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Abstract

This study aims to substantiate the feasibility of using ash accumulated at industrial facilities (in Ukraine alone, this is more than 100 thousand tons per year) in agriculture. Ash (a by-product of agricultural production) instead of disposal in landfills and environmental pollution can be used as fertilizer. Such an alternative approach to waste management in the circular economy contributes to the formation of new added value, increased food production and the implementation of environmental initiatives. The research studied the impact of applying fertilizers from sunflower husk ash at a rate of 200 and 300 kg/ha compared to conventional fertilizers and unfertilized control plots. Field studies lasted 3 years. The main performance indicators of the evaluation were: yield, quality indicators of the grown crops and agrochemical indicators of the soil. In the experiments, different methods of application were tested: main application and pre-sowing application. *Hordeum vulgare*, *Zea mays*, *Helianthus annuus*, *Solanum tuberosum*, *Solanum lycopersicum* and *Cucumis sativus* were grown in the studies. The size of the accounting plot for one crop is 0.1 ha. It has been proven that when ash is applied, the yield of agricultural crops increases by an average of 10-18%. The content of mobile phosphorus and exchangeable potassium increases by 10-22%; pH changes by an average of 0.3-0.5. An increase in the content of dry matter (proteins, fats) in the products is observed. The study found that fertilizer from sunflower husk ash contains K_2O - 28-35%, P_2O_5 - 3-7%, CaO - 9-14%, MgO - 5-7%, S - 4-6%. Does not contain chlorine. The implementation of this waste management model in the practice of agricultural enterprises will allow solving the issue of processing more than 40 thousand tons of industrial waste per year only within Ukraine. This approach is an alternative to a simple, inexpensive and accessible solution to the complex problem of waste disposal and environmental improvement.

Keywords: Biomass, Sustainability of Agricultural Resources, Agricultural waste valorization, Circular economy, Secondary resources, Bioeconomy.

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. (Skoog et al., 2014; Kobierski et al., 2017; Koseoglu et al., 2022, Horák et al., 2023). Several scientists are investigating possibility of using them as fertilizers (Ma et al., 2020; Kuntiasuti et al., 2019; Spence et al., 2020; Gorai, 2018). In particular, the emphasis is on their deoxidizing effect and the ability to improve the physicochemical properties of light soils (Adekiya et al., 2020; Paleckene et al., 2010; Odziejewicz et al., 2022; Christophe et al., 2019; Sofyan et al., 2019)

In times of change, instability, and a significant increase in the cost of traditional potash fertilizers (potash prices have increased by more than 50% over the past 3 years), rational waste conditioning can become an alternative support for national economies by using their raw materials.

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. Prices for mineral fertilizers have increased significantly on the market (more than 50% over the past 3 years), and there is a need to transition to a more economical use of land as the primary means of production. For 2025, the price of mineral fertilizers according to the forecast is to increase by 10-15%. 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, potential, and impact over 3 years on yield, product quality, and agrochemical soil parameters. It will allow the implementation of SDG goal № 12 "Responsible Consumption", 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 (Chaparro-Banegas et al., 2023; Ursavas et al., 2023; Tao et al., 2021; Sokiran et al., 2019). The transition to sustainable development and a zero-waste economy can occur through eco-innovations (Fernández et al., 2021), supporting these two trends despite the current economic, social, and environmental consequences (Manjappa, 2021). The scientific community believes that waste holds significant reserves for implementing sustainable development goals, which we must explore and reveal for future generations (Ma et al., 2024; Sosnovska et al., 2021).

Most researchers use the terms "ecological", "environmental", and eco-innovation as synonyms (Díaz-García et al., 2015). For example, K. Fussler interpreted "eco-innovations" as processes and products that contribute to sustainable development (Fussler et al., 2021). According to James (1997), "these are new products that provide the consumer and business with income, while significantly reducing the environmental impact". Eco-innovation can control pollution and mitigate its impact on the environment and society (Díaz-García et al., 2015; Koseoglu et al., 2022; Milana et al., 2022). Ecovation is the process by which businesses adopt ecological innovation to create products that are generative and recyclable. More and more companies

are turning to alternative waste processing methods instead of sending it to landfills (Murova et al., 2022).

