximal soil probing and plant indicators and showed that map-based site-specific seeding (SSS) allows the seeding rate to be aligned with the spatial fertility of the field; at the same time, excessive rates in areas with lower potential worsen economic results, indicating the need for initially high-quality zoning and then VRS.

In the context of the accuracy of productivity zones and the predictability of management effects, it is important to combine field, proximal and satellite data. B.B. Bantchina *et al*. (2024) showed that the combination of visible/near-infrared soil spectra (Vis-NIRS), satellite plant indices and ML algorithms not only allows for the correct identification of productivity zones, but also enables the prediction of yield at the zone level, which directly reinforces the rationale for VRS and VR fertilisation in production conditions. Observations of persistent differences in dry matter accumulation curves between zones are consistent with their conclusion.

The role of classification/clustering algorithms and geostatistics in the practical formation of MZ maps should be noted separately. D.J. Gallardo-Romero *et al*. (2023) demonstrated a multi-layer scheme: cleaning and interpolation of yield data, followed by classification and morphological post-processing to obtain machine-readable field productivity maps suitable for loading into equipment. This approach explains why, in this work, the use of yield stability maps and vegetation indices resulted in better alignment with the actual boundaries of productive microzones, and the VRS parameters were acceptable for agricultural machinery.

Conclusions

Studies revealed that a spatially heterogeneous productive environment significantly affects the biometric indicators of maize in the early stages of development and at the beginning of flowering. It has been determined that the productivity zone is the main factor in the formation of dry matter content and plant height, while the influence of sowing rates is additional and less pronounced. The highest dry matter content (20.4% in the early stages and 30.4% in the flowering phase) and plant height (up to 215 cm) were recorded in highly productive areas with sowing rates of 70-75 thousand seeds per hectare. In less productive areas, these indicators decreased, indicating the limiting effect of soil and microclimatic conditions. Increasing sowing rates in the early stages of development did not have a significant effect on biometric indicators, but during the flowering phase, a moderate decrease in plant height was observed in variants with increased sowing density. This indicates the emergence of competition for resources (nitrogen, light, moisture) during the active growth phase. Spatial variability in field productivity necessitates a differentiated approach to managing sowing rates. The highest sowing density efficiency was observed in highly productive areas with moderately high rates (70-75 thousand/ha), where an optimal balance between density and resource potential of the environment is ensured.

The results indicate the stable nature of the influence of productivity zones: regardless of the weather conditions in 2023-2024, spatial patterns remained unchanged, indicating the dominant role of soil potential and relief-hydrological characteristics of zones over the inter-seasonal variability of climatic conditions. Prospects for further research lie in studying the interaction of differentiated sowing with other elements of corn cultivation technology, in particular, variable fertilisation and irrigation rates, as well as in developing yield prediction models based on a combination of remote sensing data, sensor monitoring and machine learning. This will allow the creation of comprehensive recommendations for managing crop productivity in space and time.

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Conflict of Interest

None.

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Динаміка біометричних показників рослин кукурудзи за впливу норм висіву та зон продуктивності поля

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Анотація. Біометричні показники кукурудзи є важливим індикатором ефективності агротехнологій та відображають адаптивну реакцію культури на просторову неоднорідність умов вирощування. Метою дослідження було встановити вплив зональної продуктивності та норм висіву на висоту та формування сухої речовини кукурудзи на ранніх етапах органогенезу. Польові дослідження проведено у 2023-2024 рр. у межах трьох зон продуктивності поля: високої, середньої та низької. Варіювали п'ять норм висіву – від 65 до 85 тис. насінин/га. Результати досліджень свідчать, що зона продуктивності чинила основний вплив на біометричні параметри рослин, тоді як норма висіву мала додатковий, але менш суттєвий ефект. На стадії розвитку кукурудзи V2-V3 максимальні показники сухої речовини (до 23,5 %) спостерігалися у високопродуктивній зоні за норми висіву 70 тис. насінин/га. У низькопродуктивних зонах показники знижувались до 15,5 %. Висота рослин у цій фазі варіювала від 22,5 см у високій зоні до 16,6 см у низькій зоні продуктивності. У фазі початку цвітіння (R1) відзначено зменшення вмісту сухої речовини у напрямку до менш продуктивних зон: від 31,7 % (висока зона, 70 тис./га) до 25,3 % (низька зона, 85 тис./га) у 2023 р. Висота рослин варіювала від 252 см у високопродуктивних зонах до 143 см у низьких. Біометричні параметри кукурудзи можна використовувати як надійний критерій для оцінки реакції культури на диференційовані технологічні прийоми, що є перспективним напрямом у системах точного землеробства. Застосування зонально диференційованих норм висіву дозволяє підвищити ефективність використання ресурсів та оптимізувати агротехнології вирощування кукурудзи на неоднорідних за продуктивністю полях

Ключові слова: *Zea mays* L.; висота рослин; диференційована сівба; густота стояння; суха речовина

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Dynamics of vibration processes in the "tool – workpiece – bench" during material processing

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Abstract. The study aimed to identify effective methods for optimising and reducing vibration processes in the tool-workpiece-machine system to improve the stability and quality of machining. The study analysed the main types of vibrations in the tool-workpiece-machine system and determined their impact on machining quality, establishing that self-excited vibrations are the main cause of process instability. Classical approaches to cutting and a mathematical model for optimising machining parameters to reduce vibrations and increase the accuracy and efficiency of the technological process were considered. Analysis of classical methods has shown that fixed-angle and constant-feed methods provide stability and predictability of the process, while variable-feed and automatic control methods increase adaptability and reduce vibration amplitude. The simulations confirmed the effectiveness of parameter optimisation to stabilise vibrations and improve machining quality. According to the results of machining on the 1K62 machine with a T15K6 carbide tool, the roughness parameter was reduced from 6.3 to 1.6 microns due to optimisation of cutting modes and increased system rigidity. The study also showed a 40% increase in tool life when self-excited vibrations were eliminated. The generalisation of the data obtained formulated practical recommendations for the selection of machining parameters, considering the dynamic properties of the technological system, to ensure a stable cutting process and improve the quality of machining. The results obtained can be used by specialists of machine-building enterprises and scientists to improve the efficiency of production processes and product quality

Keywords: damping; amplitude; roughness; service life; oscillation; stability

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Introduction

The process of machining materials on metal cutting machines is accompanied by complex dynamic phenomena, including vibrations in the tool – workpiece – bench system. These vibrations affect cutting stability, reduce machining accuracy, degrade surface finish and accelerate tool wear. Self-excited vibrations that occur without external disturbances can lead to unstable operation of the entire technological system. The research relevance is determined by the need to study the dynamic characteristics of these processes to improve the performance and reliability of metalworking equipment. Identification of regularities in the development of vibration phenomena and the development of effective methods for their reduction make it possible to ensure stable operation of bench tools, improve the quality of the machined surface and extend the service life of the tool.

The problem of the dynamics of vibration processes in the system "tool – workpiece – bench" is relevant for improving the quality of machining and tool life. Z. Peng *et al.* (2020) identified critical machining conditions in which the vibration amplitude increases sharply due to the combination of high rotational speed and depth of cut. This highlighted the importance of optimal parameters to avoid process instability. I. Akande *et al.* (2020) demonstrated that increasing the stiffness of the machine structure significantly reduces resonant vibrations, while the introduction of damping elements increases the overall stability of the system. These measures contributed to improved machining quality and reduced tool wear. C. Kuo *et al.* (2023) determined that the shape and dimensions of the cutting edge have a direct impact on vibration, especially when machining materials with an uneven structure. This indicates the need to incorporate the geometric characteristics of the tool when developing cutting modes. Z. Li *et al.* (2021) developed nonlinear mathematical models that reproduce the dynamic processes of tool/workpiece interaction, including feedback effects, which explain the phenomenon of self-excitation of vibrations. These models further demonstrated the instability mechanisms. X. Vasanth *et al.* (2019) applied active vibration control systems using feedback, which ensured rapid damping of unwanted vibrations and increased machining accuracy. The introduction of such technologies has shown promise in industrial applications.

C. Zhao *et al.* (2022) analysed the effectiveness of various damping materials in reducing the amplitude of vibrations, identifying the best options for installation in a cutter holder. The use of such materials reduced dynamic loads on the tool. Y. Cheng *et al.* (2023) experimentally proved that increasing the rigidity of the technological system significantly improves the quality of the machined surface by reducing vibrations. Changing the cutting modes in combination with increased rigidity made it possible to reduce surface roughness. G. Weicheng *et al.* (2021) showed that proper tool clamping adjustment is a key factor in preventing vibrations that negatively affect process stability. Insufficient fixation contributed to additional vibrations. Y. Danylchenko *et al.* (2021) determined that irregularities on the workpiece surface increase the intensity of vibrations and lead to a deterioration in machining quality. Accordingly, pretreatment or workpiece preparation is essential to stabilise the process. Q. Wang *et al.* (2025b) proved that the dynamic properties of the system in the selection of cutting modes can significantly increase tool life and reduce the probability of accidents. The optimisation of parameters ensured more stable and efficient operation of the equipment.

These studies established the dependence of the vibration amplitude on cutting modes, machine design characteristics and tool geometry, developed mathematical models of the dynamic interaction between tool and workpiece, and proposed methods of active vibration control and the use of damping materials to reduce vibrations. In addition, experimental studies have confirmed the impact of system stiffness and tool clamping parameters on process stability and have shown the role of workpiece surface irregularities in amplifying vibrations. However, despite the significant achievements, there are gaps in the comprehensive consideration of the simultaneous influence of design, technological and material factors on the formation of vibration processes. Integrated approaches to vibration modelling and control, which incorporate the nonlinearity of the system and the variability of cutting conditions in real time, require additional study.

The study aimed to identify methods to optimise and reduce vibration processes in the "tool – workpiece – bench" system.

Tasks of the study:

1. To investigate the classification of types of vibrations in the tool-workpiece-machine system.

2. Consider classical approaches to the analysis of dynamic processes and vibration modelling.

3. Evaluate the effectiveness of various methods of vibration reduction and develop recommendations for their implementation.

Materials and Methods

The study conducted a comprehensive analysis of the dynamic processes in the tool – workpiece – bench system during machining with an emphasis on the physical characteristics of the elements that form the system's response to load. The study analysed various types of vibrations in the tool – workpiece – bench system to determine their characteristics and mechanisms of occurrence. The vibrations were classified into forced, free and self-excited, which determined their characteristics and impact on the technological process. This approach formulated the basis for diagnosing, monitoring and developing effective measures to reduce vibrations and improve machining stability. Also, the study analysed classical approaches to material processing in the tool – workpiece – bench system, including the following methods: free cutting method, fixed angle method, constant feed cutting method, variable feed cutting method, adjustable angle method, computer numerical control (CNC) machining method, special tool method, vibration control method, automatic adjustment method and tool pre-setting method. Each approach was addressed in terms of its technological features and potential application in production processes.

