

Agricultural waste valorization in the circular economy using sunflower husk ash as a secondary resource

Andrii Dankevych¹ · Vitalii Nitsenko² · Vitalii Dankevych³ · Edeh Friday Ogbu⁴ · Aistė Lastauskaitė⁵ · Iryna Kapelista⁶

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Abstract

The valorization of agricultural waste within the circular economy provides an opportunity to reduce waste disposal and return valuable mineral resources to agricultural production. Sunflower processing generates substantial amounts of husk, and the accumulation of ash from its industrial utilization represents an important waste-management challenge. In Ukraine alone, more than 100 thousand tonnes of such ash are generated annually. Instead of being disposed of, sunflower husk ash (SHA), a by-product of sunflower processing, can be used as a secondary mineral resource for fertilizer production. Such an approach to waste management can contribute to the formation of added value, increased agricultural production, and the implementation of environmental initiatives. This study aimed to assess the feasibility of using sunflower husk ash-based fertilizer in agriculture and to evaluate its effects on crop yield, soil agrochemical properties, and selected quality parameters of agricultural products. Field experiments were conducted during one growing season at the Slobzhanske Experimental Field of the National Scientific Center “O.N. Sokolovsky Institute for Soil Science and Agrochemistry Research”, Ukraine, on a typical heavy loam chernozem. Seven crops were evaluated under field conditions: barley (*Hordeum vulgare*), maize (*Zea mays*), sunflower (*Helianthus annuus*), potato (*Solanum tuberosum*), tomato (*Solanum lycopersicum*), table beet (*Beta vulgaris*), and cucumber (*Cucumis sativus*). The experimental treatments included without fertilizers (control), conventional NPK 16:16:16 fertilizer, and SHA-based fertilizer applied at rates of 200 and 300 kg/ha using basal application and application during pre-sowing cultivation. The size of the plot for each crop was 0.1 ha. Crop yield, soil agrochemical properties, and selected quality parameters of agricultural products were evaluated. The obtained data were processed using descriptive and comparative statistical methods, including calculation of arithmetic means and absolute and relative differences. The application of SHA-based fertilizer was associated with an increase in crop yield of approximately 10–18% compared with without fertilizers (control). The content of mobile phosphorus and exchangeable potassium in the soil increased by approximately 10–22%, while soil pH changed by approximately 0.3–0.5 units. An increase in selected quality parameters of agricultural products, including dry matter, protein, and fat content, was also observed. The SHA-based fertilizer contained 30% K₂O, 5% P₂O₅, 9% CaO, 10% MgO, and 4% S and did not contain chlorine. The results were obtained during one growing season at a single experimental site and therefore reflect the specific soil, climatic, and experimental conditions of the study. The results should therefore be interpreted descriptively rather than as statistically significant effects.

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Further studies in different natural and climatic zones and on soils with different properties are required. The results provide initial field evidence that SHA-based fertilizer can serve as a secondary mineral resource for agricultural production within a circular economy approach. Its use may contribute to the valorization of sunflower processing residues, reduction of waste disposal, and return of mineral nutrients to agricultural soils. Further field research is required to assess the consistency and broader applicability of the observed effects under different soil and climatic conditions.

Keywords Biomass · Agricultural waste valorization · Circular economy · Secondary mineral resources · Bioeconomy · Sustainability of agricultural resources

1 Introduction

Ukraine accounts for about 30% of the world's sunflower production. Approximately one-fifth of the weight of sunflower seeds is the husk. Ash after burning the husk biomass (about 30–35 thousand tons annually) is usually buried in a landfill, which is harmful to the environment. Numerous studies by scientists indicate that ash contains valuable nutrients, particularly macroelements Ca, K, P, and S, as well as microelements Zn, Cu, and Mn [1, 3, 24]. Several scientists are investigating possibility of using them as fertilizers [31] (Zgureva-Filipova et al. 2025). In particular, the emphasis is on their deoxidizing effect and the ability to improve the physicochemical properties of light soils [17, 40, 25] (Rukhani et al. 2024).

In times of change and instability, rising fertiliser prices are putting additional pressure on agricultural production and national economies. According to the World Bank, global fertiliser prices rose by more than 100 per cent in 2021 and by a further 55 per cent in 2022. Following a period of falling prices in 2023–2024, fertiliser prices rose again by approximately 18 per cent in 2025. In the first quarter of 2026, the global fertiliser price index rose by more than 12 per cent, reaching its highest level since 2022, whilst the World Bank forecasts a further increase of over 30 per cent in 2026 [64]. Under these circumstances, the rational recycling of waste could become an alternative source of mineral resources and support national economies through the use of local raw materials. Returning valuable mineral components extracted from agricultural waste to agricultural production could reduce the volume of waste disposal, improve resource efficiency and contribute to greater sustainability of agricultural systems.

The study provides essential information for farmers who grow organically pure products. Ash fertilizers can help reduce the yield gap between organic and conventional agriculture. It will give the farmers alternative resources to improve production efficiency. The specifics of ash have not been sufficiently studied. Thus, scientists must offer theoretical and technological justification for implementing new technologies aimed at the rational, environmentally safe use of ash. Conducting additional assessment of the impact of ash on crop rotation productivity, product quality, and soil fertility, and remediation of war-damaged lands.

Based on the above data, there is a need for theoretical justification and practical application of organic fertilizers from sunflower husk ash. Since the cost of mineral fertilizers accounts for 25% of the cost structure for the production of crop products, a gradual transition to the proposed fertilizers is advisable from the point of view of financial costs, environmental friendliness, and import substitution of part of mineral fertilizers that are not produced in Ukraine. The proposed approach will allow academic circles and farmers to take a broader view of the utilization of sunflower husks and the use of ash as an organic fertilizer. Considering the natural and climatic features of agriculture and the share of sunflower in the structure of sown areas, the impact of the proposed organic fertilizer on the qualitative and quantitative indicators of crop yield requires additional empirical research.

The study aimed to reveal the eco-innovative potential of sunflower husk ash as a mineral fertilizer. To investigate its composition and potential as a mineral fertilizer and to assess its effects during one growing season on crop yield, product quality, and agrochemical soil parameters. It will allow the implementation of Sustainable Development Goal 12—“Responsible Consumption and Production”, which will contribute to developing a

policy to reduce waste through measures to prevent its formation, reduce, recycle, and reuse. It is an alternative to a simple, inexpensive, accessible solution to the complex problem of waste disposal; improving the state of the environment and creating new added value from the point of implementing sustainable development goals.

According to the aim, the following tasks were set regarding the effectiveness of the eco-innovative potential of sunflower husks, namely:

- 1) to investigate the potential of the raw material base sufficient for the production of fertilizers;
- 2) to determine the indicators of the physicochemical composition of sunflower husk ash
- 3) to analyze the impact of ash on the yield of crops;
- 4) to assess the impact of ash on the quality indicators of finished products;
- 5) to investigate the impact of ash on increasing soil fertility and improving its agrochemical indicators.