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. 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 (Ma et al., 2024; Schmidt et al., 2023; Manjappa, 2024).

Biomass is the fastest-growing renewable energy sector in Ukraine. The experts' analysis showed that the pellets from the sunflower husk have a greater impact on the growth of production volumes in the Ukrainian biofuel sector. When burning sunflower husks, the amount of carbon dioxide emissions does not exceed that formed during the natural decomposition of wood. Burning granules is energy efficient; usually, the amount of non-combustible residues (ash content) does not exceed 3% (Dahunsi et al., 2021).

Today, many studies are devoted to using ash as a component of building materials, particularly works (Quaranta et al. 2011; Senyas et al. 2012; Sarvar et al., 2016). Studies on the chemical properties of ash have been carried out (Isemin et al., 2022; Shan et al., 2020; Jiang et al., 2019; Victor et al., 2017; Kaya et al., 2006; Kobierski et al., 2017; Kuntastyuti et al., 2018; Li et al., 2018). At the same time, few studies have been done on using ash in modern technological agricultural production as a fertilizer.

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 (Milana et al., 2022; Shang et al., 2020; Rosén et al., 2014; Sosnovska et al., 2021). At the same time, no specific countermeasures and soil restoration programs using it have been developed.

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., 2021; Jiang et al., 2019; Victor et al., 2017).

At the same time, an analysis of domestic and foreign scientific sources shows that the possibility of using the eco-innovation of ash as a fertilizer on an industrial scale has not been sufficiently investigated. The primary issues are: expanding the range of crops for use, additional research into the impact on product quality and the environment, and practical recommendations for the formation of technological maps for using these fertilizers in the cultivation of crops. The importance of ash in reducing soil acidification and narrowing the productivity gap between organic and conventional agriculture remains unresolved today, including organic waste in the cycle of substances.

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 (Box et al., 2015).

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

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

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_{t-i} is a component that depends on q harmonics of influences; a_i and b_i 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 leads to significant 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 (equation 1), gross production of sunflower seeds, million tons (equation 2) and the yield of this crops, t/ha (equation 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:

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

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.

The volumes of ash were calculated based on the norms of output described and approved in the national standards of Ukraine (DSTU), interstate standards (GOST) for oilseeds, products of their processing, and feedstuff (Box et al.,2015).

Field experiments were conducted during 2021–2023 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 (*Helianthus annuus* L., hybrid NK Condi, Syngenta Crop Protection AG, Basel, Switzerland), spring barley (*Hordeum vulgare* L., cultivar Stalker, Plant Breeding and Genetics Institute – National Center of Seed and Cultivar Investigation, National Academy of Agrarian Sciences of Ukraine, Odesa, Ukraine), maize (*Zea mays* L., hybrid NK Thermo FAO 330, Syngenta Crop Protection AG, Basel, Switzerland), potato (*Solanum tuberosum* L., cultivar Rocco, NORIKA GmbH, Germany), table beet (*Beta vulgaris* L. var. *conditiva*, cultivar Libero), cucumber (*Cucumis sativus* L., hybrid Allianz F1, Bejo Zaden B.V., The Netherlands), and tomato (*Solanum lycopersicum* L., 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 primary research methods used were field, laboratory-analytical, and statistical.

The plant materials used in this study consisted exclusively of cultivated agricultural crops. Their cultivation, collection, and use complied with the applicable national regulations and standard agricultural practices of Ukraine. No wild, protected, or endangered plant species were collected or used in this study. Therefore, no specific permits or licences were required.