The study addressed the cutting modes in which self-excitation of vibrations was manifested, as well as changes in the dynamic stability of the system after the introduction of a damping element and a decrease in spindle speed. A polyurethane element with a stiffness of 500 N/m was used for damping, mounted directly in the toolholder with bolt and glue connection, which ensured reliable fixation and efficient absorption of the vibrational energy of the tool. The damping element was designed to absorb up to 70% of the vibration energy in the frequency range of 100-500 Hz, which corresponds to the characteristic spectrum of self-excited vibrations during the cutting process. To eliminate the negative effects, the cutting speed was reduced to 800 revolutions per minute. In addition, a damping element was added to the design of the toolholder to absorb the vibration energy and reduce the amplitude of vibration processes. This approach modelled the influence of design and process parameters on the nature of vibration processes and substantiated the effectiveness of the selected technical solutions to improve machining stability.

A simplified mass-elastic model with damping is used to describe the dynamics of the tool – workpiece – bench system (Wang *et al*., 2025a). The model parameters are set as follows: system mass m = 5 kg, damping coefficient c=10 N-s/m, spring stiffness k=2,000 N/m. The external force acting on the system is described by the harmonic law (1):

$$F(t) = F_0 sin(wt), \quad (1)$$

where F_0=100 N, and the disturbance frequency ω is related to the spindle speed N (rpm) by formula (2):

$$w = \frac{2\pi N}{60}. \quad (2)$$

Initial conditions: $x(0) = 0$, $\dot{x}(0) = 0$. The system was analysed in the time interval $t = 0...1$ s. Then the equation of motion of the system is (3):

$$m\ddot{x} + c\dot{x} + k(x) = F_0 sin(wt), \quad (3)$$

where: where m – mass, c – damping coefficient, k – system stiffness, F_0 – amplitude of the external force, ω – frequency of the disturbance tied to the spindle speed.

As part of the study, an experimental observation of the dynamic behaviour of the tool – workpiece – bench system during turning of a steel shaft on a 1K62 machine was conducted (Fig. 1). The workpiece was made of St3sp/5 steel with a hardness of ≈200 HB, a diameter of 40 mm and a length of 200 mm. The workpiece was rigidly clamped in the machine chuck, with the free end centrally supported to ensure stability and reduce vibrations.

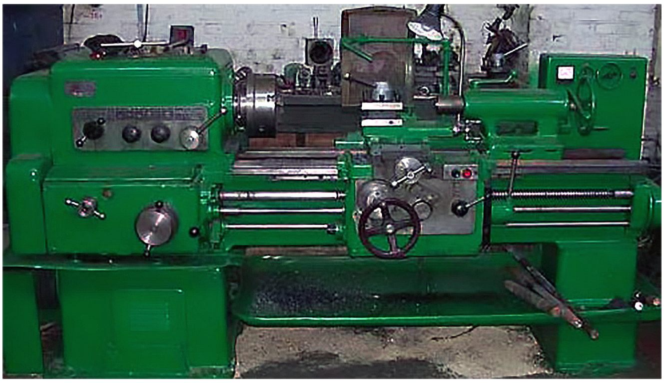

***Figure 1.** Machine 1K62*

Source: Stalmira (n.d.)

The cutting was performed with a T15K6 carbide tool (Fig. 2) with the following geometric parameters: front surface angle $\gamma = 6°$, rear surface angle $\alpha = 12°$, and apex radius $p = 0.8$ mm. The depth of cut was 1 mm, and the length of the pass was 150 mm for a single pass.

***Figure 2.** Carbide brazing plate T15K6*

Source: Metal cutting (n.d.)

To record the dynamic parameters of the system, IEPE vibration sensors with a sampling rate of 10 kHz were used, installed at three points: on the tool, on the machine spindle and on the workpiece body. The 1K62 machine and T15K6 carbide tool were selected due to their widespread use in metalworking and their ability to provide the required accuracy and stability when turning steel workpieces. The obtained experimental data were compared with classical analysis methods and modelling results to comprehensively assess the dynamic processes in the system and increase the accuracy of the conclusions. The study highlighted the main areas of vibration reduction, including increasing the stiffness of structures, using damping materials, optimising machining modes, choosing the right cutting tool geometry and using active control systems. The generalisation of the obtained results formulated practical recommendations for reducing vibrations and ensuring the stability of the technological process.

Results

The tool – workpiece – bench system is the backbone of any machining process and is a complex dynamic structure in which three key elements interact closely: the cutting tool, the workpiece and the machine components. This interaction takes place within a closed mechanical system, where each element not only performs its function but also influences the overall behaviour of the entire structure under load. The physical characteristics of each link, such as mass, stiffness and damping, determine how the system will respond to the loads, vibrations or disturbances that occur during the cutting of the material.

Different types of vibrations can occur in the system, each of which has characteristics and mechanisms of formation. Forced vibrations are caused by periodic external disturbances. Such disturbances include, for example, irregularities in the operation of a cutting tool, such as milling cutter teeth that pass through the workpiece at a certain frequency, or an uneven machine drive that creates vibrations in the machinery. These vibrations have a well-defined frequency that coincides with the frequency of the external disturbance and can usually be predicted and accounted for when setting up machining modes (Ghazali & Rahiman, 2021). Free or natural vibrations occur after a short-term perturbation of the system and are characterised by a gradual decay in time. They reflect the natural oscillatory properties of the system due to its mass, stiffness, and damping. Such vibrations can appear, for example, after a sharp push or impact, but in the absence of further disturbances, they gradually disappear without harm to the process (Ebbehøj *et al*., 2024). Self-excited vibrations are the most dangerous type, as they are formed as a result of positive feedback between the tool and the workpiece. This type of vibration persists and even increases over time if the conditions do not change and often manifests itself as regenerative vibrations during turning. They lead to instability of the cutting mode, deterioration of the machined surface quality and rapid tool wear (Insperger & Stépán, 2022). Determining the type of vibration is part of the analysis of dynamic processes in the tool – workpiece – bench system and can be used to select the most effective methods of their control. At the same time, knowledge of the characteristics of each type contributes to the development of measures to increase process stability and improve the quality of the final product.

In the context of studying the dynamics of the tool – workpiece – bench tool system, classical machining methods are of great importance, as they are widely used in industry to ensure efficiency, accuracy and stability of cutting processes. Each of these methods is characterised by certain technological features that determine its suitability for specific operating conditions. The free cutting method is effective in the mass production of parts with low accuracy requirements, when the main criterion is low cost and speed. In the absence of complex control systems, equipment, and operating costs are minimal. In such conditions, small deviations in surface quality are acceptable, and process stability is ensured by a high rate of output. However, in cases where high precision or geometry stability is required, the efficiency of this method decreases rapidly due to vibrations with an amplitude of up to 0.03-0.05 mm, which leads to rapid tool wear and deterioration of the machined surface parameters (Liu *et al*., 2021a). The fixed angle method is effective where process predictability and repeatability are substantial. Reduction of fluctuations by 15-20% ensures stable results in the mass production of parts from materials with homogeneous properties. In such cases, a good balance is struck between surface quality and productivity. However, when machining materials with a variable structure (e.g., cast or composite workpieces), the method becomes ineffective because it cannot adapt to local differences in properties, which again leads to vibrations and load fluctuations (Aydın *et al*., 2021). The constant feed cutting method ensures uniform tool wear and consistent machining quality in the mass production of parts made of homogeneous materials. The effectiveness of this method is especially high in cases where the predictability of tool life and the repeatability of surface parameters are substantial. However, when machining complex materials, as well as at different levels of system stiffness, it loses its effectiveness: vibration loads can increase by 10-15%, which degrades quality and increases tool costs (Soori & Arezoo, 2022).

The Variable Feed Cutting Method is particularly effective in high-precision machining of parts where it is necessary to minimise vibrations (20-25% reduction). This improves surface finish and reduces tool wear, even in cases of heterogeneous materials. It is most effective in the production of high-precision or critical parts where quality control takes precedence over cost. At the same time, the method is less effective for mass or low-cost production, as it requires complex control systems and expensive equipment (Muqeet *et al*., 2023). The adjustable angle method is effective in the production of parts with variable material characteristics or complex surface profiles. Due to the ability to change the cutting angle during the process, it reduces vibrations and optimises the load on the tool, which significantly increases its service life. It is especially relevant for load-sensitive materials. However, the overall efficiency in industry is limited by the high complexity of control systems and additional equipment costs (Abolghasem & Mancilla-Cubides, 2021). CNC machining has the highest efficiency in high-precision and flexible manufacturing. It provides accuracy of up to ±0.01 mm, repeatability and the ability to perform complex cutting paths. Its effectiveness is particularly high when machining parts with complex geometries or in conditions of rapid product mix changes. However, in small-scale production or with a limited budget, its effectiveness is reduced due to significant capital investment and the need for highly qualified personnel (Wang *et al*., 2025b). The special tool method is effective in serial and mass production, when the use of tools with special geometry or wear-resistant materials can significantly reduce replacement costs and improve surface quality (wear is reduced by up to 30%). The greatest effect is achieved when producing identical parts in large batches. However, efficiency is significantly reduced in small-scale production due to the high cost of manufacturing and maintaining specialised tools (Geng *et al*., 2021).

The vibration control method is effective in applications where the main objective is to ensure process stability and extend tool life. With the use of dampers or active systems, the vibration amplitude can be reduced to 0.02 mm, making this method valuable in high-precision machining. However, its effectiveness in widespread industrial applications is limited by the high cost of the systems and the complexity of integration (Akdeniz & Arslan, 2024). The automatic adjustment method is most effective in cases where the process needs to be adapted in real time. It is efficient in processing materials with variable properties, complex shapes and structures, where parameter stability is relevant. This increases the accuracy and reliability of production. However, due to the complexity of the hardware and software, as well as the high price, the effectiveness of this method in conventional mass production is reduced (Liu *et al*., 2021b). The tool pre-setting method is effective in batch and mass production, where it is necessary to reduce changeover time. Precise tool calibration can improve stability and accuracy up to ±0.02 mm. The method is most effective in production with repeated machining cycles. However, in small-scale or pilot production, its effectiveness decreases, as the time spent on setup is not offset by the benefits (Mohamed *et al*., 2022). Thus, the considered classical methods of machining in the tool – workpiece – bench system have specific technological features that determine their feasibility depending on production conditions, material characteristics, and product quality requirements. Each of them demonstrates efficiency in certain production situations, but none of them provides a universal solution to the problem of vibrations and process instability. Therefore, current trends in mechanical engineering are aimed to integrate automated and adaptive approaches with classical technologies. In this context, the study of the dynamic behaviour of the system during cutting is of particular importance, since oscillatory processes largely determine the surface quality, machining accuracy and tool life.