2 Literature review

Economic growth has led to negative consequences for society and the environment. Environmental responsibility has become a key issue worldwide [6, 18, 54, 56, 60]. The transition to sustainable development and a zero-waste economy can be achieved through eco-innovations [15, 69] that support these two trends, despite the current economic, social, and environmental consequences [33, 59]. The scientific community recognizes that waste has considerable potential to contribute to the achievement of sustainable development goals, which we must explore and unlock for future generations [4, 10, 19, 26, 32, 55].

Most researchers use the terms “environmental”, “nature conservation” and “eco-innovation” as synonyms [12, 13, 34]. According to James [21]—are new products that generate income for consumers and businesses, significantly reducing the impact on the environment. Eco-innovation is the process of implementing environmental initiatives to create products with new added value and the possibility of reuse and recycling. More and more companies are switching to alternative methods of waste processing instead of waste disposal in landfills [38].

Everything saved is considered to be earned. Thus, researchers must view large-scale anthropogenic waste not as trash but as man-made minerals. It requires the development of new waste management policies and the discovery of their ecological and innovative potential. The circular economy is no longer a trend but the new norm. A rapidly changing world expects scientists to innovate, digitize, and collaborate across sectors. At the same time, little practical research is currently devoted to the demand for secondary raw materials, the interest in which is growing rapidly. Supply chain transparency is becoming critical for market players. Utilizing internal reserves, in particular, uncovering the potential of waste and its practical application, is critically important in the new environment, and there should be more such research today.

The foundation of new research should be creating innovative systems based on sustainable development and the Sustainability of Agricultural Resources [44, 48, 61, 68]. Scientists, politicians, and big business should now focus on exploring the untapped eco-innovation potential of waste that is currently unexplored. Implementing these policies will increase not only the country’s economic competitiveness, but also the well-being and quality of life of people [32].

In the conditions of military operations, biomass has become the fastest growing renewable energy sector in Ukraine. Studies show that when burning sunflower husks, the amount of carbon dioxide emissions is equal to the emissions formed during the natural decomposition of wood. At the same time, the ash yield does not exceed 3% or 30 kg from 1 ton of sunflower husks [8].

Recent studies have shown that biomass ash can affect not only soil properties but also crop yields and product quality. Shahare et al. [51] reported the effect of biomass ash on sunflower yield, oil content, and protein content, while Gupta et al. [17] demonstrated an increase in rice yield without adverse changes in the concentrations of inorganic arsenic and cadmium in the grain. These results indicate that the effect of biomass ash depends on its

composition, application rate, soil properties, and crop type, underscoring the need for further evaluation of specific types of ash, such as sunflower hull ash.

Studies on the chemical properties of ash have been carried out [23, 30, 63]. At the same time, few studies have been done on using ash in modern technological agricultural production as a fertilizer.

Zgureva-Filipova et al. (2025) demonstrated the potential of sunflower husk ash for fertiliser production. The resulting biofertiliser contained approximately 30% K_2O , confirming that sunflower husk ash can serve as a source of nutrients for plants and contribute to the return of mineral resources to agricultural production. These results once again demonstrate the potential of sunflower husk ash within the framework of circular nutrient management and the utilisation of agricultural waste. Rukhani et al. (2024) showed that ash from agricultural biomass contains mineral nutrients, particularly K, Ca, Mg and P, which may contribute to its potential use in agricultural applications. However, its agronomic effect depends on the composition of the ash, the origin of the biomass, soil properties and the application rate. These findings confirm the feasibility of using agricultural biomass ash as a secondary source of nutrients in crop production.

Regarding the availability of ash constituents to plants, our research confirmed that the major elements are 80% assimilated in the first year, with the exception of phosphorus, which has an availability of 20%. However, [29] found high phosphorus availability and low cadmium availability to plants across four types of biomass ash, indicating both the material's value as a nutrient source and the low mobility of cadmium. Li et al. [30] demonstrated that potassium availability from biomass ash depends on soil pH and clay content, thereby confirming the influence of soil properties on nutrient availability. Isemin et al. [20] showed that torrefaction can promote slag formation, which may reduce the availability of micronutrients in sunflower husk ash for plant uptake.

Ash has been considered a tool for reducing the impact of radioactive contamination of territories. The basis of the ash (30%) is potassium; it is a chemical analogue of ^{137}Cs and, therefore, can compete with cesium, getting into plants [10, 36, 46, 52]). At the same time, no specific countermeasures and soil restoration programs using it have been developed.

Zajac et al. [66] found that the concentration of heavy metals in biomass ash depends on the type of biomass and the combustion temperature. In their study, which examined ash from sunflower husks, Cr, Cu, Ni, Pb, Zn and other elements were detected, confirming the need for chemical analysis and control of application rates before using the ash as a fertiliser. Consequently, assessing the environmental safety of biomass ash is an important consideration for its use in agriculture.

Ash is a natural alkaline mineral fertilizer that differs favorably from chemical fertilizers in the absence of chlorine compounds harmful to crops such as potatoes, tomatoes, cucumbers, cabbage, currants, strawberries, grapes, citrus fruits, flax, legumes, and some others. Ash as a fertilizer contains potassium in the form of a potassium (pearl) compound (K_2CO_3) that is readily soluble in water and available to plants. The high calcium carbonate content in ash allows it to reduce soil acidity (Zhai et al. 2019) [63, 67].

A retrospective review of the literature indicates a lack of information on the effectiveness of ash use by farmers on an industrial scale. The primary issues are: availability of sunflower husk ash for plants and its impact on the soil; assessment of its impact on product quality; improvement of stress resistance of agricultural crops; practical recommendations on application norms and technological maps of the use of these fertilizers in growing crops. The importance of ash in reducing soil acidification and reducing the productivity gap between organic and conventional agriculture.

Moreover, using ash as a fertilizer opens up additional opportunities for implementing sustainable development in other areas, including bioenergy, growing environmentally friendly food products, and land reclamation. These issues are insufficiently covered in the literature and practice and require additional research.

3 Materials and methods

The source data on the production of basic products were received from the State Statistics Service of Ukraine (Ukrstat.org) and based on the website of OECD/FAO, “OECD-FAO Agricultural Outlook”, OECD Agriculture statistics (database).

We calculated the forecast of sunflower seed production volumes. To demonstrate the possibilities of the eco-innovation potential of sunflower husk ash.

A basic model of the Box-Jenkins time series was used to predict the balance of sunflower production in Ukraine. This model is widely used in Economics to predict the results of future periods using data sets from the past to present. The advantage of the model is that it implements an autoregressive approach using the so-called “moving average”, which allows us to describe both stationary and non-stationary sets (linear vectors) of statistics. In the scientific literature, such a model is also called an ARMA (p, q)—model (autoregressive moving-average model)—it is a model of statistical analysis that uses time series data either to understand a set of data better or to predict future trends [5].

ARMA (p, q) model in the analytical form can be represented as:

$$y_t = \sum_{i=1}^p a_i y_{t-i} + \sum_{i=1}^q b_q \epsilon_{q-i} \quad (1)$$

Where y_t is the predicted parameter for the period t (years), which corresponds to the indexation of a natural number with the index $i = 1, 2, 3 \dots p$; ϵ_{q-i} is a component that depends on q harmonics of influences; a_i and b_q are the coefficients of AR and MA parts.