Field trials were conducted at the Slobozhansky experimental field on typical heavy loam chernozem according to the following scheme: Without fertilizers (control); the primary treatment with NPK 16:16:16 at a dose of 300 kg/ha and 200 kg/ha, respectively, for pre-sowing cultivation; the primary ASH treatment at a dose of 300 kg/ha and 200 kg/ha for pre-sowing cultivation. The repetition was made three times. The size of the control plots for one crop is 0.1 ha.

Soil samples were taken after harvest, and plant samples were taken during harvest. For chemical soil analysis, a combined sample weighing 1000 g was formed from 3 spot samples weighing approximately 250 g, and sampling was performed with a soil sampler from two layers: 0-5 and 5-20 cm. The samples were taken from a representative sample weighing not more than 20 g to determine the gross content of mineral components (Kuntyastuti et al., 2018).

Then, three samples were taken from 1 plot (0.1 ha), which were then combined into one weighted average sample, to determine the quality of products. Samples were taken based on the geolocation of sampling for soil analysis.

At the same time, a 1-point test sample in the section of plants included: *Hordeum vulgare* (1000 g), *Zea mays* (1000 g of green mass in the phase of waxy maturity), *Helianthus annuus* (1000 g), *Solanum tuberosum* (from 1 tuber, 3-4 roots), *Solanum lycopersicum* (3-4 fruits), *Cucumis sativus* (3-4 fruits). 1/2 or 1/4 of large fruits were taken and crushed in a homogenizer for analysis. After thorough mixing, at least two samples of 25–50 g each were taken from the average chopped sample of vegetables.

According to current regulations, the samples were analyzed in the certified laboratory of organic fertilizers and humus NSC IGA (certificate №100-154/2014 dated 01.08.2014). In particular, product quality was determined on an infrared spectrophotometer ICS-4250. The atomic absorption spectrometry method was applied to determine microelements content (Fe, Mn, Zn, Cu, Co, Mo); Magnesium and Calcium content were

determined by the complexometric titration method. The phosphorus was determined on a photocolorimeter KFK-2, and the potassium and sodium content were determined on a flame photometer PFP-7 (Schmidt et al., 2023).

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 (Figure 1), and this, according to calculations, can cover the needs of 70% of organic farms with high-quality fertilizers in Ukraine.