A dynamic model with damping of the tool – workpiece – bench system is key for analysing and predicting the behaviour of the complex mechanical system during the cutting process. The model is based on the representation of the system as an oscillating one with mechanical parameters of mass, stiffness and damping interacting under the influence of external forces. The motion of the system is described by differential equations that consider the physical characteristics of the elements (Wang *et al.*, 2025c). The main approach that describes the dynamic behaviour of the system is the classical modelling of the motion of an oscillating system with an external cutting force (4). The external force in the model is described by a harmonic law, where the amplitude of the force is set experimentally, and the frequency of the perturbation is directly related to the spindle speed. Two modes were calculated for the study:

$$N = 120\frac{r}{pm} : w = \frac{2\pi\times120}{60} = 125.66\, rad/s, \quad (4)$$

$$N = 800\frac{r}{pm} : w = \frac{2\pi\times800}{60} = 83.78\, rad/s. \quad (5)$$

Therefore, it is possible to correctly incorporate the effect of rotational speed on the dynamic behaviour of the system in different machining modes (3). The simulation (Fig. 3) addresses the phenomenon of self-excitation of vibrations, when the cutting force depends on the current and previous states of the system.

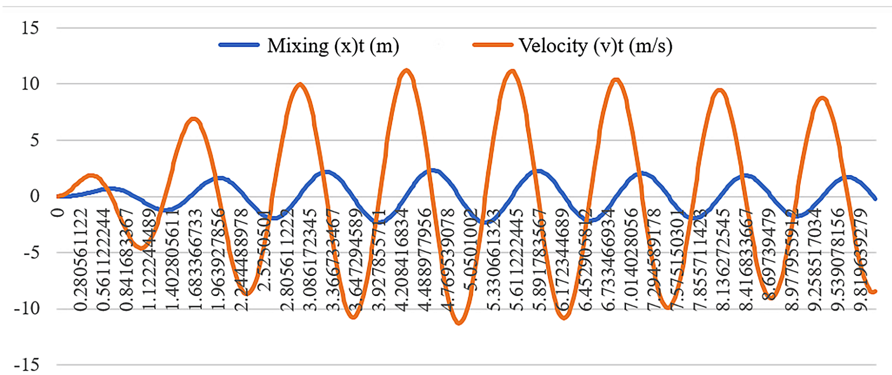

Figure 3. *Oscillations of the tool – workpiece – bench system*
Source: compiled by the authors

The calculated data obtained indicate that the maximum amplitude of oscillations x(t) is about 0.031 m, the maximum oscillation velocity reaches approximately 0.83 m/s, and the maximum acceleration is approximately 31.78 m/s². Such a dynamic model can simulate the behaviour of the system in various processing modes, assess the impact of design and process parameters on process stability, and develop methods for vibration control and damping. The model serves as the basis for further process optimisation aimed to improve machining quality and reducing tool wear. The dynamic model with damping of the tool-workpiece-machine system is used for theoretical and practical study of vibration processes and serves as a basis for the analysis of machining materials.

The obtained theoretical regularities can predict possible manifestations of instability in real machining conditions, which is confirmed by experimental studies on specific machine tools and under specific cutting conditions. In a lathe, the phenomenon of self-excitation of vibrations was recorded at a rotational speed of 1,200 revolutions per minute and a feed rate of 0.3 millimetres per revolution. The quantitative indicators were maximum vibration amplitude of about 0.031 m, maximum acceleration of about 31.78 m/s^2. Additionally, vibration was observed in the form of a characteristic noise in the working area and a wave structure of the workpiece surface. The surface roughness parameter Ra before the adjustments was 6.3; after the adjustments, it was 1.6. These vibrations were manifested in the form of a characteristic noise felt in the work area, as well as in the form of a wave surface on the machined part. In addition, accelerated wear of the cutting insert was observed, indicating instability of the cutting modes and increased dynamic load on the tool. The implementation of these measures led to the stabilisation of the dynamic operation of the machine tool and the tool – workpiece – bench system (Table 1).

Table 1. *Comparison of turning parameters before and after implementation of vibration reduction measures*

Parameter	Before adjustments	After adjustments
Spindle rotation speed (rpm)	1,200	800
Feed rate (mm/rpm)	0.3	0.3
Vibration amplitude	High	Significantly reduced
Surface roughness Ra	6.3	1.6
Wear and tear of the cutting insert	Accelerated	Reduced
Stable cutting conditions	Unstable	Stable

Source: compiled by the authors

After the adjustments were made, vibrations were significantly reduced and virtually disappeared, which ensured more stable operation of the process. The improved surface quality was confirmed by a reduction in roughness from Ra 6.3 to Ra 1.6, which indicates a more uniform and smoother surface of the part. In addition, the reduction of vibrations contributed to the extension of the cutting tool life, which increased by approximately 40%, reducing operating costs and increasing the efficiency of the production process. This example demonstrates that controlling the dynamic processes in the tool-workpiece-machine system is critical to achieving high machining quality and long tool life. The use of damping elements in combination with optimised cutting conditions is an effective way to reduce vibrations and improve overall process stability. This approach also reduces the probability of defects on machined surfaces and reduces the risk of accidents during machine operation. Therefore, these measures contribute to increased productivity, quality and cost-effectiveness of metalworking production.

Practical recommendations for optimising processes and reducing vibrations in the tool-workpiece-machine system are based on reducing the amplitude of vibrations that affect the quality of the machined surface, the accuracy of parts and tool life. This is achieved through both design changes and adjustments to process parameters. Increasing the rigidity of the machine's structure reduces mechanical deformations during machining and, consequently, the amplitude of oscillations, which improves the stability of operation. It also reduces the impact of external factors such as workpiece irregularities or impacts. Damping elements made of elastic materials, lubricants, or anti-vibration supports absorb vibration energy, reducing the amplitude of vibrations. This reduces tool wear and stress on the machine's mechanisms and reduces noise during machining.

Optimisation of the machining conditions, including the selection of cutting speed, feed rate and depth of cut, helps to avoid resonant frequencies and ensures a more even distribution of cutting forces. This improves surface finish, process stability and tool life. Selection of a tool with the right geometry, including cutting angles and cutting edge shapes, helps reduce dynamic loads during operation, which increases machining accuracy and wear resistance of the cutting part. Active vibration-damping systems with feedback, which monitor vibration parameters in real time and promptly correct them, help maintain process stability. The introduction of such systems increases production efficiency, reduces rejects and extends the life of equipment. Thus, an integrated approach, including stiffening, damping, mode optimisation, tool selection and the use of active damping systems, helps to improve the dynamic stability of the tool-workpiece-machine system, which has a positive impact on the quality and reliability of machining.

Discussion

The study confirmed that the tool – workpiece – bench system is a complex mechanical structure where the interaction between the elements largely determines the dynamic behaviour during machining. The analysis showed that the mass, stiffness, and damping properties of each component affect the overall stability and susceptibility to vibration. This confirmed the need for detailed modelling of the system as an oscillating structure to predict its response to external and internal disturbances. This problem was also studied by C. Li *et al.* (2021), where the results confirmed that the dynamics of the tool – workpiece – bench system, incorporating mass stiffness and damping, is a key factor in ensuring the stability of the machining process. Each element of the system has its mass stiffness characteristics that determine its ability to withstand vibrations. Consideration of damping can improve the accuracy of modelling of the system's behaviour under load and predict instabilities.

N.E.O. Ogunnowo *et al.* (2021) also demonstrated that the influence of mechanical parameters on machining stability is manifested through changes in the dynamic stiffness of resonant frequencies and the ability of the system to dampen vibrations. Insufficient stiffness or mass misalignment can lead to self-excited vibrations that degrade machining quality. Precise matching of mechanical parameters minimises the risk of vibrations and increases the efficiency of the process. Notably, the interaction of stiffness and damping in a system is not always linear and can make it difficult to predict its behaviour. This is especially relevant when the characteristics of individual components change during operation due to wear or thermal deformation. Therefore, for an accurate analysis, it is necessary to use complex models that incorporate nonlinear effects and the variability of parameters over time. The results of the study showed that the main causes of vibrations in the tool – workpiece – bench system are related not only to external factors, such as fluctuations in cutting force or material unevenness, but also to the internal characteristics of the system itself. Insufficient stiffness of the elements, geometric instability of the tool or workpiece, and oscillations in the machine drive created conditions for the development of both forced and self-excited vibrations. The interaction of these factors made it difficult to control the process dynamics.

Researchers D. Doan *et al.* (2021) concluded that the causes of vibrations in the system are mostly related to insufficient structural rigidity, fluctuations in cutting forces, and geometric instability of the elements. Low stiffness contributes to the emergence of resonance phenomena that amplify vibrations. Fluctuations in cutting forces, in turn, can occur due to uneven machining or changes in the contact conditions between the tool and the workpiece. J.V. Abellán-Nebot *et al.* (2024) determined that the factors that cause dynamic processes in cutting include both the internal mechanical properties of the system and external operating conditions. The interaction between the tool and the workpiece material, as well as the effects of temperature changes and wear, influences the machining process. Together, these factors form complex dynamic processes that affect the quality and stability of the machining process. These results confirm the above study, as they demonstrate a direct correlation between system stiffness and vibration intensity. A decrease in stiffness leads to an increase in vibrations, which is consistent with theoretical models of dynamic instability. In addition, the influence of fluctuations in cutting forces and geometric irregularities further complicates the system's behaviour, which is also reflected in the experimental results.

The identified types of vibrations – forced, free, and self-excited – had different effects on the system operation. Forced vibrations caused by external periodic disturbances proved to be quite predictable and could be controlled by adjusting the processing modes. Free vibrations quickly damped and did not cause any serious problems. The most difficult were self-excited vibrations, which, due to positive feedback, could increase and lead to significant deterioration in the technological process. It is worth noting the study by S. Sarath & P. Paul (2021), demonstrating that there are several types of vibrations in a machining system: forced, free (natural), and self-excited. Each type has characteristics of occurrence and propagation, which are determined by the characteristics of the system and operating conditions. Forced vibrations arise due to external influences, free vibrations are due to internal properties, and self-excited vibrations are associated with nonlinear interactions between the tool and the workpiece. J. Du *et al.* (2022) concluded that vibrations negatively affect the quality and stability of machining, causing surface defects, reduced accuracy, and increased tool wear. Instability caused by vibrations can lead to uneven material removal and noise during operation. Controlling and minimising vibrations is essential to ensure process reliability and improve the final machining results. This data is consistent with the results of the current study, as it confirms the different nature of vibrations and their impact on the dynamic behaviour of the system. In particuar, the distincltion between types of vibrations further demonstrates the mechanisms of their occurrence and direct measures to control them. This confirms that effective vibration control improves the stability and quality of machining. In the study by A. Rud (2025), it was shown that under dynamic loads, the spring elements of tillage tools undergo critical deformations, which reduce the stiffness of the structure and may lead to unstable vibrodynamic modes.