According to the presented scientific research needs, the main task is to develop the strategic forecast until 2025. Therefore, the traditional ARMA(p, q) model must be modified to form relevant estimates.

The modification aimed to level the influence of high-amplitude harmonics of random oscillations in these time series of past periods. The random fluctuations of high-amplitude harmonics for long-term forecasts form a certain initial deviation from the relevant estimates, the effect of which increases with each subsequent period, which may lead to larger deviations for remote values (large values of indices i).

Therefore, the algorithm is the following. Using the autoregressive approach and the moving average, a polynomial equation is formed for each data set (vector). Then, there is the analysis of the amplitudes of random harmonics. In the aggregate of amplitudes, irregular high-amplitude components whose values are higher than a specific, expertly established threshold value are distinguished by the comparison method. The next step of the algorithm is to reapply the traditional ARMA(p, q) algorithm to the specified, but already modified, data sets (vectors).

The main parameters used were sown area, gross harvest, and yield, and the economic indicators are the price of grain and the profitability. During the growing season, there are changes in the size of sown areas, which are primarily associated with crop losses due to changes in weather and climatic conditions.

For the convenience of further research, forecasting, analysis, and comparison of trends, linear vectors were presented in the analytical form. The polynomial approximation method was used for the data representation. It allowed to form polynomial equations of the first stage of application of ARMA(p, q)—algorithm, namely: to predict the area of sunflower crops, million hectares (Eq. 1), gross production of sunflower seeds, million tons (Eq. 2) and the yield of this crops, $t \text{ ha}^{-1}$ (Eq. 3).

Thus:

$$y = -0,116x^3 + 0,8x^2 + 0,616x + 14,01 \quad (2)$$

$$y = 0,15x^3 - 1,25x^2 + 3,6x + 3.5 \quad (3)$$

$$y = -0,05x^3 + 0,4x^2 - 0,85x + 3.1 \quad (4)$$

Where y is the value of the named forecast factor in the units mentioned above, x and is the corresponding period according to its index $i = 1, 2, 3 \dots p$.

Equations (2), (3), and (4) obtained in the first stage of using the algorithm were modified to linear equations in the next stage, respectively:

1. For the area under sunflowers, million hectares:

$$y = 2,19x + 13,15 \quad (5)$$

2. For the gross production of sunflower seeds, million tons:

$$y = 0,47x + 5,7 \quad (6)$$

3. For sunflower yield, t ha⁻¹:

$$y = 0,11x + 2,45 \quad (7)$$

These modified equations were used in further analytical studies of the balance of sunflower production in Ukraine. Analytical presentation of the data allowed them to be used in addition to forming the absolute value of the forecast factor in the relevant units and to compare the dynamics of these factors. For this purpose, a comparative analysis of slope ratios (coefficients in arguments) of forecast value trends was used. The study showed that the dynamics of increasing the area under sunflower crops is more than an order of magnitude higher than the growth of sunflower yields, and the growth rate of gross production of sunflower seeds represents less than one-fifth of the growth rate of crop area (Box et al., 2015).

The volumes of sunflower hulls and the corresponding amount of ash were calculated based on the relevant requirements and calculation methods for sunflower seeds and their processed products, as established in Ukrainian regulatory documents and standards [14].

Sunflower husk ash fertilizer is obtained according to TU U 20.1-38170694-001:2016 from ash after burning sunflower husks.

Field experiments were conducted at the Slobozhanske experimental field of the National Scientific Center “O.N. Sokolovsky Institute for soil science and agrochemistry research”, Doslidne village, Chuhuiv district, Kharkiv region, Ukraine (49.726683° N, 36.922198° E). The study included sunflower (hybrid NK Condi, Syngenta Crop Protection AG, Basel, Switzerland), spring barley (cultivar Stalker, Plant Breeding and Genetics institute – National center of seed and cultivar investigation, National Academy of Agrarian Sciences of Ukraine, Odesa, Ukraine), maize (hybrid NK Thermo FAO 330, Syngenta Crop Protection AG, Basel, Switzerland), potato (cultivar Rocco, NORIKA GmbH, Germany), table beet (cultivar Libero), cucumber (hybrid Allianz F1, Bejo Zaden B.V., The Netherlands), and tomato (hybrid Ivanhoe RZ F1, Rijk Zwaan Zaadteelt en Zaadhandel B.V., The Netherlands). Certified seeds and planting materials were obtained either directly from the breeders or through their authorized distributors. Seeds of the Libero table beet cultivar were purchased from Supermarket Nasinnia (Ukraine), while seeds of the Allianz F1 cucumber hybrid were purchased from Gardentime (Ukraine). All crops were cultivated under standard agronomic practices.

The study involved only commercially cultivated agricultural crops using certified seeds or planting materials obtained from breeders or authorized suppliers. No wild, protected, or endangered plant species were involved.

Field trials were conducted at the Slobozhansky experimental field on a typical heavy loam chernozem according to the following treatment scheme:

- without fertilizers (control);
- basal application of NPK 16:16:16 at a rate of 300 kg ha⁻¹ and application during pre-sowing cultivation at a rate of 200 kg ha⁻¹;
- basal application of sunflower husk ash (SHA) at a rate of 300 kg ha⁻¹ and application during pre-sowing cultivation at a rate of 200 kg ha⁻¹.

The plot size for each crop was 0.1 ha. Accordingly, the results are presented using a descriptive and comparative approach and are not interpreted as statistically significant effects. Three subsamples were taken from each 0.1-ha plot to determine the quality parameters of the agricultural products. The subsamples were combined into one composite sample for laboratory analysis and were not considered independent biological replicates.

The fertilizer application rates were selected taking into account the crop requirements and the agrochemical characteristics of the experimental soil. The field experiment was conducted on a typical heavy loam chernozem with a relatively high nutrient status, particularly with respect to potassium. Therefore, maximum fertilizer application rates were not used. Moderate experimental rates of 0.3 t ha⁻¹ for basal application and 0.2 t ha⁻¹ for application during pre-sowing cultivation were selected, approximately corresponding to moderate application rates used for cereal crops under the prevailing soil conditions. These rates were used consistently across the tested crops to provide a comparable basis for evaluating the effects of the fertilizer treatments.

Soil samples were taken after harvest, and plant samples were taken during harvest. For chemical soil analysis, a composite sample weighing approximately 1,000 g was formed from three spot samples weighing approximately 250 g each. Soil sampling was performed using a soil sampler from two layers: 0–5 and 5–20 cm. The composite samples were homogenized, and laboratory subsamples were subsequently taken for chemical analysis, including determination of the gross content of mineral components [27].

Three subsamples were taken from each 0.1-ha plot to determine the quality parameters of the agricultural products. The subsamples were combined into one composite sample for laboratory analysis and were not considered independent biological field replicates.

A one-point plant sample was collected for each crop and included barley (1,000 g), maize (1,000 g of green mass at the waxy maturity stage), sunflower (1,000 g), potato (one tuber and 3–4 roots), table beet (one root), tomato (3–4 fruits), and cucumber (3–4 fruits). One-half or one-quarter of large fruits were taken and crushed using a homogenizer for analysis. After thorough mixing, at least two subsamples of 25–50 g each were taken from the homogenized sample for laboratory analysis.