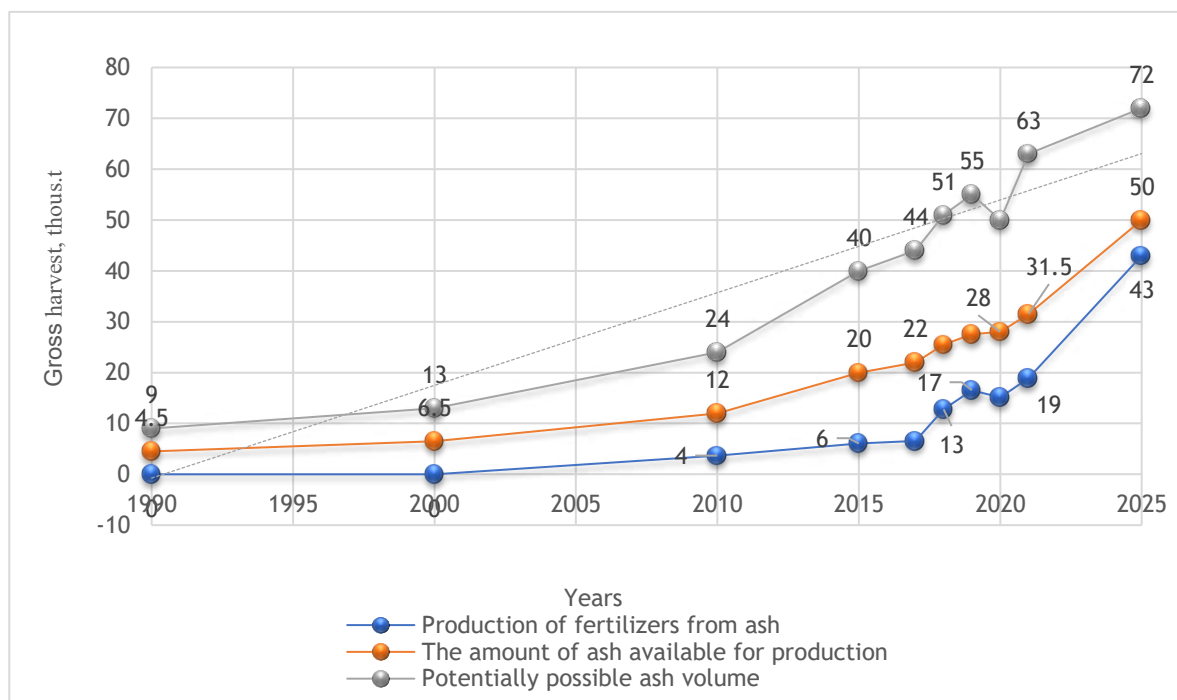


Figure 1. Balance of raw materials and production volumes of fertilizers from sunflower husk ash, 1990-2025

Source: created based on the statistical reports (up to 2023) (OECD/FAO, 2023) and the authors' research (2024-2025)

Sunflower husk ash fertilizer is a complex mineral potassium-phosphorus fertilizer of vegetable origin recommended for use in organic agriculture according to the MAOS standard for organic production and processing, which is equivalent to Council Resolution (EC) № 834/2007 and Organic Production & Processing Standard 889/2008.

The results of laboratory and analytical work with samples of ash are shown in Figure 2. The main active ingredient of the fertilizer is potassium, which is 28-32% 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) (Dankevych et al., 2023; Kakar et al., 2020).

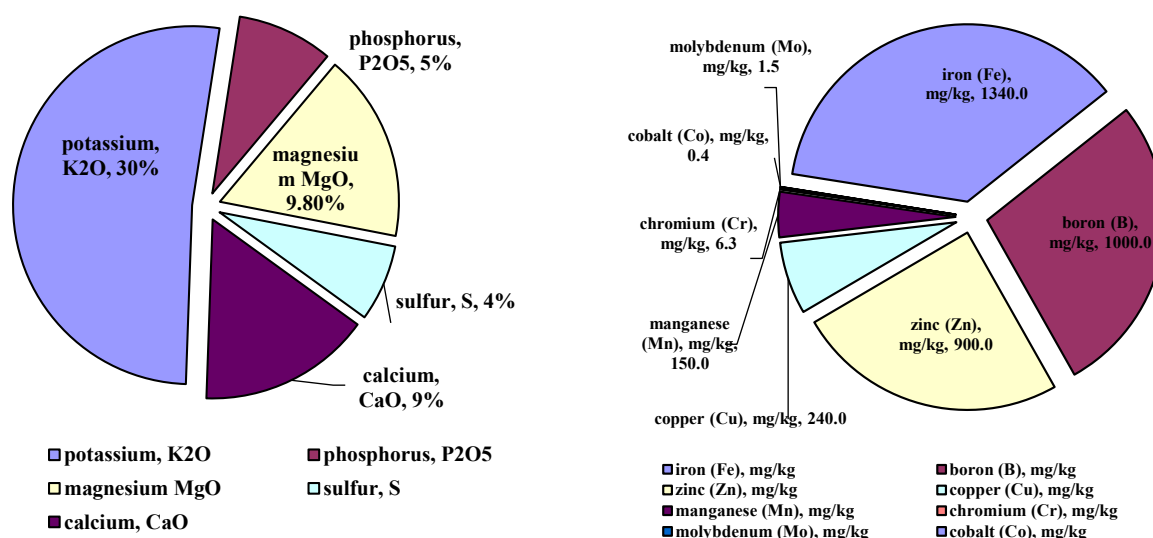


Figure 2. Chemical composition of fertilizer received from sunflower husk ash

Source: based on the authors' research

With 1 ton of granular ash, at least 85.1 kg of Calcium, 49.7 kg of Magnesium, 37.5 kg of Sulfur, 51 kg of total Phosphorus, and 209.8 kg of total Potassium can be applied in the soil. In addition to Potassium (K₂O) and Calcium (CaO), it contains 5% Phosphorus (P₂O₅), 8-12% Magnesium (MgO), and 8-16% Sulfur (S). The total content of active substances of macronutrients of the fertilizer is not less than 70% (Li et al., 2018).