The mathematical modelling of the system tool – workpiece – bench tool as an oscillating system, incorporating mass, stiffness, damping and variable cutting force, demonstrated the mechanisms of vibration development and predicted the conditions of their occurrence. The dependence of the cutting force on previous oscillatory movements (memory effect) was considered, which explained the mechanism of self-excitation. This model created opportunities for further development of methods for controlling the system dynamics. M. Zahaf & M. Benghersallah (2020) also conducted a study that confirmed that the self-excitation model with the memory effect in cutting addresses the dependence of the cutting force on previous system states, which is relevant for an accurate description of the process dynamics. This approach helps explain the occurrence of periodic and chaotic oscillations that cannot be predicted by simple linear models. By considering the memory effect, it becomes possible to analyse in more detail the conditions for the appearance of self-excited vibrations and develop methods for their control. Z. Peng *et al.* (2023) also determined that oscillations with damping and nonlinear interaction are characterised by complex dynamics, where damping reduces the amplitude of oscillations, and nonlinearity leads to the emergence of new modes of system behaviour. This approach can be used to model real-world processing conditions where the interaction of system elements is not simple and linear. Analysis of these processes is necessary for optimising process conditions and improving processing stability. Comparing the data obtained in the course of research, it is possible to conclude that the memory effect is significant in the formation of self-excited oscillations. This factor complicates the system's behaviour and requires the use of complex nonlinear models for accurate forecasting. At the same time, consideration of damping can be used to develop effective methods for reducing the amplitude of vibrations and increasing the stability of the process.

T. Mohanraj *et al.* (2024) concluded that vibrations have a significant impact on machining quality, causing surface irregularities and dimensional accuracy of parts. In addition, they accelerate the wear of tools and equipment components, which reduces their service life. Constant dynamic loads can also lead to damage and malfunctions in machine tools, increasing the risk of accidents. S. Han *et al.* (2021) found that the effects of dynamic processes in the machining system are reflected in the final product in the form of defects and inconsistent quality. Vibrations can cause loosening of fasteners and deformation of machine components, which requires frequent repairs and maintenance. For this reason, controlling and minimising vibrations is key to ensuring equipment reliability and high product quality.

Analysis of the study results determined that vibration processes have a complex effect on both machining quality and equipment service life. They cause a decrease in accuracy, surface defects and accelerated wear of cutting tools and mechanical components. Therefore, ensuring effective control of the dynamic characteristics of the system is a key condition for increasing productivity and ensuring the safety of production equipment. The study also found that effective methods of reducing vibrations are based on increasing structural rigidity, using damping materials and specialised tools, optimising cutting modes, and implementing active vibration damping systems. The application of these measures ensures increased process stability, improved product quality and reduced operating costs, which is a substantial area of development in modern engineering.

Conclusions

In the course of the study, three main types of vibrations characteristic of the tool – workpiece – bench system were identified: forced vibrations arising under the influence of periodic external forces; natural (resonant) vibrations associated with the natural frequencies of the oscillating system and regenerative (self-excited) vibrations that appear as a result of the memory effect of the cutting process and are the most dangerous for machining stability. The analysis of ten classical approaches determined their technological features, advantages and limitations. The study determined that traditional methods ensure stability only under certain conditions, while adaptive and automated approaches are better suited to changes in the dynamic characteristics of the system, but require more complex and expensive equipment.

The study addressed a dynamic model of the system based on the equation of motion with consideration of mass, stiffness, damping and cutting force with memory effect. This approach can predict the complex nonlinear behaviour of a technological system and determine the conditions for the occurrence of self-excited oscillations. The simulation showed that the maximum amplitude of oscillations x(t) is about 0.031 m, the maximum velocity is 0.83 m/s, and the maximum acceleration is 31.78 m/s^2. Comparison of the simulation results with experimental data confirmed the negative impact of vibrations on surface roughness, dimensional accuracy, tool life, and machine tool safety. In addition, experiments on a 1K62 lathe with a T15K6 carbide tool showed a decrease in the roughness parameter from 6.3 μm to 1.6 μm due to optimisation of cutting modes and increased system rigidity. The study also determined that the elimination of self-excited vibrations increases tool life by 40%.

The study results show the effectiveness of combining classical methods with adaptive approaches and engineering solutions to reduce vibrations. The study recommended using mathematical modelling at the stage of selecting machining modes to predict vibration processes, as well as to integrate damping elements and increase the rigidity of the system to ensure the stability of the cutting process and improve the quality of finished parts. Prospects for further research include studying the influence of temperature factors and wear on the dynamic behaviour of the tool – workpiece – bench system.

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Динаміка вібраційних процесів у системі “інструмент – заготовка – верстат” при обробці матеріалів

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Анотація. Мета дослідження полягала у визначенні ефективних методів оптимізації та зниження вібраційних процесів у системі “інструмент – заготовка – верстат” для підвищення стабільності та якості обробки. У дослідженні проведено аналіз основних видів вібрацій у системі “інструмент – заготовка – верстат” та визначено їхній вплив на якість обробки, встановивши, що самозбуджувані вібрації є основною причиною нестабільності процесу. Розглянуто класичні підходи до різання та математичну модель оптимізації параметрів обробки, спрямовану на зменшення вібрацій і підвищення точності та ефективності технологічного процесу. Аналіз класичних методів показав, що методи з фіксованим кутом і постійною подачею забезпечують стабільність і передбачуваність процесу, тоді як методи з перемінною подачею та автоматичним регулюванням підвищують адаптивність і зменшують амплітуду вібрацій. Моделювання підтвердило ефективність оптимізації параметрів для стабілізації коливань і підвищення якості обробки. За результатами обробки на верстаті 1К62 твердосплавним інструментом типу Т15К6 встановлено зменшення параметра шорсткості з 6,3 до 1,6 мкм за рахунок оптимізації режимів різання та підвищення жорсткості системи. Дослідження також показало зростання ресурсу інструменту на 40 % при усуненні самозбуджених коливань. Узагальнення отриманих даних дозволило сформулювати практичні рекомендації щодо вибору параметрів обробки з урахуванням динамічних властивостей технологічної системи з метою забезпечення стабільного процесу різання та підвищення якості обробки. Отримані результати можуть бути використані фахівцями машинобудівних підприємств і науковцями для підвищення ефективності виробничих процесів і якості продукції

Ключові слова: демпфування; амплітуда; шорсткість; ресурс; коливання; стабільність

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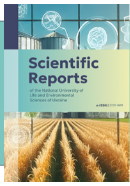

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Features of piglet metabolism under the application of monoglycerides

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Abstract. Optimising piglet metabolism in the early postnatal period is an important task in modern animal husbandry. The use of functional additives such as SCFA-M can have a positive effect on protein and energy metabolism, reduce stress, and improve the productivity and health of piglets. The aim of the study was to determine the effect of SCFA-M on protein and energy metabolism and the general physiological condition of animals in the early rearing stage. The study was conducted on 42-day-old piglets divided into control and experimental groups; the animals in the experimental group received SCFA-M as part of their diet. The evaluation was carried out using biochemical methods of blood analysis to determine the levels of major metabolites and the activity of key enzymes; statistical processing was performed with a check of the normality of distribution and the corresponding parametric/non-parametric criteria. The use of SCFA-M significantly modulated protein metabolism: total protein increased by 9.1% ($P > 0.05$), globulins by 31.8% ($P > 0.001$), while the protein coefficient decreased by 16.5% ($P > 0.001$) . Aminotransferase activity was lower, indicating less stress on the liver. Blood urea and urea nitrogen levels decreased by 16.5% and 20%, respectively, indicating more efficient nitrogen utilisation. Carbohydrate and mineral metabolism also improved: glucose increased to 6.48 mmol/L (+47.9%; $P > 0.001$), calcium absorption increased by 10%, and phosphorus absorption increased by 28.9% ($P > 0.001$). The results obtained expand understanding of the mechanisms of action of monoglycerides and confirm the feasibility of their use in pig farming; at the same time, they require further research with longer monitoring, performance evaluation and intestinal homeostasis indicators. The practical significance lies

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in the possibility of using SCFA-M as part of support programmes for piglets in the post-weaning period, with a possible reduction in the need for antibacterial agents and an improvement in animal welfare

Keywords: SCFA-M; protein metabolism; enzymes; energy metabolism; mineral metabolism

Introduction

The post-weaning period in pig farming was accompanied by a high risk of metabolic destabilisation, diarrhoea and growth suppression caused by stress, diet changes and intestinal microbiome restructuring. The need for antibiotic-free strategies to support barrier function and metabolism is driving demand for functional lipid supplements. During this period, it is particularly important to maintain the stability of the intestinal environment and control opportunistic microflora, as these factors determine the animal's ability to effectively absorb nutrients. In addition, the increased susceptibility of young animals to infectious agents, combined with restrictions on the use of antibiotics, stimulates the search for new approaches to feeding.

C.S. White *et al.* (2024) noted that short- and medium-chain fatty acid monoglycerides (SCFA/MCFA) combine antimicrobial and metabolic-modulating properties. They emphasised that, unlike free acids, monoglycerides are more stable in the intestinal lumen, are better tolerated and act over a wider pH range; they are capable of disrupting the lipid membranes of pathogens while serving as an energy substrate for enterocytes and commensal bacteria. The authors also emphasised that these properties create the conditions for strengthening the barrier function of the intestine and improving the absorption of nutrients. Z. Cui *et al.* (2020) found that under standard housing conditions, SCFA/MCFA monoglycerides had no significant effect on the average performance of weaned piglets, but there were positive signals regarding intestinal health and metabolic markers. The researchers also emphasised that the effects may be more pronounced under conditions of stress or infection, indicating the potential of such supplements in specific scenarios.

Researchers L. Li *et al.* (2022) showed that in multifactorial feeding schemes, the effects of monoglycerides on growth and feed conversion were variable but were accompanied by improvements in selected indicators of intestinal homeostasis and inflammatory response. They added that monoglycerides can modulate metabolic processes and immune responses even in the absence of a significant impact on overall production performance. L.L. Thomas *et al.* (2020) determined that adding a mixture of monoglycerides to piglets reduced the gain/feed ratio in ETEC-infected pigs and reduced the severity of intestinal disorders while maintaining the local immune response. The authors noted that these properties make monoglycerides a promising tool for reducing antibiotic use in intensive farming programmes.

