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CONTENT

SECTION: ACCOUNTING AND TAXATION

Яценко Н.М., Попадюк О.О., Попович Я.М.
СУЧАСНІ ТЕХНОЛОГІЇ В БУХГАЛТЕРСЬКОМУ ОБЛІКУ ТУРИСТИЧНИХ ПІДПРИЄМСТВ…… 20

Брайко В.
РОЛЬ ЗОВНІШНЬОГО АУДИТУ В ЗАБЕЗПЕЧЕННІ ЕФЕКТИВНОСТІ КОРПОРАТИВНОГО УПРАВЛІННЯ……... 23

SECTION: AGRICULTURAL SCIENCES

Бойко О.Г.
РІСТ І РОЗВИТОК РОСЛИН ГОРОХУ ЗАЛЕЖНО ВІД АГРОТЕХНІЧНИХ ЗАХОДІВ…… 25

Sydiakina O., Ivaniv M.
PHOSPHORUS NUTRITION: GLOBAL TRENDS, CHALLENGES FOR UKRAINE, AND INNOVATIVE SOLUTIONS…….. 27

Polovyy V., Rovna H., Yashchenko L.
SOURCES OF CO2 EMISSION AND ITS SEQUESTRATION IN MAIZE AND SOYBEAN ON LOAMY SAND RETISOL…….. 32

SECTION: ARCHITECTURE AND CONSTRUCTION

Chudyk I., Dobryanskyy I., Dobryanska L.
MODERN METHODS OF ANTI-CORROSION PROTECTION OF METAL STRUCTURES…… 36

Білов Ю.О., Анін В.І.
НАДІЙНІСТЬ ОРГАНІЗАЦІЙНО-ТЕХНОЛОГІЧНИХ КЕРУЮЧИХ СИСТЕМ БУДІВНИЦТВА…….. 39

Бабенцова О.С., Вербовецька В.В., Курілович К.В., Сліпченко В.Р.
ЗНАЧЕННЯ ТА РОЛЬ МУЗЕЇВ У СУЧАСНОМУ СУСПІЛЬСТВІ….. 43

SECTION: ART HISTORY AND LITERATURE

Шевцова І., Бонь Ю., Чепелюк К.
КОНЦЕПТУАЛЬНА СЕМАНТИКА НАЦІОНАЛЬНОГО ТРАДИЦІЙНОГО ХОРЕОГРАФІЧНОГО МИСТЕЦТВА ЗАКАРПАТТЯ…….. 46

факторами, які вивчалися, призвело до зростання висоти рослин гороху.

Висновки. 1. У період досліджень – 2024 році, у фазі повних сходів ми отримали густоту рослин 116-121 шт/м^2, яка неістотно різнилася за варіантами досліду. Польова схожість на ділянках контрольного варіанту у 2024 році була у межах 90 % у сорту Отаман та 91,5 % у сорту Меценат. На варіантах, де застосовували мінеральні добрива польова схожість була дещо вища, і становила відповідно по сортах 91,3 та 92,8%.

2. Найбільша висота рослин у фазу фізіологічної стиглості за період досліджень у 2024 році була відмічена у варіантах де вносили в основне удобрення фосфорно-калійні добрива ($P_{70}K_{70}$), у передпосівну культивацію середні дози азотних добрив (N_{40}) у сорту Отаман – 100,4 см та у сорту Меценат – 105,9 см, що відповідно на 12,6 см та 14,8 см більше у порівнянні з варіантом, де мінеральні добрива не вносили.

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PHOSPHORUS NUTRITION: GLOBAL TRENDS, CHALLENGES FOR UKRAINE, AND INNOVATIVE SOLUTIONS

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Phosphorus is one of the essential macronutrients required for the proper growth and development of plants. It plays a crucial role in energy exchange processes, the synthesis of nucleic acids, root system formation, and the maturation of fruits and seeds. Adequate phosphorus supply to plants contributes to increased yields, improved product quality, and enhanced resilience of crops to adverse environmental conditions [1].

Phosphorus fertilizers are the primary source of this element for agricultural lands. As the natural content of available phosphorus in soils gradually depletes due to its

removal with harvests and processes that convert it into unavailable forms, it is essential to restore the phosphorus balance regularly. Optimal use of phosphorus fertilizers helps maintain soil fertility, ensures stable development of agroecosystems, and increases the efficiency of using other nutrients.