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 or 0.09%, Copper (Cu) 240 mg/kg or 0.024%, Manganese (Mn) - 150 mg/kg or 0.015%, Chromium (Cr) - 6.3 mg/kg or 0.00063%, and Molybdenum (Mo) - 1.5 mg/kg or 0.00015%.

According to the results of phenological and biometric observations in field studies, fertilizer made from sunflower husk ash positively affected growth, development, yield, and quality of crops (Tables 1-3). Due to the granular form, the ash dissolves gradually, is not washed out of the soil, and has an aftereffect in subsequent years.

Sunflower husk ash showed better results compared to the application of traditional phosphorus-potassium fertilizer (comparison option) and compared to the control (option without fertilizer application), both during the main 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 tendency for the advantage of autumn treatment (Table 1).

It was established (Table 1) that after the primary and pre-sowing ASH treatment at 0.2-0.3 t/ha, the increase in yield of corn silage was 11-13% (yield under control - 31.0 t/ha), the increase in plant height was at the level of 8.1-9.9 cm. Cucumis sativus yield was 13-15%, with the number of Cucumis sativus 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). Compared to the treatment with traditional phosphorus-potassium fertilizer (comparison option), the increase was 8-11%. The average weight of Solanum lycopersicum 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).

The increase in the yield of Helianthus annuus was from 9 to 12% compared with the control group (yield

in the control: 1.76 t/ha). Compared with introducing traditional phosphorus-potassium fertilizer (comparison option), the increase was 3.8 - 4.2%. The increase in the yield of *Solanum tuberosum* tubers was from 14 to 17% compared to the control (the yield in the control is 28.6 t/ha) and 5.5-7.7% compared to the traditional phosphorus-potassium fertilizer treatment (comparison option). The increase in the grain yield of bright *hordeum vulgare* on variants with the primary ASH treatment at the rate of 0.3 t/ha was 7% more compared to the control (yield at the control - 2.02 t/ha), after the pre-sowing ASH treatment for the cultivation at the rate of 0.2 t/ha was 9%.

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

Table 1. The effect of ash on crop yield under different treatment methods and doses

Version		Yield, t/ha (average of 3 repetitions)						
		Helianthus annuus (NK Condi hybrida, Syngenta)	Hordeum vulgare (Stalker varietas (electio Ucrainica)	Zea mays (Thermo hybrida FAO-330, Syngenta)	Solanum tuberosum (Rocco varietas, Austria)	Beta vulgaris (Beta vulgaris var. conditiva, Libero) varietas,	Cucumis sativus (Allianz varietas)	Solanum lycopersicum (Ivanhoe RZ F1 varietas)
Without fertilizers (control)		1.76	2.02	31	28.6	17.7	71	81
The primary treatment of NPK 16:16:16 at a dose of 0.3 t/ha		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		1.89	2.14	33.2	31.2	18.9	77	90
The primary treatment of ASH at a dose of 0.3 t/ha		1.92	2.17	34.5	32.5	20.2	80	94
ASH treatment for pre-sowing cultivation at a dose of 0.2 t/ha		1.97	2.2	34.9	33.6	21.1	82	98
ASH/control	spring treatment, %	9	7	11	14	14	13	16
	autumn treatment, %	12	9	13	17	19	15	21
ASH/NPK	spring treatment, %	3.8	3.3	4.9	5.5	8.0	9.6	8.0
	autumn treatment, %	4.2	2.8	5.1	7.7	11.6	6.5	8.9

Source: based on the authors' research

The statistical analysis of the research results showed that not all crops are sensitive to changes in the quality indicators against the background of ASH treatment. In particular, the impact was insignificant on *Hordeum vulgare*, *Zea mays*, *Helianthus annuus*, *Solanum tuberosum*, and *Solanum lycopersicum*.