A. Kumar *et al.* (2022) showed that in a model of necrotic enteritis in poultry, monoglyceride mixtures demonstrated barrier-strengthening effects but did not always translate into improved performance. They further emphasised that the effectiveness of such additives is highly dependent on the composition of the mixture and the specific conditions of the disease, which is important for the adaptation of feeding programmes. L. Li *et al.* (2023) investigated the effect of α-GML in sows during late gestation and lactation and found an increase in piglet weight at weaning and a change in nutrient digestibility, indicating an indirect effect on the early postnatal period of piglets. The authors emphasised that maintaining the health of sows can have long-term consequences for the productivity and sustainability of offspring.

Researchers M. Yang *et al.* (2024) concluded that the effectiveness of monoglycerides is largely determined by the dose, diet matrix, age and physiological condition of the animals, as well as the epizootic situation. They added that combining monoglycerides with other functional ingredients can significantly enhance their positive effects on gut health and immune response. S. Park *et al*. (2024) emphasised that the results of monoglyceride use depend on the dose, diet composition and housing conditions, adding that combinations with other functional components can significantly enhance the positive effects on performance and gut health. The authors also noted that such strategies may be useful for optimising antibiotic-free programmes in pig and poultry farming.

The aim of the study was to determine the corrective effect of adding SCFA-M to the diet of 42-day-old piglets on nitrogen metabolism, markers of hepatocellular load, and indicators of carbohydrate and mineral homeostasis.

Material and Methods

The study was conducted in 2022-2023 at a commercial pig farm located in the Dnipropetrovsk district, Dnipropetrovsk region. For the experiment, 100 three-breed hybrid piglets of DanBred genetics aged 42 days were selected; animals "analogous" in age and live weight after stratification by weight were randomly divided into two groups: control and experimental (50 heads in each). The piglets were kept in group pens in accordance with the stocking density standards established in the EU: 0.20 m^2/head for a weight range of 10-20 kg and 0.30 m^2/head for 20-30 kg; actually provided with 0.22-0.24 and 0.33-0.36 m^2/head, respectively. The piglets had free access to water and were fed a complete feed ration without restrictions according to the same schemes in both groups, with the exception of the addition of an experimental supplement in the experimental group.

The microclimate was maintained within stable limits: temperature 22-26 °C, relative humidity 55-65 %, ventilation – mechanical; a fixed photoperiod of 16L:8D was maintained. Before the start of the experiment, the animals were clinically examined; only clinically healthy piglets were allowed to participate. Weaning from sows was carried out on the 26th day of life; the experiment began at 42 days of age. The experimental group aged 42-77 days received a diet containing a composition of short- and medium-chain fatty acid monoglycerides (SCFA-M, C3-C12), manufactured to order by PARTNERAGRO 2016 LLC at the production facilities of NETAG B.V. (The Netherlands), at a dose of 1.0 kg/t of compound feed. According to the quality certificate, the ratio of glyceride fractions (mass %) was as follows: monoglycerides – 31%, diglycerides – 18%, triglycerides – 1%, free glycerol – 14%.

The glycerol-esterified acids included: propionic (C3), butyric (C4), caprylic (C8), capric (C10) and lauric (C12) acids. The addition was carried out in a production mixer with technological control of batch homogeneity. The control group received an identical basic diet without SCFA-M. To assess the metabolic status of piglets in both groups, biochemical studies were conducted, for which whole blood without anticoagulant was collected from 10 piglets from the experimental and control groups at 42, 56 and 77 days of age for further serum extraction. In blood serum samples, the Miura-200 automatic biochemical analyser (Italy) was used with ready-made reagent kits manufactured by Spinreakt (Spain), Dialab (Austria), Cormay (Poland) and HTI (USA) to determine the content of total protein (with biuret reagent), albumin (with bromocresol green), urea (enzymatically by Berthelot's reaction), creatinine (by the rate of formation of the creatinine-picrate complex in the Jaffe reaction), glucose (by the glucose oxidase method), total calcium (with arsenazo III) and inorganic phosphorus (with ammonium molybdate).

The activity of transaminase enzymes (ALT and AST) was determined kinetically using a set of Spinreakt reagents (Spain), and alkaline phosphatase (ALP) activity was determined by the rate of 4-nitrophenol formation (Cormay, Poland). Laboratory studies were conducted at the Biosafety-Center Research Centre for Biosafety and Environmental Control of Agricultural Resources at Dnipro State Agrarian and Economic

University. Data processing was performed in GraphPad Prism 9. The normality of distribution was evaluated using the Shapiro-Wilk test separately for each group and time point; the homogeneity of variances was evaluated using the Brown-Forsyth/Levene test. The main approach for intergroup comparisons was two-factor ANOVA (factors: "group" and "age") with post-hoc Tukey. For violations of the assumptions of normality/homogeneity, non-parametric analogues were used: Kruskal-Wallis with post-hoc Dunn or paired Mann-Whitney comparisons within individual time points. Multiple comparisons were corrected using the Benjamini-Hochberg procedure (FDR 5%). Data are presented as $\bar{X} \pm SD$; statistical significance was accepted at $P < 0.05$. The study was conducted in accordance with Directive 2010/63/EU of the European Parliament and of the Council (2010) and ARRIVE 2.0 guidelines (Percie du Sert *et al.*, 2020).

Results and Discussion

The study analysed the effect of SCFA-M on protein metabolism indicators in piglets at different stages of growth. The levels of total protein, albumin, globulin, protein coefficient, as well as urea and creatinine concentrations in blood serum were evaluated (Fig. 1). It was found that on the 42nd day of the study, the total protein level in the blood serum of pigs in the control group, which were not fed SCFA-M, was 53.5 g/L (SD = 6.57), while in pigs in the experimental group, which received SCFA-M, it was 51.4 g/L (SD = 3.53). The albumin content in the blood serum of piglets in the control group was 27.9 g/L (SD = 1.9), while in the experimental group it was 26.7 g/L (SD = 2.1). The globulin level in the blood serum of the control group piglets was 25.6 g/L (SD = 6.7), while in the experimental group it was 24.7 g/L (SD = 4.6). The protein coefficient was almost the same in both groups (1.12-1.16 conventional units), and the urea level was 2.17 mmol/l in the control group versus 2.08 mmol/l in the experimental group. Thus, at the initial stage of the study, the difference between the groups was insignificant.

On day 56, the total protein level in the blood serum of the control group piglets decreased to 50.4 g/L (SD = 4.17), while in the experimental group receiving SCFA-M, it increased to 55.0 g/L (SD = 4.52), which was 9.1% higher ($P < 0.05$). The albumin content in the blood serum of piglets in the control group increased to 28.7 g/L (SD = 3.5), while in the experimental group it remained lower – 26.4 g/L (SD = 3.8), i.e., 8% lower. The most pronounced changes were observed in the globulin content: in the control group, its amount decreased to 21.7 g/L (SD = 1.95), while in the experimental group, it increased to 28.6 g/L (SD = 2.59), a difference of 31.8% ($P < 0.001$). The protein coefficient in the blood serum of piglets in the control group rose to 1.33 conventional units (SD = 0.67), while in the experimental group it decreased to 1.11 conventional units (SD = 0.34), reflecting the predominance of globulin fractions under the action of SCFA-M ($P < 0.001$). The urea level in the control group was 2.3 mmol/L, while in the experimental group it decreased to 1.92 mmol/L (-16.5%; $P < 0.05$).

By day 77, the total protein level in the blood serum of the control group piglets decreased to 49.0 g/L (SD = 1.63), while in the experimental group it remained high at 52.6 g/L (SD = 2.84), which was 7.3% higher ($P < 0.01$). The albumin content in the control group was 28.6 g/L (SD = 2.5), and in the experimental group it was 26.5 g/L (SD = 2.1), which is 7.3% lower ($P < 0.05$). In contrast, the globulin content in the control group decreased to 20.4 g/L (SD = 2.31), while in the experimental group it remained significantly higher – 26.1 g/L (SD = 2.56), with a difference of 27.9% ($P < 0.001$). The protein coefficient in the blood serum of piglets in the control group rose to 1.40 conventional units (SD = 0.31), while in the experimental group it remained low – 1.06 conventional units (SD = 0.15), a difference of 24.3% ($P<0.001$). At the same time, the urea level in the control group increased to 3.33 mmol/L (SD = 0.96), while in the experimental group it increased only to 2.21 mmol/L (SD = 0.45), which is 33.6% lower ($P < 0.01$). Creatinine levels increased in both groups, but remained lower in the experimental group (87.5 mg/100 ml vs. 92.7 mg/100 ml). The data obtained indicate that feeding SCFA-M contributed to maintaining higher levels of total protein and globulins, reducing the protein coefficient, and limiting the growth of nitrogenous metabolites in the blood of piglets.