According to current regulations, the samples were analyzed in the certified Laboratory of Organic Fertilizers and Humus of the National Scientific Center “Institute for Soil Science and Agrochemistry Research” (NSC IGA), certificate № 100–154/2014 dated 1 August 2014.

Product quality was determined using an ICS-4250 infrared spectrophotometer. Atomic absorption spectrometry was applied to determine the contents of the microelements Fe, Mn, Zn, Cu, Co, and Mo. Magnesium and calcium contents were determined using the complexometric titration method. Phosphorus content was determined using a KFK-2 photocolormeter, while potassium and sodium contents were determined using a PFP-7 flame photometer.

Analysis of potentially toxic elements in the water extract of SHA. As supplementary information on the potential mobility of mineral components from sunflower husk ash (SHA), a water extract of SHA was analyzed for a range of elements, including potentially toxic elements. Sample preparation and determination of the mass fraction of elements, including Cd, Cr, Ni, Pb and other elements, were performed by inductively coupled plasma atomic emission spectrometry according to RM.UL 5.4–100. Arsenic and mercury were additionally determined by inductively coupled plasma–mass spectrometry (ICP-MS) according to Method 6020B. The analyses were performed by the Ukrainian Laboratory of Quality and Safety of Agricultural Products of the National University of Life and Environmental Sciences of Ukraine, accredited according to DSTU EN ISO/IEC 17025:2019. The reported results characterize the water extract of SHA and therefore provide information on the potentially soluble fraction of the analyzed elements rather than their total concentrations in the solid ash.

The primary research methods used were field, laboratory-analytical, and statistical. The obtained data were processed using descriptive and comparative statistical methods. Arithmetic mean values were calculated for the analytical measurements, and absolute and relative differences (%) between the fertilizer treatments and without fertilizers (control) were determined. The results were summarized in the corresponding measurement units and percentages and used to compare crop yield, soil properties, and quality parameters of the agricultural products obtained under the different treatments. The present manuscript reports the results obtained during one growing

season of the field experiment. Because the available dataset did not contain primary observations from independent biological field replications, inferential statistical tests were not performed. Arithmetic mean values were calculated for the available analytical measurements.

4 Results

The current production of fertilizers from sunflower ash in 2021 was 19 thousand tons/year, but may increase up to 31.5 thousand tons/year, if all available ash is used. The study shows that at an average rate of cultivation of about 17 million tons of sunflower per year in the next 5 years in Ukraine about 50 tons of ash will be formed (Fig. 1), and this, according to calculations, can cover the needs of 70% of organic farms with high-quality fertilizers in Ukraine.

The SHA-based fertilizer investigated in this study has progressed beyond the experimental or conceptual stage and is currently used in agricultural production. The product is a complex mineral potassium–phosphorus fertilizer of plant origin recommended for use in organic agriculture in accordance with the MAOS standard for organic production and processing, which is equivalent to Council Regulation (EC) № 834/2007 [58] and Organic Production & Processing Standard 889/2008 [57]. Its practical use by agricultural enterprises provides additional evidence of the applicability of the technology. At the same time, practical use and certification should not be considered substitutes for replicated scientific field experiments or comprehensive characterization of the solid ash.

The results of laboratory and analytical work with samples of ash are shown in Fig. 2. The main active ingredient of the fertilizer is potassium, which is 30% of the total. This happens due to the water-soluble and easily accessible to plants form of carbonates (K_2CO_3) and sulfates (K_2SO_4) [9, 22].

Fertilizers are saturated with a wide range of trace elements, in particular: iron (Fe)–1.34 g/kg or 0.134%, boron (B)–1 g/kg or 0.1%, zinc (Zn)–900 mg kg⁻¹ or 0.09%, copper (Cu) 240 mg kg⁻¹ or 0.024%, manganese (Mn)–150 mg kg⁻¹ or 0.015%, chromium (Cr)–6.3 mg kg⁻¹ or 0.00063%, and molybdenum (Mo)–1.5 mg kg⁻¹ or 0.00015%.

The analysis of the water extract of SHA showed that Cd, Ni and Pb were below the reported quantification threshold of 0.10 mg kg⁻¹. The concentrations of Cr and As were 2.94 and 0.17 mg kg⁻¹, respectively, while Hg was detected at 2 µg kg⁻¹. The results provide additional information on the elemental composition of the

Fig. 1 Balance of raw materials and production volumes of fertilizers from sunflower husk ash, 1990–2025. Source created based on the statistical reports (up to 2023) [41] and the authors' research (2024–2025)

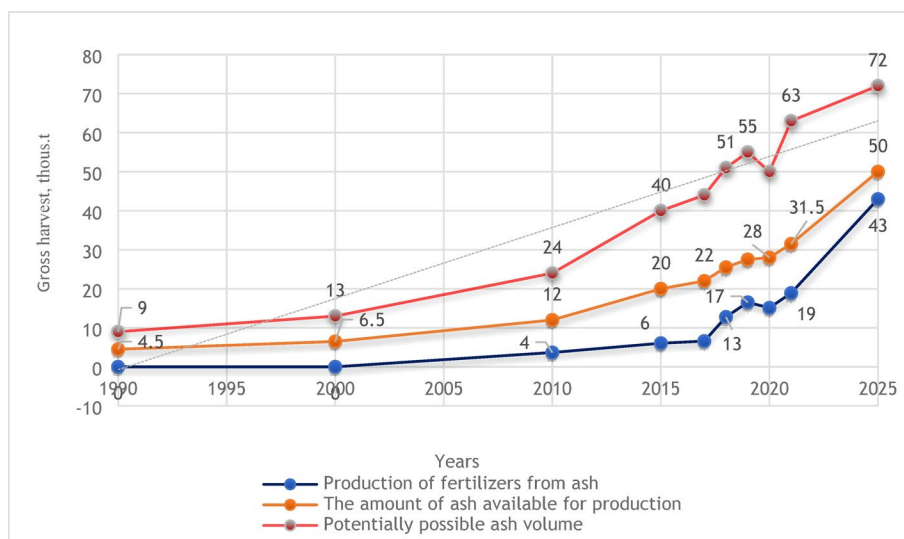


Fig. 2 Chemical composition of fertilizer received from sunflower husk ash. *Source* based on the authors’ research