The increase in the yield of *Helianthus annuus* after implementation of ASH ranged from 9 to 12%, with more intense accumulation of dry matter and oil in *Helianthus annuus*, in particular, fat increased by 9% when using both variants of treatment over 0.2-0.3 t/ha ASH (Table 2).

Table 2. The impact of ASH on the quality of crops

Option		Contents (average of 3 repetitions)					
		Fat Sunflower Seed, % on dry matter	Potato Protein, % on dry matter	vitamin C mg, %		Nitrates, mg/kg	
				Cucumis sativus (Allianz varieties)	Solanum lycopersicum (Ivanhoe RZ F1 varieties)	Cucumis sativus (Allianz varieties)	Solanum lycopersicum (Ivanhoe RZ F1 varieties)
Without fertilizers (control)		44.0	4.6	4.1	3.5	119.4	138.1
The main treatment of NPK 16:16:16 at a dose of 0.3 t/ha		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		46.9	5.5	4.5	3.7	117.1	131.9
The primary treatment of ASH at a dose of 0.3 t/ha		48.0	5.8	5.0	4.0	113.0	124.9
ASH treatment for pre-sowing cultivation at a dose of 0.2 t/ha		48.0	5.9	5.1	4.1	112.2	122.9
ASH/control, %	spring treatment	9%	26%	22%	14%	-5%	-10%
	autumn treatment	9%	28%	24%	17%	-6%	-11%
ASH/NPK, %	spring treatment	1.1%	7.4%	11.1%	8.1%	-4.1%	-5.5%
	autumn treatment	2.3%	7.3%	13.3%	10.8%	-4.2%	-6.8%

Source: based on the authors' research

The primary and pre-sowing use of ash from sunflower husks 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 phosphorus-potassium fertilizer (comparison option) and in contrast with the control group (option without fertilizers). The increase in vitamin C content was observed: in solanum lycopersicum - from 14 to 17%, cucumis sativus - 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 traditional phosphorus-potassium fertilizer (comparison option).

The protein increase in Solanum tuberosum was from 26 to 28% compared to the control group (the control indicator was 4.6% on dry matter). Compared with the traditional phosphorus-potassium fertilizer (comparison option), the increase was about 7.3%. The main and pre-sowing implementation of ash from sunflower husks resulted in reducing the content of nitrates in both compared with the use of the traditional phosphorus-potassium fertilizer (comparison option) and the control group (option without fertilizers) for cucumbers and tomatoes by 5-11%. At the same time, the results of phenological and biometric observations in the field research showed the absence of significant deviations between the data of qualitative indicators for autumn and spring treatment.

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 primary and pre-sowing

use of ASH positively impacted the soil's nutrient regime. The analysis of the ASH influence on the qualitative characteristics of the soil was estimated when growing *Hordeum vulgare*, *Solanum tuberosum*, and *Solanum lycopersicum* (Table 3).