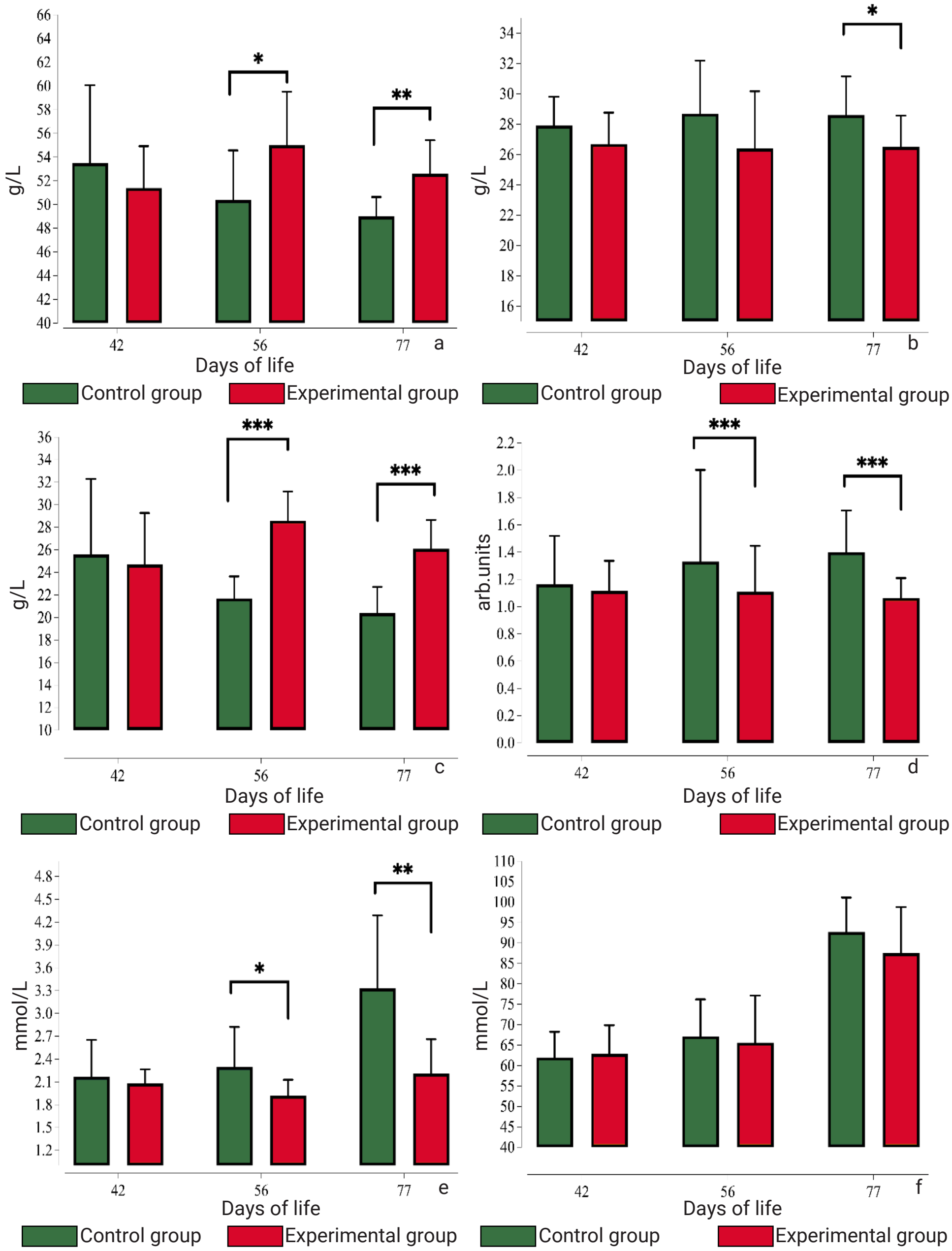

Figure 1. *Indices of protein metabolism in piglet blood serum under the influence of SCFA-M*

Note: a – total protein content, g/L; b – albumins, g/L; c – globulins, g/L; d – protein coefficient, arb. units; e – urea, mmol/L; f – creatinine, mmol/L; M ± SD; n = 10; * – P < 0.05; ** – P < 0.01; *** – P < 0.001 – compared with the control group

Source: developed by the authors

The changes in the protein coefficient recorded in the study are consistent with the data of L.E. Duvall *et al.* (2023), who noted that such changes may indicate a shift in the balance between protein synthesis and immune response. The decrease in urea and urea nitrogen levels in the blood of piglets in the current study under the influence of short- and medium-chain fatty acid monoglycerides (by 16.5% and 20%, respectively, P < 0.05) indicates an improvement in protein metabolism and a decrease in protein catabolism. These observations partly contrast with the results of other scientific studies. In particular, K.A. Barbosa *et al.* (2023) observed an increase in urea levels with monoglycerides/tributyrin (P < 0.05). Similarly, researchers J.A. Santos-Marcos *et al.* (2019) noted an increase in urea concentration (P < 0.05) in the plasma of starter piglets fed monoglycerides. The discrepancies in the results can be explained by various factors. The study by K.A. Barbosa *et al.* (2023) included tributyrin, which is a source of butyrate and is actively metabolized in intestinal cells, which may affect overall protein metabolism. At the same time, differences in the growth phase of piglets, diet matrix, and epizootic background could modify the metabolic response of animals to the supplement.

The second direction of the study was to investigate changes in enzymatic activity and mineral metabolism in piglets under the influence of SCFA-M. The study examined the dynamics of ALT, AST, alkaline phosphatase, as well as serum glucose, calcium, and phosphorus levels (Fig. 2). On day 42, ALT activity in the blood serum of pigs in the control group was 87.2 U/L (SD = 17.65), while in animals receiving SCFA-M it was 81.7 U/L (SD = 13.84). A similar trend was observed for AST: 87.2 U/L (SD = 15.72) in the control group versus 81.6 U/L (SD = 16.55) in the experimental group. At the same time, alkaline phosphatase activity was significantly higher in the experimental group of piglets – 358.68 U/L (SD = 53.41) versus 254.19 U/L (SD = 61.15) in the control group (+41.1%; P < 0.001). Glucose levels also tended to increase with SCFA-M – 5.38 mmol/L (SD = 0.63) versus 4.72 mmol/L (SD = 0.94) in the control group, while calcium concentration was slightly lower – 2.36 mmol/L (SD = 0.39) versus 2.54 mmol/L (SD = 0.51). At the same time, the phosphorus level in the experimental group exceeded the control by 32.9% – 4.2 mmol/L (SD = 0.67) versus 3.16 mmol/L (SD = 0.20; P < 0.001).

By day 56, enzyme activity in the blood serum of piglets in both groups had decreased, but with varying intensity. Thus, ALT in the control group was 78.0 U/L (SD = 14.17), while in the experimental group it was 71.4 U/L (SD = 15.33), which is 8.5% lower. AST decreased to 78.3 U/L (SD = 20.20) in the control group and to 63.8 U/L (SD = 42.16) in the experimental group, a difference of 18.5%. Alkaline phosphatase activity decreased to 213.23 U/L (SD = 31.19) in the control group and to 251.76 U/L (SD = 33.71) in the experimental group, i.e. by 18.1% higher (the difference is not significant). A decrease in the activity of these enzymes in the blood serum of piglets under the action of SCFA-M until the 55th day of life may indicate a reduction in the load on the liver and a decrease in the level of hepatocellular damage. The glucose concentration in the control group decreased to 4.38 mmol/L (SD = 0.96), while in the experimental group it increased sharply to 6.48 mmol/L (SD = 0.57), which was 47.9% higher (P < 0.001). Calcium levels in the control group decreased to 2.00 mmol/L (SD=0.36), while in the experimental group they increased to 2.20 mmol/L (SD = 0.35), exceeding the control by 10%. Phosphorus levels were 3.05 mmol/L (SD = 0.29) in the control group and 3.93 mmol/L (SD = 0.29) in the experimental group, which was 28.9% higher (P < 0.001).

On day 77, stabilisation or even opposite dynamics of individual indicators were noted. In the blood serum of piglets in the control group, ALT decreased to 69.5 U/L (SD = 7.40), while in the experimental group it increased to 76.9 U/L (SD=14.63), which was 10.6% higher. A similar trend was observed for AST: 68.8 U/L (SD = 15.89) in the control group versus 84.3 U/L (SD = 12.65) in the experimental group (+22.5%; P < 0.05). Alkaline phosphatase activity remained virtually unchanged – 222.69 U/L (SD = 28.11) in the control group and

225.64 U/L (SD = 31.32) in the experimental group. The glucose concentration in the control group was low – 4.31 mmol/L (SD = 0.81), while in the experimental group it was 5.62 mmol/L (SD = 0.60), which is 30.4% higher (P < 0.05), indicating activation of gluconeogenesis and improved energy metabolism. This may provide animals with the additional energy needed for growth. The calcium level in the control group decreased to 1.89 mmol/L (SD = 0.12), and in the experimental group to 1.82 mmol/L (SD = 0.08). The most pronounced change was in phosphorus: 2.98 mmol/L (SD = 0.17) in the control group versus 4.21 mmol/L (SD = 0.38) in the experimental group, which is 41.3% higher (P < 0.001), indicating a prolonged effect of SCFA-M on mineral metabolism in piglets.

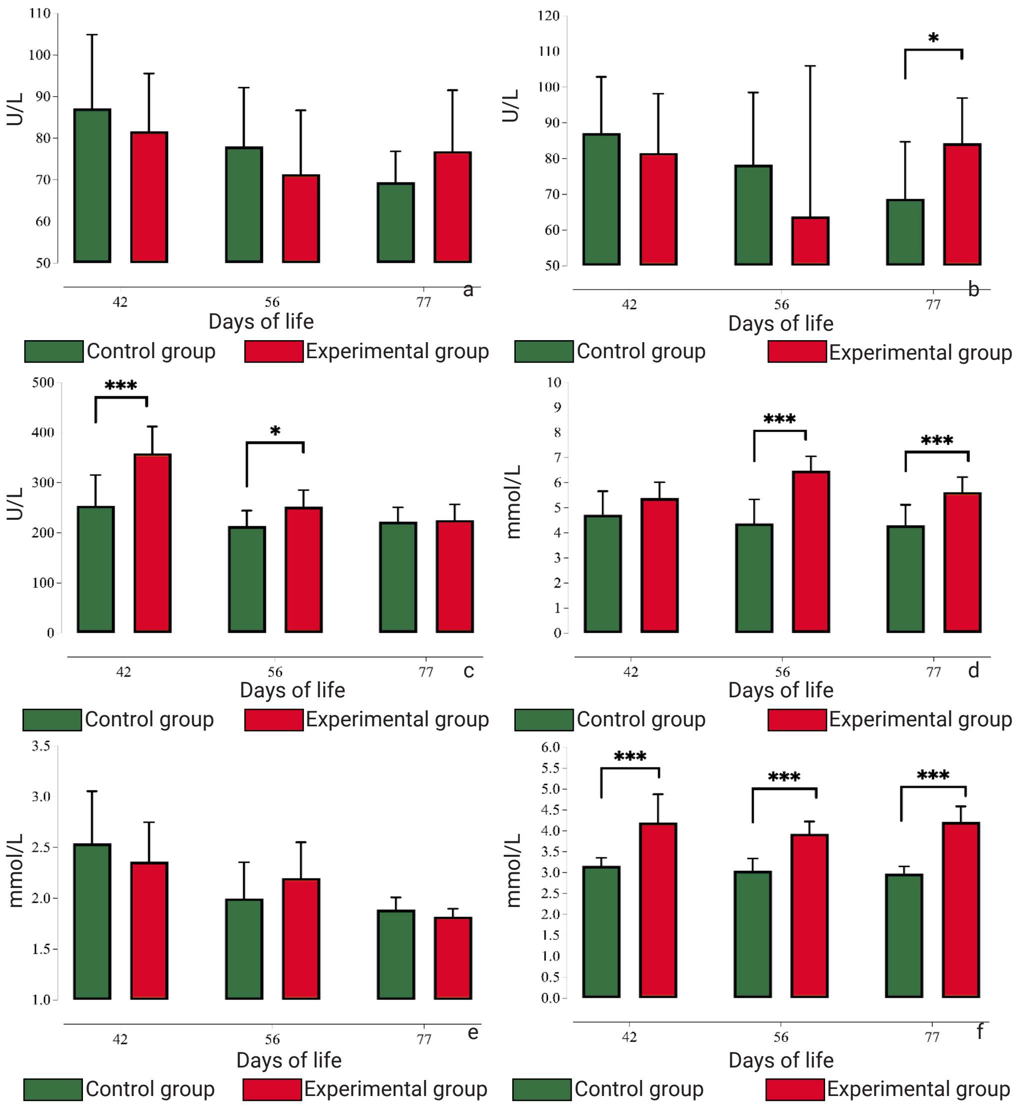

Figure 2. *Biochemical parameters of piglet blood serum under the influence of SCFA-M*