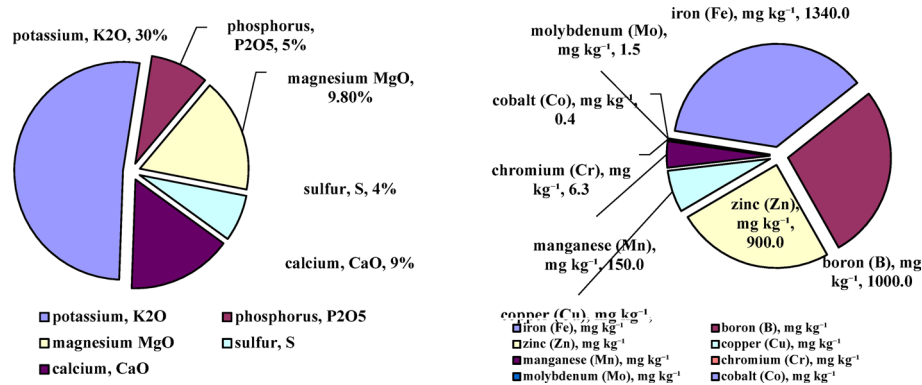
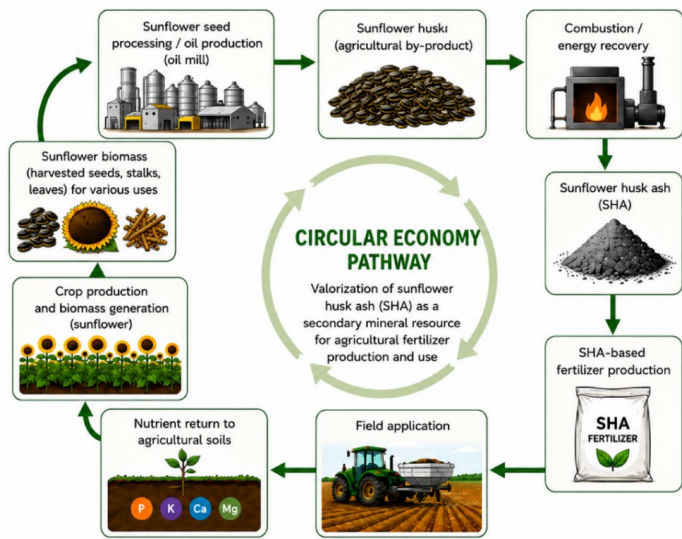


Table 1 Potentially toxic elements detected in the water extract of sunflower husk ash. *Source* based on the authors’ research

Element	Result
Cd, mg kg ⁻¹	<0.10
Cr, mg kg ⁻¹	2.94
Ni, mg kg ⁻¹	<0.10
Pb, mg kg ⁻¹	<0.10
As, mg kg ⁻¹	0.17
Hg, µg kg ⁻¹	2

Fig. 3 Circular economy pathway for the valorization of sunflower husk ash (SHA) as a secondary mineral resource for agricultural fertilizer production and use. *Source* based on the authors’ research



water-soluble fraction of SHA. However, these data cannot be interpreted as total concentrations of potentially toxic elements in the solid ash (Table 1).

Within the circular economy framework, sunflower husks can be valorized through energy recovery, with the resulting sunflower husk ash (SHA) subsequently returned to agricultural production as a secondary mineral resource. This creates a circular pathway linking sunflower processing, waste reduction, resource recovery, and the return of mineral nutrients to agricultural soils. The pathway considered in this study is presented in Fig. 3.

SHA contains 30 per cent K₂O, 5 per cent P₂O₅, 9 per cent CaO, 10 per cent MgO and 4 per cent S. Accordingly, 1 tonne of SHA contains approximately 300 kg of K₂O, 50 kg of P₂O₅, 90 kg of CaO, 100 kg of MgO and 40 kg of sulphur. When applied to agricultural soils, these mineral components are returned to the soil and re-enter the

nutrient cycle, contributing to the restoration of mineral resources and the circular use of nutrients in agricultural production.

According to the results of phenological and biometric observations in field studies. Higher values of selected growth, yield, and quality indicators were observed following SHA application (Tables 1, 2 and 3). Due to its granular form, the ash may dissolve gradually, potentially contributing to a more gradual release of nutrients into the soil.

Higher observed values were recorded for the SHA treatment than for the conventional NPK 16:16:16 treatment and the control (option without fertilizer application), both during the basal application and during application for pre-sowing cultivation. The increase ranged from 2.8 to 11.6% of the crop, depending on the crop type, with a basal application (Table 2).

The results in Table 1 showed that after the basal application and pre-sowing sunflower husk ash treatment at 0.2–0.3 t ha⁻¹, the increase in yield of corn silage was 11–13% (yield under control – 31.0 t ha⁻¹), the increase in plant height was at the level of 8.1–9.9 cm. Cucumber yield was 13–15%, with the number of cucumber increased by 10%, and their average weight by 5%. The increase in the yield of table beet roots ranged from 14 to 19% compared to the control yield (yield under control – 17.7 t ha⁻¹). Compared to the treatment with conventional NPK 16:16:16 fertilizer (comparison option), the increase was 8–11%. The average weight of tomato was increased by 6.0–8.4 g, and the increase in yield was by 16–21% compared to the control yield (yield on the control – 81 t ha⁻¹).

The increase in the yield of sunflower was from 9 to 12% compared with the control group (yield in the control: 1.76 t ha⁻¹). Compared with introducing conventional NPK 16:16:16 fertilizer (comparison option), the increase was 3.8–4.2%. The increase in the yield of potato tubers was from 14 to 17% compared to the control (the yield in the control is 28.6 t ha⁻¹) and 5.5–7.7% compared to the conventional NPK 16:16:16 fertilizer treatment (comparison option). The increase in the grain yield of bright hordeum vulgare on variants with the basal application sunflower husk ash treatment at the rate of 0.3 t ha⁻¹ was 7% more compared to the control (yield at the control – 2.02 t ha⁻¹), after the pre-sowing sunflower husk ash treatment for the cultivation at the rate of 0.2 t ha⁻¹ was 9%.

The results of phenological and biometric observations in the field research showed higher observed yields following the autumn application of SHA for the central processing (0.3 t ha⁻¹), where the yield increase for the studied group of crops ranged from 9 to 21% versus 7–16% after the pre-sowing ash treatment for the crop at the rate of 0.2 t ha⁻¹ compared to the control group. In general, using two treatment options of 0.2–0.3 t ha⁻¹, sunflower husk ash treatment showed the best dynamics in the yield growth compared to traditional fertilizer (comparison option), the increase was from 2.8 to 8.9%.

The descriptive analysis of the research results indicated that responses in quality parameters varied among crops. For barley, maize, sunflower, potato, and tomato, only small changes in the measured quality indicators were observed.

The increase in the yield of sunflower after application of sunflower husk ash ranged from 9 to 12%, with more intense accumulation of dry matter and oil in sunflower, in particular, fat increased by 9% when using both variants of treatment over 0.2–0.3 t ha⁻¹ SHA (Table 3).

The basal application of SHA and its application during pre-sowing cultivation resulted in: the increase in the content of vitamin C, the accumulation of protein, and the reduction in the content of nitrates, both in comparison with traditional fertilizer (comparison option) and in contrast with the control group (option without fertilizers). The increase in vitamin C content was observed: in tomato—from 14 to 17%, cucumber—from 22 to 24% compared to the control groups (option without fertilizers) and 8.1–10.8% and 11.1–13.3%, respectively, compared with the use of conventional NPK 16:16:16 fertilizer (comparison option).