Rational application of phosphorus fertilizers requires consideration of many factors, including soil type, phosphorus availability levels, characteristics of the cultivated crop, and applied agronomic technologies. Modern fertilizers with a high phosphorus uptake coefficient and the application of precision agriculture methods help improve the effectiveness of phosphorus nutrition and reduce negative impacts on the environment [2, 3].

Global use of phosphorus fertilizers increased from 2000 to 2020, reaching its peak 2020 at 47.753 million tons. Since 2020, there has been a trend toward a decrease: in 2022, it was 41.855 million tons. The majority of phosphorus fertilizers are used in countries in Asia and America, as demonstrated in Fig. 1.

In Ukraine, the use of phosphorus fertilizers from 2000 to 2004 was relatively low, ranging from 33 to 85 thousand tons. From 2005 to 2010, there was a significant increase, particularly in 2006 and 2007, with 128.8 and 168.8 thousand tons respectively. From 2011 to 2015, usage stabilized between 195 and 240 thousand tons. The years 2016 to 2020 marked a record growth in the use of phosphorus fertilizers, peaking in 2020 at 432.7 thousand tons. The year 2022 showed a reduction to 323.9 thousand tons, which is associated with active military actions on the territory of our country and a decrease in agricultural activity.

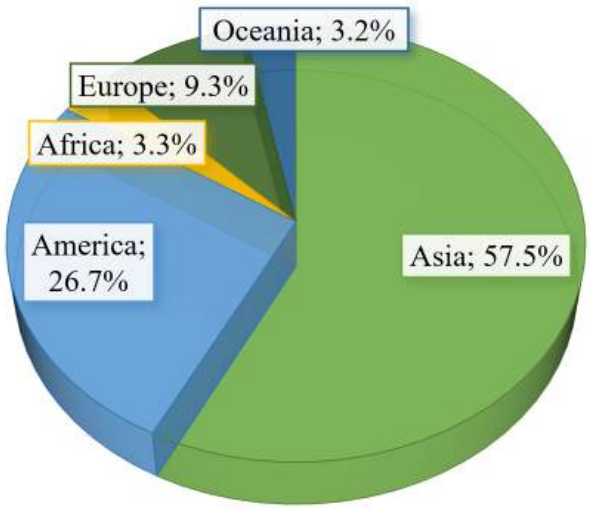

Figure 1. Share of regions in global agricultural use of phosphorus fertilizers (average for 2020–2022), %. Source: compiled by the author based on [4]

However, a more informative indicator that reveals the essence of the studied issue is not the total volumes of phosphorus fertilizer usage but their applied quantity per hectare of arable land (Fig. 2). The highest values of this indicator are demonstrated by the Asian region (40.96 kg/ha), which can be attributed to several factors, among which the main ones include the high intensity of agricultural production, especially in countries such as China and India; significant dependence of the farming sector on

fertilizers to ensure food security; and government support programs for farmers, including subsidies for mineral fertilizers [5].