Note: a – ALT activity, U/L; b – AST activity, U/L; c – ALP activity, U/L; d – glucose content, mmol/L; e – calcium content, mmol/L; f – phosphorus content, mmol/L; * – P < 0.05; ** – P < 0.01; *** – P < 0.001 – compared to the control group

Source: developed by the authors

Researchers J.L. Genova *et al.* (2020) used alkaline phosphatase (ALP) to study intestinal disorders such as intestinal dysbiosis. In the current study, no effect of SCFA-M supplementation on ALP activity in the blood serum of piglets was found, which indirectly indicates a normal balance of the microbiome in the digestive tract. This fact is particularly important because ALP is often used as a sensitive biomarker of intestinal mucosal damage; its stable values confirm the absence of pathological changes and allow to conclude that the barrier function of the intestine is preserved even during the stressful post-weaning period. Thus, it can be assumed that SCFA-M creates favourable conditions for maintaining the homeostasis of the intestinal ecosystem. Evaluating the effect of combined monoglyceride supplements on blood metabolites, a promising effect on health, metabolism, and nutrient absorption has been reported. Such effects were observed by P. Nowak *et al.* (2019) through blood analysis, which revealed an increase in the concentration of total protein, albumin, glucose and triglycerides in combination with a low concentration of urea. The results of the current study partially correspond with these data: in the experimental group of piglets receiving SCFA-M, an increase in total protein and glucose in the blood was also observed, indicating an improvement in nitrogen balance and activation of energy metabolism. At the same time, lower albumin levels combined with higher globulin fractions may indicate a shift in metabolism towards strengthening the immune response, which is an adaptive reaction of the body during weaning. Thus, SCFA-M provides a more comprehensive immunometabolic effect than individual classic supplements.

Improvement of intestinal trophic status in pigs, antibacterial activity against various bacteria when monoglycerides are administered Monoglycerides are accompanied by modulation of blood metabolites (e.g., glucose and urea) in weaned piglets. SCFA-M can improve the absorption of minerals such as calcium and phosphorus, which is reflected in an increase in their blood levels. This is important for bone growth and meeting the structural needs of the body. Higher blood phosphorus levels were observed in the experimental group of piglets throughout the experiment ($P < 0.001$).

To assess the relationships between protein, nitrogen, enzyme, and mineral-carbohydrate metabolism circuits, a correlation analysis of blood biochemical parameters was performed in 56-day-old piglets in the control group and under the influence of SCFA-M (Table 1). It was found that in 56-day-old piglets of the control group, there was a close positive correlation between total protein content and albumin content in blood serum ($r = 0.89$; $P < 0.001$) and between the protein coefficient and albumin content ($r = 0.77$; $P < 0.01$), while urea content directly correlated with calcium content ($r = 0.76$; $P < 0.05$) and inversely correlated with the protein coefficient ($r = -0.65$; $P < 0.05$).

Table 1. *Correlation matrix of biochemical blood parameters in 56-day-old piglets exposed to SCFA-M*

Indicators	Total protein	Albumin	Globulin	Urea	Creatinine	AST	ALT	ALP	Glucose	Ca
					Control group					
Albumin	0.89	–	–	–	–	–	–	–	–	–
Globulin	0.55	0.10	–	–	–	–	–	–	–	–
Urea	-0.15	-0.43	0.45	–	–	–	–	–	–	–
Creatinine	0.23	0.16	0.21	0.53	–	–	–	–	–	–
AST	-0.21	-0.37	0.22	0.27	-0.26	–	–	–	–	–
ALT	-0.24	-0.16	-0.22	-0.48	-0.20	-0.22	–	–	–	–
ALP	0.04	0.02	0.05	-0.58	-0.55	0.03	0.56	–	–	–
Glucose	0.49	0.60	-0.04	-0.53	0.05	-0.67	0.25	0.45	–	–
Ca	-0.30	-0.40	0.08	0.76	0.48	0.48	-0.42	-0.41	-0.45	–
P	-0.1	-0.01	-0.21	-0.58	-0.22	0.00	0.60	0.23	-0.13	-0.59

Table 1. *Continued*

Indicators	Total protein	Albumin	Globulin	Urea	Creatinine	AST	ALT	ALP	Glucose	Ca
Experimental group										
Albumin	0.82	–	–	–	–	–	–	–	–	–
Globulin	0.55	-0.03	–	–	–	–	–	–	–	–
Urea	0.47	0.59	-0.04	–	–	–	–	–	–	–
Creatinine	0.27	0.54	-0.33	0.46	–	–	–	–	–	–
AST	0.17	0.03	0.26	0.29	0.33	–	–	–	–	–
ALT	0.05	-0.10	0.23	0.14	0.00	0.66	–	–	–	–
ALP	-0.06	0.32	-0.57	0.35	0.53	0.52	0.35	–	–	–
Glucose	-0.09	0.16	-0.40	0.07	0.01	-0.70	-0.1	-0.17	–	–
Ca	0.24	0.14	0.22	-0.42	-0.28	-0.4	-0.21	-0.35	0.11	–
P	0.38	0.61	-0.23	0.53	0.52	0.33	-0.19	0.45	-0.26	0.01

Note: values are reliable: P < 0.05 – r = 0.63-0.76; P < 0.01 – r = 0.77-0.86; P < 0.001 – r= ≥ 0.87; n = 10
Source: compiled by the authors

A negative correlation between glucose content and AST activity was established (r = –0.67; P < 0.05). Under the action of SCFA-M, a strong correlation between total protein content and albumin was maintained (r = 0.82; P < 0.01), and the negative correlation between glucose and AST remained (r = –0.70; P < 0.05), while the relationships between urea and Ca content and between urea and the protein coefficient, which were characteristic of the control group, became reversed and unreliable (P > 0.05). In addition, the contribution of albumin to the protein coefficient value increased (r = 0.86; P < 0.01), and a positive association of creatinine with this protein coefficient appeared (r = 0.63; P < 0.05). Taken together, this indicates a strengthening of "albumin determinism" of the protein coefficient indicator and a weakening/decoupling of nitrogen-mineral associations, which is consistent with a possible redistribution of nitrogen from catabolism to deposition in tissues and a less pronounced enzymatic load on the liver.

Correlation analysis of blood biochemical parameters in 77-day-old piglets in the control group showed the preservation of "structural" protein bonds (Table 2): the protein coefficient indicator closely correlated with albumin content (r = 0.90, P < 0.001) and inversely with globulin content (r = –0.96, P < 0.001), while albumin and globulin were negatively correlated (r = –0.78, P < 0.01); there was also a positive correlation between the liver enzymes ALT and AST (r = 0.63, P < 0.05) and positive associations between phosphorus content and albumin (r = 0.81, P < 0.01) and protein coefficient (r = 0.71, P < 0.05). At the same time, in the experimental group (SCFA-M), the protein profile shifted towards the globulin fraction: total protein directly correlated with globulin content (r = 0.71, P < 0.05), while maintaining the "structural" links between the protein coefficient and albumins (r = 0.69, P < 0.05) and globulins (r = –0.88, P < 0.001). Additionally, there were significant relationships between alkaline phosphatase activity and total protein (r = 0.67, P < 0.05) and globulin content (r = 0.71, P < 0.05), which may reflect enhanced tissue remodelling/intestinal growth component. The negative correlation between glucose content and AST activity remained (r = –0.68, P < 0.05), while the ALT and AST correlation characteristic of the control disappeared in the experiment (r = 0.09; P > 0.05), as did the relationship between phosphorus and albumin and the protein coefficient. Taken together, this indicates that on day 77, SCFA-M is associated with a predominance of globulin-dependent contribution to total protein and the appearance of ALP associations, while decoupling the phosphate circuit from the protein ratio and weakening the relationship between transaminases; This can be interpreted as signs of a redistribution of protein/mineral metabolism without increasing the hepatocellular load.

Table 2. *Correlation matrix of biochemical blood parameters in 77-day-old piglets exposed to SCFA-M*

Indicators	Total protein	Albumin	Globulin	Urea	Creatinine	AST	ALT	ALP	Glucose	Ca
Control group										
Albumin	0.45	–	–	–	–	–	–	–	–	–
Globulin	0.21	-0.78	–	–	–	–	–	–	–	–
Urea	0.08	-0.14	0.21	–	–	–	–	–	–	–
Creatinine	-0.25	-0.07	-0.10	0.43	–	–	–	–	–	–
AST	0.09	0.2	-0.15	-0.22	-0.45	–	–	–	–	–
ALT	0.46	0.33	-0.04	0.35	-0.03	0.63	–	–	–	–
ALP	0.00	0.15	-0.17	-0.25	0.12	-0.32	-0.21	–	–	–
Glucose	0.04	0.3	-0.30	-0.51	0.09	0.16	-0.14	-0.07	–	–
Ca	0.00	-0.45	0.50	0.03	-0.53	-0.32	-0.48	-0.14	-0.51	–
P	0.40	0.81	-0.60	0.25	0.07	-0.09	0.28	0.29	0.03	-0.34
Experimental group										
Albumin	0.49	–	–	–	–	–	–	–	–	–
Globulin	0.71	-0.26	–	–	–	–	–	–	–	–
Urea	0.31	0.02	0.33	–	–	–	–	–	–	–
Creatinine	0.61	0.15	0.55	0.05	–	–	–	–	–	–
AST	-0.14	-0.09	-0.09	0.28	0.43	–	–	–	–	–
ALT	-0.33	-0.21	-0.19	-0.02	0.00	0.09	–	–	–	–
ALP	0.67	0.04	0.71	0.44	0.37	0.06	0.00	–	–	–
Glucose	-0.03	0.27	-0.25	-0.34	-0.54	-0.68	-0.4	-0.28	–	–
Ca	-0.01	0.14	-0.12	0.40	-0.57	-0.18	-0.27	0.15	0.57	–
P	0.04	-0.29	0.28	-0.04	0.26	0.17	-0.17	0.09	0.25	0.26

Note: values are reliable: $P < 0.05$ – $r = 0.63$-0.76; $P < 0.01$ – $r = 0.77$-0.86; $P < 0.001$ – $r = \geq 0.87$; $n = 10$
Source: compiled by the authors