Table 3. The influence of ASH on agrochemical indicators of black soil under the cultivation of crops

Option	Contents (average of 3 repetitions)								
	pH			P ₂ O ₅ , mg / 1 kg of soil			K ₂ O, mg / 1 kg of soil		
	<i>Hordeum vulgare</i> (Stalker varieties (electio Ucrainica))	<i>Cucumis sativus</i> (Allianz varieties)	<i>Solanum tuberosum</i> (Rocco varieties, Austria)	<i>Hordeum vulgare</i> (Stalker varieties (electio Ucrainica))	<i>Cucumis sativus</i> (Allianz varieties)	<i>Solanum tuberosum</i> (Rocco varieties, Austria)	<i>Hordeum vulgare</i> (Stalker varieties (electio Ucrainica))	<i>Cucumis sativus</i> (Allianz varieties)	<i>Solanum tuberosum</i> (Rocco varieties, Austria)
Without fertilizers (control)	7.0	6.8	6.9	71.3	61.0	75.0	128.8	116.5	163.0
The primary treatment of NPK 16:16:16 at a dose of 0.3 t/ha	7.1	6.9	6.73	82.3	71.7	87.0	129.9	126.9	176.0
Treatment of NPK 16:16:16 under pre-sowing cultivation at a dose of 0.2 t/ha	7.0	7.0	6.71	82.5	72.2	87.0	130.7	127.2	178.0
The primary treatment of ASH at a dose of 0.3 t/ha	7.5	7.2	7.40	84.7	73.5	92.0	133.5	128.3	182.0
ASH treatment for pre-sowing cultivation at a dose of 0.2 t/ha	7.3	7.4	7.41	86.4	73.9	94.0	134.8	128.8	186.0
ASH/control, %	7.1	5.9	7.2	19	20	23	4	10	12
	4.3	8.8	7.4	21	21	25	5	11	14
	5.6	4.3	10.0	2.9	2.5	5.7	2.8	1.1	3.4
	4.3	5.7	10.4	4.7	2.4	8.0	3.1	1.3	4.5

Source: based on the authors' research

When treating ASH, hydrogen atoms are replaced by other chemical elements (often calcium or magnesium), followed by acid decomposition and salt formation. This study proved that the deoxidizing effect of ash on the soil, in particular, compared with the control (option without fertilizers), when 300 kg of ASH were applied for the primary treatment 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 ASH from an agronomic point of view will manifest itself better on acidic soils with a lower level of buffering. The paramount importance of ASH 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 primary and pre-sowing ASH treatment during the cultivation of crops improved.

The humus content of mobile forms of Phosphorus and Potassium in typical black soil (chernozem) was higher in comparison with the control and with the variants where the traditional phosphorus-potassium fertilizer was applied. The content of mobile forms of Phosphorus and Potassium after the primary and pre-sowing application of fertilizers increased 1.3 times compared to the option without fertilizers treatment.

These studies show that upon ash treatment, the amount of Phosphorus available to plants increases significantly, both due to its release from soil organic matter and due to the displacement of iron and Aluminum by Calcium from hardly soluble calcium phosphates and phosphates, the availability of which is higher for plants. The primary and pre-sowing ASH treatment resulted in the improvement of the basic agrochemical properties in typical black soil (chernozem): the content of mobile phosphorus and exchangeable potassium in layer 0-20 increased by 17-19 and 19-23 mg per 1 kg 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 significantly. It requires the development of adaptive technologies that will meet environmental requirements and modern market relations of commodity producers.

The formation of the crop largely depends on fertilizers, the increase in their consumption, and the expansion of the assortment. At the same time, it leads to ecologically unlimited, irrational use of the production resources and, as a result, to a significant anthropogenic burden. The rational functioning of the system "soil-plant-animals" requires the inclusion of waste in the cycle of substances (Lewu et al.,2020; Dankevych et al.,2024).

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 (Ye et al.,2020; Ma, 2020).

Granular ash is an environmentally friendly fertilizer that contains significantly fewer toxic elements, such as lead, cadmium, arsenic, and fluorine, compared to the content of these toxins in traditional fertilizers (Skoog et al.,2014; Kobierski et al.,2017).

This fertilizer is especially relevant on light soils, which are characterized by acidic, potassium-poor soils, a significant part of which is contaminated with radionuclides, military operations, and excessive acidification due to uncontrolled fertilizer application. 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 (Mench et al.,2018; Ostapchuk et al.,2021).