The protein increase in potato was from 26 to 28% compared to the control group (the control indicator was 4.6% on dry matter). Compared with the conventional NPK 16:16:16 fertilizer (comparison option), the increase was about 7.3%. The main and pre-sowing application of ash from sunflower husks resulted in reducing the content of nitrates in both compared with the use of the conventional NPK 16:16:16 fertilizer and the control group (option without fertilizers) for cucumbers and tomatoes by 5–11%. At the same time, the results of phenological

Table 2 The effect of ash on crop yield under different treatment methods and doses. *Source* based on the authors' research

Version	Yield, t ha ⁻¹						
	Sunflower (NK Condi hyb- rida, Syngenta)	Barley (Stalker varietas (electio Ucrainica)	Maize (Thermo hybrida FAO-330, Syngenta)	Potato (Rocco varietas, Austria)	Table beet (Libero) varietas, Germania)	Cucumber (Allianz varietas)	Tomato (Ivanhoe RZ F1 varietas)
Without fertilizers (control)	1.76	2.02	31	28.6	17.7	71	81
The basal application of NPK 16:16:16 at a dose of 0.3 t ha ⁻¹	1.85	2.1	32.9	30.8	18.7	73	87
Treatment of NPK 16:16:16 under pre-sowing cultivation at a dose of 0.2 t ha ⁻¹	1.89	2.14	33.2	31.2	18.9	77	90
The basal application of SHA at a rate of 0.3 t ha ⁻¹	1.92	2.17	34.5	32.5	20.2	80	94
Application of SHA during pre-sowing cultivation at a rate of 0.2 t ha ⁻¹	1.97	2.2	34.9	33.6	21.1	82	98
SHA versus control, %	9	7	11	14	14	13	16
Pre-sowing cultivation, %							
Basal application, %	12	9	13	17	19	15	21
Pre-sowing cultivation, %	3.8	3.3	4.9	5.5	8.0	9.6	8.0
SHA versus NPK, %							
Basal application, %	4.2	2.8	5.1	7.7	11.6	6.5	8.9

Table 3 The impact of sunflower husk ash on the quality of crops. *Source* based on the authors' research

Option		Contents					
		Fat content in sunflower seeds, % of dry matter	Protein content in potato, % of dry matter	Vitamin C, mg 100 g ⁻¹ fresh weight		Nitrates, mg kg ⁻¹ fresh weight	
				Cucumber(Allianz varietas)	Tomato (Ivanhoe RZ F1 varietas)	Cucumber(Allianz varietas)	Tomato (Ivanhoe RZ F1 varietas)
Without fertilizers (control)		44.0	4.6	4.1	3.5	119.4	138.1
The basal application of NPK 16:16:16 at a dose of 0.3 t ha ⁻¹		47.5	5.4	4.5	3.7	117.8	132.2
Treatment of NPK 16:16:16 under pre-sowing cultivation at a dose of 0.2 t ha ⁻¹		46.9	5.5	4.5	3.7	117.1	131.9
The basal application of SHA at a rate of 0.3 t ha ⁻¹		48.0	5.8	5.0	4.0	113.0	124.9
Application of SHA during pre-sowing cultivation at a rate of 0.2 t ha ⁻¹		48.0	5.9	5.1	4.1	112.2	122.9
SHA versus control, %	Pre-sowing cultivation, %	9%	26%	22%	14%	-5%	-10%
	Basal application, %	9%	28%	24%	17%	-6%	-11%
SHA versus NPK, %	Pre-sowing cultivation, %	1.1%	7.4%	11.1%	8.1%	-4.1%	-5.5%
	Basal application, %	2.3%	7.3%	13.3%	10.8%	-4.2%	-6.8%

and biometric observations in the field experiment showed no notable differences in the qualitative indicators between autumn and spring treatments.

Adding ash to acidic soil makes its reaction close to neutral. The ash has a highly alkaline reaction and is successfully used to reduce soil acidity. Along with the enrichment of the soil and reducing acidity, the ash improves its structure, promotes its loosening, creates a favorable soil microflora, which has a beneficial effect on the health of plants, their survival, yield, decorative qualities, and immunity. The basal application of SHA and its application during pre-sowing cultivation were associated with changes in the soil nutrient regime. The analysis of the sunflower husk ash influence on the qualitative characteristics of the soil was estimated when growing barley, potato and tomato (Table 4).

When treating sunflower husk ash, hydrogen atoms are replaced by other chemical elements (often calcium or magnesium), followed by acid decomposition and salt formation. The results showed a deoxidizing effect of ash on the soil compared with the control (option without fertilizers), when 300 kg of SHA were applied for the basal application on chernozem with a typical hard-loam pH (6.8–7.4), the pH value changed on average by 0.5 units. When 200 kg of ash was applied for pre-sowing cultivation, the pH value changed on average by 0.3 units. This ameliorative effect of sunflower husk ash from an agronomic point of view will manifest itself better on acidic soils with a lower level of buffering. The paramount importance of SHA for soil fertility is that it is a source of calcium, which prevents the loss of the most valuable part of the soil—humus. The results of field research showed that the agrochemical characteristics of typical chernozem on the variants with the basal application and pre-sowing sunflower husk ash treatment during the cultivation of crops improved.

The humus content of mobile forms of phosphorus and potassium in typical heavy loam chernozem was higher in comparison with the control and with the variants where the conventional NPK 16:16:16 fertilizer was applied.

Table 4 Agrochemical properties of a typical heavy loam chernozem under different fertilizer treatments. *Source* based on the authors' research

Option	Contents									
	pH					P2O5, mg kg ⁻¹ of soil				
	Barley, (Stalker varieties (electio Ucrainica)	Cucumber (Allianz varieties)	Potato (Rocco varieties, Austria)	Barley, (Stalker varieties (electio Ucrainica)	Cucumber (Allianz varieties)	Potato (Rocco varieties, Austria)	Barley, (Stalker varieties (electio Ucrainica)	Cucumber (Allianz varieties)	Potato (Rocco varieties, Austria)	Potato (Rocco varieties, Austria)
Without fertilizers (control)	7.0	6.8	6.9	71.3	61.0	75.0	128.8	116.5	163.0	163.0
The basal application of NPK 16:16:16 at a dose of 0.3 t ha ⁻¹	7.1	6.9	6.73	82.3	71.7	87.0	129.9	126.9	176.0	176.0
Treatment of NPK 16:16:16 under pre-sowing cultivation at a dose of 0.2 t ha ⁻¹	7.0	7.0	6.71	82.5	72.2	87.0	130.7	127.2	178.0	178.0
The basal application of SHA at a rate of 0.3 t ha ⁻¹	7.5	7.2	7.40	84.7	73.5	92.0	133.5	128.3	182.0	182.0
Application of SHA during pre-sowing cultivation at a rate of 0.2 t ha ⁻¹	7.3	7.4	7.41	86.4	73.9	94.0	134.8	128.8	186.0	186.0
SHA versus control, %	7.1	5.9	7.2	19	20	23	4	10	12	12
	4.3	8.8	7.4	21	21	25	5	11	14	14
SHA versus NPK, %	5.6	4.3	10.0	2.9	2.5	5.7	2.8	1.1	3.4	3.4
	4.3	5.7	10.4	4.7	2.4	8.0	3.1	1.3	4.5	4.5

The content of mobile forms of phosphorus and potassium after the basal application and pre-sowing application of fertilizers increased 1.3 times compared to the option without fertilizers treatment.