Thus, the introduction of SCFA-M into the diet of piglets was accompanied by controlled modulation of protein, nitrogen and energy metabolism. In 56-day-old piglets, an increase in the protein fraction due to globulins and a decrease in the protein coefficient were noted against the background of a less pronounced enzymatic load on the liver and signs of lower protein catabolism. Enzyme markers of intestinal pathology did not change, which is consistent with the absence of enteropathies. At the same time, an improvement in energy status and higher mineral supply were observed. Until the end of the study, the trend persisted with a more pronounced "globulin" profile. An increase in AST activity without a synchronous increase in ALT is considered to be extrahepatic adaptation associated with muscle tissue growth rather than liver damage. These effects are consistent with the literature data on the barrier, immunomodulatory and metabolic effects of SCFA/MCFA monoglycerides. A comparison of the results obtained with the data of C. Neath *et al.* (2022) allows to trace both common features and differences. In their *in vitro* study, the authors found that pig pathogens were highly sensitive to certain active ingredients in feed additives, particularly monoglycerides, which determines their potential as an alternative to antibiotics in the fight against pathogens such as *Escherichia coli* and *Clostridium perfringens*. The current *in vivo* study demonstrated a broader spectrum of action of SCFA-M: in addition to the possible antibacterial effect confirmed by stable ALP values, there was an improvement in protein metabolism (increase in total protein and globulins), a decrease in urea levels, activation of the energy circuit (increase in glucose) and optimisation of mineral supply (higher phosphorus levels). This indicates that under physiological conditions, monoglycerides are capable of exerting not only the direct antimicrobial effect noted by C. Neath *et al.* (2022), but also indirect immunomodulatory and metabolic effects. Thus, the results of the current study extend the conclusions of *in vitro* studies, emphasising the practical significance of SCFA-M as a functional feed additive in the post-weaning period.

Additionally, the results of J. Lan *et al.* (2021), obtained on broilers, confirm the immunomodulatory potential of α-glycerol monolaurate, which manifested itself in increased immune function and positive changes in the intestinal microbiota. Despite the difference in the object of study, the similarity of the effects indicates a universal mechanism of action of monoglycerides associated with the modulation of the immune response and maintenance of intestinal homeostasis. In the current experiment, similar effects were observed through an increase in the globulin fraction in the protein profile of piglets and a stable association between protein metabolism and enzyme markers. This suggests that SCFA-M may combine the properties described in both pig and bird studies, providing a multi-component effect on metabolic and immune status.

Analysing the results in the context of the review by D.H. Nguyen *et al.* (2020), it should be noted that these authors emphasised the multifaceted effect of organic acids and monoglycerides, which simultaneously act as antimicrobial agents, regulators of the intestinal environment and modifiers of metabolism. Such additives have been shown to maintain the stability of the microbiota, improve the digestibility of nutrients, and increase energy efficiency. In the current study, these conclusions are confirmed by practical results: the stability of enzyme markers, increased glucose, and improved mineral absorption are consistent with the concept of the systemic action of SCFA/MCFA. Thus, the data from D.H. Nguyen *et al.* (2020) provide a theoretical basis for explaining the mechanisms that have been confirmed experimentally.

There are no publicly available studies on the effect of SCFA-M supplementation on protein profile, nitrogenous metabolites, enzymes, and mineral-carbohydrate balance in piglets. Most similar studies focus on productivity, intestinal morphology, immunomarkers, and selective serum indicators, which allows to reasonably position this study as unique in terms of the range of indicators. A summary of the data obtained shows that a significant increase in total protein and globulins in the blood serum of piglets receiving SCFA-M was accompanied by a decrease in the protein coefficient and urea concentration. This dynamic indicates a reorientation of protein metabolism towards activation of the immune response and a decrease in the intensity of protein catabolism, which is consistent with the ideas of Y. Saco & A. Bassols (2023) about the role of protein fractions in the formation of immune reactivity. Thus, the results confirm the immunomodulatory effect of SCFA-M and emphasise its difference from mixtures with tributyrin, for which an increase in urea levels has been described in the literature, which may indicate other mechanisms of action and a different direction of nitrogen metabolism.

At the midpoint of the study, a decrease in ALT and AST activity was observed in the SCFA-M group, corresponding to a decrease in hepatocellular load (Egeli *et al.*, 1998). Similar effects with normalisation of liver biochemical markers and restoration of intestinal barrier function are described by Q. Zhang *et al.* (2022) when using monolaurin in PEDV-infected piglets. At the final stage of the experiment, an increase in AST was recorded without a parallel increase in ALT, which is interpreted as extrahepatic adaptation associated with muscle mass growth, similar to the reports in the works of C.S. White *et al.* (2024) on the maintenance of intestinal integrity and immune responses. At the same time, glucose concentration in the SCFA-M group increased significantly, indicating activation of energy metabolism; this is consistent with reviews of the functional properties of medium-chain fatty acid monoglycerides. The absence of significant differences in ALP levels indicates the absence of enteropathies, which is consistent with the findings of J.L. Genova *et al.* (2020), where ALP is used as an indicator of intestinal disorders.

Throughout the experiment, significantly higher levels of inorganic phosphorus were found in the blood of piglets receiving SCFA-M, while calcium levels changed less markedly. Given the impact of water quality on homeostasis (Ahmadi *et al.*, 2024), it is advisable to interpret changes in glucose and mineral profile indicators taking this potential confounder into account. This dynamic is consistent with the mechanistic models of bone tissue growth and mineral requirements in pigs proposed by M. Lautrou *et al.* (2020), which emphasise the key role of the optimal phosphorus-calcium ratio for mineralisation processes. An increase in phosphorus levels against the background of SCFA-M feeding may indicate its more efficient absorption and a potentially positive effect on bone tissue formation.

Thus, the results of the experiment show that SCFA-M is an effective tool for supporting metabolic processes, including mineral metabolism, and is of direct importance for the growth and structural development of young animals. The identified changes in the protein profile, decreased protein catabolism, and improved energy and phosphorus supply reflect the multifactorial effect of the supplement on the physiological state of animals. The data obtained are consistent with literature reports on the role of monoglycerides in maintaining homeostasis, but at the same time expand on them through comprehensive biochemical analysis, creating a scientific basis for the introduction of SCFA-M into antibiotic-free pig farming technologies.

Conclusions

The use of SCFA-M in piglet diets has a positive effect on protein metabolism, as evidenced by an increase in total protein and globulin levels in the blood, as well as a decrease in the protein coefficient, indicating an improvement in the balance between protein synthesis and immune response. In particular, the administration of SCFA-M in the 42-77-day period was accompanied by an increase in total protein content by 9.1% ($P < 0.05$) and globulins by 31.8% ($P < 0.001$) on day 56 with a decrease in the protein coefficient by 16.5% ($P < 0.001$), a decrease in urea content by 16.5% ($P < 0.05$) and urea nitrogen by 20%, an increase in glucose by 47.9% ($P < 0.001$), an increase in calcium content by 10% and phosphorus by 28.9% ($P < 0.001$), as well as a decrease in ALT activity by 8.5% and AST by 18.5% in the blood serum of animals. On day 77, the effects persisted with a "globulin" profile: total protein was 7.3% higher ($P < 0.01$), globulin content was 27.9% higher ($P < 0.001$), albumin was 7.3% lower ($P < 0.05$), urea was 33.6% lower ($P < 0.01$), glucose was 30.4% higher ($P < 0.05$), while AST activity increased by 22.5% ($P < 0.05$) without a parallel increase in ALT.

Correlation analysis confirmed the strengthening of "albumin determinism" of the protein coefficient indicator on day 56 ($r = 0.86$; $P < 0.01$) and the predominance of globulin contribution to total protein on day 77 of the piglet's life ($r = 0.71$; $P < 0.05$) with a stable negative association of glucose with AST activity at both points ($P < 0.05$), which in general indicates a redistribution of protein and nitrogen metabolism towards a decrease in catabolism and maintenance of energy and mineral status without signs of increased hepatocellular load. The activation of energy metabolism is manifested by an increase in glucose levels, which provides animals with the additional energy necessary for growth. SCFA-M contributes to the improvement of mineral absorption, in particular calcium and phosphorus, which has a positive effect on bone tissue growth and the overall development of piglets. The established effect of

SCFA-M on metabolic parameters confirms their effectiveness as a functional feed additive aimed at improving animal productivity and health. Further research should focus on studying the long-term effects of SCFA-M, their combination with other functional additives, as well as the mechanisms of immune response and digestive tract microbiome regulation.

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Conflict of Interest

None.

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Особливості метаболізму поросят за умов застосування моногліцеридів

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Анотація. Оптимізація метаболізму поросят у ранньому постнатальному періоді є важливим завданням сучасного тваринництва. Використання функціональних добавок, таких як SCFA-M, здатне позитивно впливати на білковий та енергетичний обмін, сприяти зниженню стресу, поліпшенню продуктивності та здоров'я поросят. Мета дослідження полягала у визначенні впливу SCFA-M на білковий і енергетичний метаболізм та загальний фізіологічний стан тварин на етапі раннього вирощування. Дослідження проводили на поросятах віком 42 дні, розподілених на контрольну та дослідну групи; тварини дослідної групи отримували SCFA-M у складі раціону. Оцінювання здійснювали біохімічними методами аналізу крові з визначенням рівнів основних метаболітів і активності ключових ензимів; статистичну обробку виконували з перевіркою нормальності розподілу та відповідними параметричними/непараметричними критеріями. Застосування SCFA-M достовірно модулювало білковий обмін: загальний білок зріс на 9,1 % ($P > 0,05$), глобуліни – на 31,8 % ($P > 0,001$), тоді як білковий коефіцієнт знизився на 16,5 % ($P > 0,001$). Активність амінотрансфераз була нижчою, що свідчить про менше навантаження на печінку. Рівні сечовини та азоту сечовини у крові зменшилися на 16,5 % і 20 % відповідно, вказуючи на ефективніше використання азоту. Вуглеводний і мінеральний обміни також покращилися: глюкоза підвищилася до 6,48 ммоль/л (+47,9 %; $P > 0,001$), засвоєння кальцію – на 10 %, фосфору – на 28,9 % ($P > 0,001$). Отримані результати розширюють уявлення про механізми дії моногліцеридів і підтверджують доцільність їх використання у практиці свинарства; водночас потребують подальших досліджень із тривалішим моніторингом, оцінкою продуктивності та показників інтестинального гомеостазу. Практична значущість полягає у можливості використання SCFA-M як елемента програм підтримки поросят у поствідлучний період, з потенційним зменшенням потреби в антибактеріальних препаратах та покращенням благополуччя

Ключові слова: SCFA-M; білковий обмін; ферменти; енергетичний обмін; мінеральний обмін

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