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) the processes of nitrate formation in the soil are intensified, which contributes to a significant increase in total and protein nitrogen and the predominance of nitrate content over ammonia nitrogen against the background of increasing nitro toxicity and increasing carbon dioxide release by the soil (Wiktor et al.,2017; Denysiuk et al.,2023; Dankevych et al.,2023; Salim, 2021).

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 variety of nutrient ratios in the pellet allows for adequate nourishment of the full range of crops (grain varieties, oilseeds, industrial and forage crops) and achieves high profitability. Being an alkaline fertilizer (pH 10-11), granular ash has a high neutralizing ability, which helps reduce soil acidity, making it very effective on acidic soils. 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 (Salim et al., 2021; Kakar et al., 2020).

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 (Zajac et al., 2018). According to Li (Li et al., 2018), 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.

Applying ash to the soil is a proper way to grow environmentally friendly products, increase yields, restore soil fertility, increase humus, obtain ecologically friendly products without pesticides and herbicides, and, as a consequence, improve health and life expectancy. 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 (Prodanchuk et al., 2023; Assefa et al., 2019; Señas et al., 2012; Scarpellini et al., 2022).

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 (Scarpellini et al., 2022; Rennings, 2000).

Implementing eco-innovation technologies requires consolidating efforts and a broad partnership with the entire society (farmers, authorities, businesses, politicians, certification bodies, consumer organizations, etc.). This strategy was designed to revive domestic agricultural production, ensure comprehensive capital improvement, and socio-economic and ecologically balanced transformation of rural areas and settlements.

6. Implications, Limitations, and Future Research

This study highlights the crucial role of the eco-innovative potential of sunflower husk ash in addressing sustainable development issues. The need for strict regulatory measures and transition to ecological ways of solving the problem of waste disposal was emphasized. Practical actions include switching to ash as fertilizer and using it in organic farming. It will help to reduce the contamination of areas and contribute to solving social and ecological issues.

The research is based on statistical data and a mathematical model, and may not fully reflect real-time conditions. In addition, the effect of this fertilizer may differ on different soil types. The hostilities in Ukraine also complicate the implementation of these initiatives and may affect the accuracy of the conclusions.

Future research should be based on monitoring data from field research on this fertilizer. The study should investigate the long-term impact of ash husk fertilizers on the development of agriculture in different natural and climatic zones. International cooperation in this direction will provide a complete understanding of the

effectiveness of using these fertilizers. For further research, it is crucial to assess the socio-ecological aspect of the eco-innovation potential of sunflower husk ash in the context of sustainable development.

7. Conclusions

The study confirms the eco-innovative potential of ash as a fertilizer. Using ash waste made it possible to return nutrients (potassium, phosphorus, macro- and microelements) to the ecosystem. With 1 ton of granular ash, at least 85 kg of Calcium, 49 kg of Magnesium, 37 kg of Sulfur, 50 kg of total Phosphorus, and 290 kg of total Potassium can be applied in the soil. The generation of new added value is essential for the economic growth of the national economy and the creation of employment for the population. Using ash as fertilizer will solve the problem of disposing of about 40 thousand tons of waste/year.

Field studies confirm the suitability of ash as a fertilizer for use in agricultural production. From a practical point of view, this is a new tool for increasing farmers' sustainability. The fertilizer positively affects yield, product quality, and soil fertility elements. In particular, the yield increase is up to 20% compared to the control (variant without fertilizers). Mobile phosphorus and exchangeable potassium content increased by 10-22%; pH changed by an average of 0.3-0.5 values. Using ash contributes to improving product quality and plant resistance to natural and climatic factors (drought, frost). In particular, an increase in dry matter content (proteins, fats) was observed.

The findings of this study will offer governments and researchers valuable insights to inform the development of new waste management programs. The study's empirical results provide a basis for decision-makers to create favorable conditions and introduce tax and financial incentives for enterprises that will implement these changes.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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