These studies show that ash treatment can increase the amount of phosphorus available to plants. The basal application and pre-sowing sunflower husk ash treatment resulted in the improvement of the basic agrochemical properties in typical heavy loam chernozem: the content of mobile phosphorus and exchangeable potassium in layer 0–20 increased by 17–19 and 19–23 mg kg⁻¹ of soil, respectively.

5 Discussion

A systematic solution to the complex problem of increasing the efficiency of using bioresources as an important eco-innovative factor for restoring soil fertility and increasing crop productivity is associated with the need to expand fundamental and applied research. It requires the development of adaptive technologies that will meet environmental requirements and modern market relations of commodity producers.

Agricultural waste represents a potential resource and a source of added value. Environmental initiatives make it possible to return resources to the economic cycle and reduce anthropogenic load [11, 28, 39].

To solve the problem of providing energy resources, it was proposed that ash from sunflower husk be used to produce complex mineral fertilizers. It made it possible not only to address the issue of industrial waste recycling but also to obtain quality fertilizer suitable for use in organic production [31, 65].

This fertilizer is especially relevant on light soils, which are characterized by acidic, potassium-poor soils. The use of potassium-calcium fertilizer reduces the accumulation of radionuclides in plants, because in the absence of potassium and calcium in the soil, plants begin to absorb their “substitutes intensively”—cesium and strontium [35, 42].

The use of sunflower husk ash as a secondary mineral resource provides an opportunity to valorize a by-product of sunflower processing and return mineral nutrients to agricultural soils instead of disposing of the ash. In this context, SHA-based fertilizer represents a practical pathway for linking agricultural waste valorization, resource recovery, and circular economy principles. Its lower purchase cost compared with conventional NPK fertilizer may provide an additional economic incentive for agricultural enterprises, further strengthening the practical potential of this approach. The findings indicate the potential of this approach for integrating agricultural waste management with agricultural production.

The results obtained in this study are generally consistent with the findings of other recent works. In particular, they align in showing that biomass ash can alter soil chemical properties and nutrient availability. It is noted, however, that the magnitude of these effects depends on ash composition, application rate, soil properties, and crop type. In studies conducted on acidic soils, authors report an increase in soil pH and the availability of P, K, Ca, and Mg [1]. At the same time, other researchers (using higher doses) note minor changes in pH and phosphorus (P) content in a field trial, but increased potassium availability [3]. Recent studies [62] in addition to increasing soil pH and potassium availability after ash application, have demonstrated improvements in stress resistance and plant growth.

In this study, conducted on typical heavy loamy chernozem, the increase in available phosphorus and exchangeable potassium by approximately 10–22% and the change in soil pH by 0.3–0.5 units are comparable to the responses described in the literature. These results also indicate that the agronomic effects of biomass ash depend on the specific soil and site and should be evaluated taking into account the initial soil properties, ash composition, and application rate.

The yield and quality responses observed in this study are generally consistent with the results of previous experimental studies on the application of biomass ash. Shahare et al. [51] reported the effect of biomass ash on sunflower yield, oil content, and protein content, while [17] demonstrated an increase in rice yield without an increase in the concentrations of inorganic arsenic and cadmium in the grain. Studies on corn have also shown that the application of biomass ash can affect yield, grain chemical composition, and nutrient uptake. At the same

time, the magnitude and direction of these effects vary depending on the composition of the ash, the application rate, soil properties, and crop type.

Fertilizer safety is an important consideration when using biomass ash in agriculture, particularly with regard to potentially toxic elements. Previous field studies have shown that the application of biomass ash does not necessarily lead to an increase in cadmium accumulation in the aboveground tissues of plants, although the response of plants may depend on the type of ash and the application rate [7, 29]. Therefore, the safety of biomass ash should be assessed taking into account its elemental composition, application rate, soil properties, as well as the potential mobility and uptake of potentially toxic elements [53]. In this study, concentrations of Cd, Ni, and Pb below 0.10 mg kg^{-1} were detected in the aqueous extract of SHA, while the concentrations of Cr and As were 2.94 and 0.17 mg kg^{-1} , respectively, and that of Hg was $2 \text{ } \mu\text{g kg}^{-1}$. These results characterize the potentially soluble fraction and cannot be interpreted as total concentrations in solid SHA or as direct evidence of compliance with regulatory requirements.

The use of ash changes the conditions of soil nutrition of plants, causing an active intensification of the mobilization of nutrients in a digestible form for plants. The soils are characterized by better conditions of nitrogen and phosphate regimes, with the accumulation of humic compounds due to the formation of humic acids. Under these conditions, (1) the mobility of soil phosphorus is increased; (2) an increase in total and protein nitrogen is intensified and the predominance of nitrate content over ammonia nitrogen is stimulated against the background of increased nitrotoxicity and increased release of carbon dioxide by the soil [47, 63].

Thus, the effect of ash on soil fertility and crop yields can be represented as a set of interdependent processes: (1) the effect of fertilizers on the physico-chemical and physical properties of the soil; (2) the direct impact of fertilizers on the life of higher plants and microorganisms; and (3) strengthening of processes of internal soil metabolism: adsorption by fertilizers of soil nutrients with improvement of a nourishing mode of the development of plants and strengthening of biological activity. The result of this interaction is to increase soil fertility, increase crop yields, and improve crop quality.

The observed increase in crop yield may be associated with the mineral composition of SHA and its contribution to the availability of essential nutrients, particularly potassium, phosphorus, calcium, and magnesium. Changes in soil pH and nutrient availability may also improve the conditions for root development and nutrient uptake. The differences in crop response may be related to species-specific nutrient requirements, root system characteristics, and differences in nutrient uptake and utilization. Therefore, the observed responses should be considered as the result of the interaction between the mineral composition of SHA, soil properties, application rate, and crop-specific physiological requirements.

The nutrient composition of the granulated SHA-based fertilizer may support the supply of mineral nutrients to crops; however, crop-specific responses and economic performance require further evaluation under different soil and production conditions. Being an alkaline fertilizer (pH 10–11), granular ash has a high neutralizing ability, which helps reduce soil acidity. Since the fertilizer contains up to 25% of calcium and magnesium carbonates (CaO, MgO), 1 ton of it is equivalent to 0.35 tons of lime in terms of neutralizing ability [22, 47].

It is advisable to apply granulated ash in the fall. It allows for the optimal availability of nutrients in the organogenesis of crop development. The main risk of spring application for pre-sowing cultivation is drought. When the top layer of soil dries out, the granules lie without dissolving until mid-July.

Using biomass ash as a fertilizer needs further and detailed research with long-term monitoring of the impact on soils, as Zajac specified [66]. According to Li [30], the presence before ash treatment should be estimated. Before returning such products to agricultural soil, the plant's availability of nutrients when mixed with soil should be assessed.

The solution to the whole ecological and resource situation in Ukraine depends on waste management, because, on the one hand, waste is the main factor of environmental pollution, and, on the other hand, a specific part of the resource and energy potential that is “frozen” in it [2, 49, 50].

The results of a more in-depth study of this issue by society may be necessary for developing policies aimed at creating new industries, solving environmental problems, and addressing social problems based on them. This

eco-innovation policy should be aimed at education, public awareness, involvement of stakeholders, research institutes, and government agencies [45, 49].