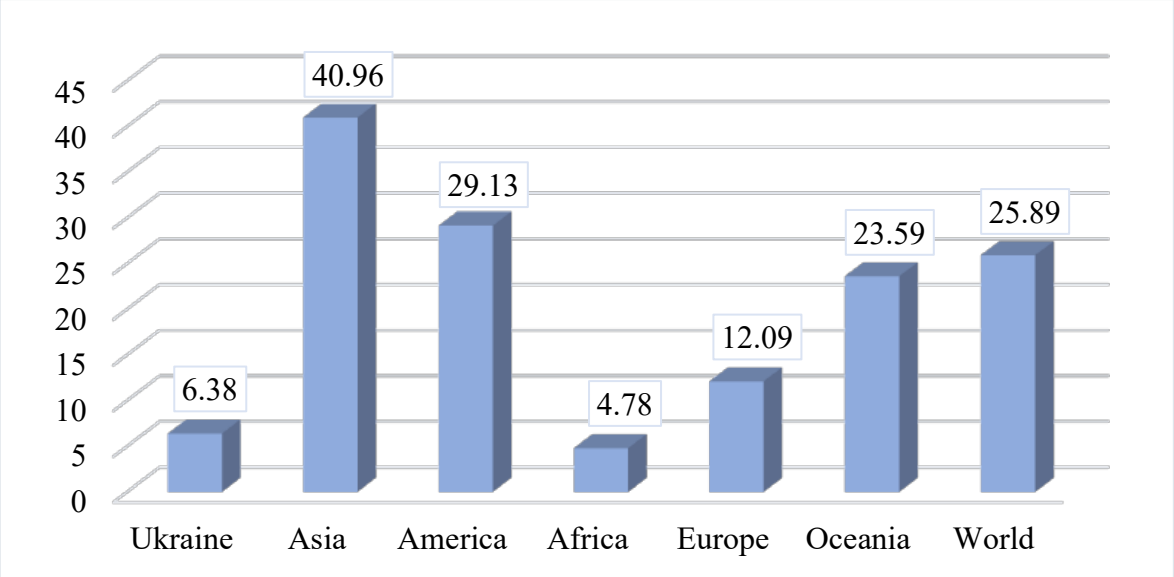

Figure 2. Use of phosphorus fertilizers per arable land area (average for 2000–2022), kg/ha
Source: compiled by the author based on [4]

The American continent ranks second after Asia regarding phosphorus fertilizer application per hectare of arable land (29.13 kg/ha). In the USA, Brazil, and Argentina, advanced plant nutrition technologies are actively implemented, with optimal calculated fertilizer rates based on the planned yield level, actual nutrient content in the soil, and their removal from the harvested crops. One of the reasons for this is the intensive cultivation of crops such as corn and soybeans, which have significant phosphorus removal [6].

European countries apply phosphorus fertilizers in moderate amounts (12.09 kg/ha), which is associated with a high level of soil phosphorus availability, strategies for ecological farming, and regulations on fertilizer use by EU directives, as well as broader use of organic fertilizers as an alternative to mineral ones [7].

The high level of phosphorus fertilizer application in Oceania (23.59 kg/ha) is explained by the use of intensive agricultural technology, low natural phosphorus content in Australian soils, and the need to replenish it, as well as the use of advanced agrotechnologies to maintain soil fertility [8].

The African continent is characterized by the lowest volumes of phosphorus fertilizer application among all world regions (4.78 kg/ha). The main reasons are the limited availability of mineral fertilizers due to their high cost, the dominance of small farms using traditional farming methods, and the presence of low-fertility soils, further exacerbating nutrient deficiency [9].

The global level of phosphorus fertilizer use (25.89 kg/ha) indicates that many agricultural regions apply moderate amounts of phosphorus fertilizers. However, regional disparities demonstrate that in some countries, there is either excessive or insufficient use of these fertilizers, which affects soil conditions and overall agricultural production efficiency.

The average level of phosphorus fertilizer application in Ukraine is one of the lowest in the world (6.38 kg/ha). This is explained by the limited financial capabilities

of farmers to purchase phosphorus fertilizers and the increase in the use of organic fertilizers due to the rapid development of the organic market in our country [10].

Another important reason is the use of traditional fertilization approaches. In Ukraine, many agricultural enterprises, especially small and medium-sized farms, continue to use traditional methods of fertilizing the crops they grow. This is related to historical practices, economic factors, a lack of knowledge about innovative approaches, and insufficient access to modern technologies. Fertilizers are often applied according to standard norms without considering the actual condition of the soils and the needs of the crops being grown. There is a widespread practice of applying predominantly nitrogen fertilizers, while the balance of phosphorus and potassium is often ignored [11].

In many regions of Ukraine, soil acidification is observed, which leads to a decrease in the effectiveness of the applied fertilizers. Liming is generally not applied or is carried out at insufficient rates, which contributes to soil depletion. Fertilizers are applied uniformly across the entire area without accounting for soil heterogeneity. The absence of agrochemical soil analysis significantly reduces the effectiveness of fertilization [12].

Due to irrational fertilization, the yield and quality of agricultural products may be lower than in farms that use modern technologies. Modern agrochemical analysis methods allow for precise nutrient content determination in the soil and adjustment of fertilizer application rates, which will help optimize nutrient balance and improve soil fertility. Promising innovations include differentiated fertilizer applications based on soil mapping and GPS and drone technologies to monitor crop conditions [13, 14].

Thus, Ukraine is characterized by low levels of phosphorus fertilizer use, which creates risks of reduced yields due to soil depletion. Rational management of phosphorus nutrition is critically important for the sustainable development of agriculture, especially in regions with low fertilizer application rates. At the same time, traditional fertilization methods still used in many Ukrainian farms have several significant drawbacks that negatively affect agricultural production efficiency and soil conditions. Implementing innovative technologies will enhance the productivity of the farm sector, reduce environmental risks, and make the agrarian Ukrainian industry more competitive.

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