Waste management requires the concerted efforts of the entire community (farmers, government authorities, the business sector, the scientific community, etc.). This strategy was developed to generate new added value and implement environmental initiatives aimed at the balanced transformation of rural areas.

6 Implications, limitations, and future research

The findings indicate the potential of sunflower husk ash-based fertilizer to contribute to the valorization of agricultural processing by-products and the return of mineral nutrients to agricultural soils. From a circular economy perspective, the conversion of sunflower husk ash into a fertilizer product provides a practical pathway for transforming an ash waste stream into a secondary mineral resource for agricultural use.

The sunflower husk ash-based fertilizer investigated in this study has progressed beyond the experimental or conceptual stage and is currently used in agricultural production. It is a complex mineral potassium–phosphorus fertilizer of plant origin recommended for use in organic agriculture in accordance with the MAOS standard for organic production and processing, which is equivalent to Council Regulation (EC) № 834/2007 and Organic Production & Processing Standard 889/2008. Its practical use by agricultural enterprises provides contextual information on the potential applicability of the developed approach. However, practical use and certification do not replace replicated scientific field experiments or comprehensive characterization of the solid ash.

The main limitation of the present study is that the field experiment was conducted during one growing season at a single experimental site on a typical heavy loam chernozem. Therefore, the results reflect the specific soil, climatic, and experimental conditions of the study and cannot be directly generalized to other soil types, climatic zones, or production systems. In addition, the available dataset did not contain the primary observations from independent biological field replications; therefore, inferential statistical tests were not performed. The reported differences were consequently evaluated using descriptive and comparative approaches.

Another limitation concerns the characterization of potentially toxic elements. The solid sunflower husk ash used in the field experiment was not directly analyzed for the total concentrations of potentially toxic elements. Additional analytical data were obtained for a water extract of sunflower husk ash, which characterized the potentially soluble fraction of the analyzed elements. These results provide additional information on the material but cannot be interpreted as total concentrations of potentially toxic elements in the solid ash or as direct evidence of regulatory compliance of the solid fertilizer material. Comprehensive characterization of potentially toxic elements directly in the solid SHA remains necessary for a complete assessment of its environmental safety.

Further research will include replicated multi-year field experiments across different natural and climatic zones, soil types, and crops. These studies will focus on the long-term effects of SHA-based fertilizer on crop productivity, soil fertility, nutrient availability, and the quality of agricultural products, as well as on establishing crop- and soil-specific application rates.

Further analytical characterization of the solid sunflower husk ash is also required, particularly with respect to potentially toxic elements, physicochemical properties, nutrient availability, and variability between production batches. Such studies will strengthen the scientific basis for evaluating the environmental characteristics and broader applicability of SHA-based fertilizer.

Future research will also address the broader socio-economic and environmental implications of processing and utilizing sunflower husk ash, particularly regarding resource efficiency, waste reduction, and contributions to circular agricultural production systems. International and interdisciplinary collaboration will facilitate comparative field studies and the further development of science-based approaches for the wider implementation of agricultural waste processing technologies.

7 Conclusions

The results obtained during one growing season provide initial field evidence of the potential of sunflower husk ash-based fertilizer as a secondary mineral resource for agricultural production within a circular economy approach. The application of the fertilizer was associated with an increase in crop yield of approximately 10–18% compared with without fertilizers (control), together with changes in selected soil agrochemical properties. The content of mobile phosphorus and exchangeable potassium increased by approximately 10–22%, while soil pH changed by approximately 0.3–0.5 units. An increase in selected quality parameters of agricultural products, including dry matter, protein, and fat content, was also observed.

The abundant availability of sunflower hulls as a byproduct of sunflower processing provides a substantial resource base for fertilizer production. Using sunflower hull ash as a secondary mineral resource makes it possible to increase the value of this byproduct, reduce the volume of ash disposal, and return mineral nutrients to agricultural soils. In this context, sunflower hull-based fertilizers represent a practical way to combine agricultural waste management, resource recovery, and the principles of the circular economy. The results obtained demonstrate the potential of this approach for integrating agricultural waste management with agricultural production.

At the same time, the results should be interpreted within the specific soil, climatic, and experimental conditions of the study. The experiment was conducted during one growing season at a single experimental site. The available dataset did not contain primary observations from independent biological field replications; therefore, inferential statistical tests were not performed, and the observed differences should be interpreted descriptively rather than as statistically significant effects.

Additional analysis of a water extract of sunflower husk ash provided information on the potentially soluble fraction of selected elements. Cd, Ni, and Pb were reported as $<0.10 \text{ mg kg}^{-1}$, while Cr and As were 2.94 and 0.17 mg kg^{-1} , respectively, and Hg was $2 \text{ } \mu\text{g kg}^{-1}$. However, these results characterize the water extract and cannot be interpreted as total concentrations of potentially toxic elements in the solid ash or as direct evidence of regulatory compliance of the solid fertilizer material. Direct characterization of potentially toxic elements in the solid SHA remains necessary for a comprehensive assessment of its environmental safety.

Further field studies need to be carried out in various natural and climatic zones, on different soil types, with different crops and during different growing seasons, in order to assess the reliability of the results obtained and to determine application rates appropriate for specific crops and soils. Further characterisation of solid SHA is also required, including the analysis of potentially toxic elements and the variability of its physico-chemical properties between batches. Such studies will provide a stronger scientific basis for assessing the potential for wider application of SHA-based fertilisers and their role in the circular management of agricultural resources.

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Declarations

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Authors and Affiliations

Andrii Dankevych^{1,2}  · Vitalii Nitsenko^{3,4}  · Vitalii Dankevych⁵  · Edeh Friday Ogbu⁶  ·
Aistė Lastauskaitė³  · Iryna Kapelista⁷ 

✉ Vitalii Nitsenko
vitalii.nitsenko@nung.edu.ua; vitalii.nitsenko@go.kauko.lt

Andrii Dankevych
dankevichIE@nuft.edu.ua

Vitalii Dankevych
dankevych2017@gmail.com

Edeh Friday Ogbu
friday.edeh@kiu.ac.ug

Aistė Lastauskaitė
aiste.lastauskaite@kaunokolegija.lt

Iryna Kapelista
Kapelistaja.irina@ukr.net

¹ Department of Economics and Law, National University of Food Technology, Kyiv, Ukraine

² Department of National Security, Public Management, and Administration, Zhytomyr Polytechnic State University, Zhytomyr, Ukraine

³ Faculty of Business, Kauno Kolegija Higher Education Institution, 50362 Kaunas, Lithuania

⁴ Department of Entrepreneurship and Marketing, Institute of Economics and Management, Ivano-Frankivsk National Technical Oil and Gas University, Ivano-Frankivsk, Ukraine

⁵ Faculty of Law Public Administration and National Security, Polissia National University, Zhytomyr, Ukraine

⁶ Department of Research & Innovations (D-RICE), Kampala International University (Main Campus), Kampala, Uganda

⁷ Department of Public Administration, Interregional Academy Personnel Management, Kyiv, Ukraine