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The effect of growth stimulants based on humic acids from Ukrainian lignite and biochar from agricultural residues on the growth and development of lettuce (*Lactuca sativa*)

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Abstract. Significant amounts of plant-based waste are generated annually in the agricultural and food industries, including straw, corn residues, nutshells, and fruit pits. Disposing of this waste often relies on basic methods that avoid further processing, presenting an urgent environmental challenge. One efficient solution is converting biomass into biochar, which serves as a soil amendment. Developing cost-effective recycling methods has become critical with the increasing scarcity and rising cost of raw materials. The Dnipro Lignite Coal Basin in Ukraine offers extensive lignite reserves, enabling the production of affordable, high-quality humates for soil enhancement. In this study, wheat and barley straw were pelletized with barley bran at a 90:10 ratio. Pyrolysis was conducted at 500 °C with a heating rate of 5 $°C \cdot min^{-1}$ and a one-hour holding time. The resulting biochar was added to a lettuce cultivation substrate at a 1:10 biochar-to-peat ratio. Humic substances derived from lignite were applied in 3% and 9% aqueous solutions, and environmental conditions, such as humidity and temperature, were monitored throughout the 35-day trial. Results showed that granulated biochar increased lettuce rosette diameter by 7.5% compared to perlite substrates and by 11.6% compared to peat. Additionally, 3% humate solutions enhanced rosette diameter by 11.6% and biomass weight by 25.77%. These findings confirm that biochar from agricultural residues and lignite-derived humates effectively boost lettuce yield and quality.

Key words: Agro-ecology, biochar, biomass, agricultural residues, lignite-derived humates, soil quality, *Lactuca sativa*, growth stimulants, carbon cycle, crop, renewable resources.

INTRODUCTION

Waste utilization is one of the most pressing challenges of the modern era. The annual accumulation of waste in Europe continues to rise, causing severe harm to the environment (Kshitij et al., 2022). Although not all types of waste are suitable for recycling, many can be repurposed to produce new materials or used as raw resources. The rapid development of the 'green' economy shifts the focus from waste disposal to recycling, prioritizing the transformation of waste into new materials. This strategy broadens the resource base and enables efficient recycling, reducing the cost of final products. A significant quantity of plant-based waste and agricultural by-products is generated annually, including fruit tree pits, nutshells, cereal husks, acorns, straw, corn residues, sunflower hulls, and bamboo waste (Nunes et al., 2020; Barr et al., 2022; Xu et al., 2022; Huang et al., 2023; Qin et al., 2023; Torres-Lara et al., 2023; Y. Wang et al., 2023; Alonso-Gómez et al., 2024). The disposal of such waste often incurs substantial costs (Koul et al., 2022), as transportation and removal from fields or gardens can be expensive. Incineration remains the most common disposal method but poses serious environmental risks. This process pollutes the environment, fails to yield valuable by-products, and is increasingly restricted in many countries due to its adverse effects (Wen et al., 2020; Sharma et al., 2022). Incineration of biomass contributes to global warming, climate change, air and water pollution, and the accumulation of heavy metals in plants. Additionally, the low specific density and insufficient combustion heat of certain biomass types complicate transportation and reduce the feasibility of this disposal method. Cultivating environmentally friendly agricultural products, particularly freshly grown vegetables and salads, is critically important. These crops are among the most nutritionally valuable, supplying approximately one-third of the daily energy requirements of the human body. They are key sources of carbohydrates, proteins, essential oils, biologically active compounds, and mineral elements (Zanin et al., 2019). Organic farming practices are gaining widespread adoption, with organo-mineral fertilizers, biological agents, and humic preparations playing essential roles in sustainable crop production (Canellas et al., 2015). Optimal plant growth and development depend on favorable environmental conditions, which are not always achievable. Soil moisture is particularly crucial, as plants are highly sensitive to its levels. A lack of moisture leads to physiological and biochemical changes in plant tissues, ultimately reducing both crop quality and productivity (Canellas & Olivares, 2014). The Dnipro coal basin in Ukraine contains extensive lignite reserves, offering a cost-effective source for producing high-quality humates to enhance soil properties (Starostenko et al., 2024). The use of biostimulants in agriculture is widely prevalent, with these substances being derived from various raw materials Table 1. A biostimulant such as biochar has broader applications across various fields, as described in our previous publication (Miroshnichenko et al., 2024). Biochar production from agricultural residues for soil quality improvement aligns with the circular economy's principles. This method of utilization reduces CO_2 emissions and lowers the cost of the final product.

Table 1. Directions for the use of biostimulants and raw materials for their production

Direction of use of biostimulant	Raw materials	Ref.
growing red seaweed Kappaphycus	brown seaweed-derived	(Munisamy et al., 2023)
cultivation of agricultural crops	wastewater	(Pérez-Aguilar et al., 2024)
plant cultivation	grass clippings, pruning waste, wood chips	(Ghoreishi et al., 2024)
the remediation of gold mine tailings	leaf extract biostimulants	(Mlalazi et al., 2024)
for growing all types of plants	peat	(Balode et al., n.d.)
enhancing cucumber plantlet growth	chitin and gelatin	(Costa et al., 2024)
paddy ecosystem	rice husk	(Zhang et al., 2024)
restoration of soil in landfills encounters	peanut shell	(Liao et al., 2024)

Fertilizers containing humic compounds have significantly benefited plant growth, promoting root development and improving water and nutrient uptake. Foliar application of humic substances reduces the ash index of saline solutions and increases their carbon content, mitigating the harmful effects of high salt concentrations on plants. These fertilizers are formulated as physiologically active, water-soluble salts of humic acids with alkali metals, providing a practical solution for sustainable agriculture (Arancon et al., 2006; Fatima et al., 2021). The production of humates from lignite in the Dnipro Coal Basin of Ukraine will significantly expand the raw material base for biostimulants, reduce the cost of agricultural crop cultivation, and contribute to the restoration of Ukraine's depleted soils resulting from military activities (Filho et al., 2024). The relevance of this study lies in its contribution to the promotion of circular economy principles, the reduction of CO_2 emissions during biomass decomposition in agricultural fields, and the expansion of the raw material base (Cheng et al., 2024). This research emphasizes the production of cost-effective humates from readily available resources through a zero-waste lignite processing approach, where the solid residue is utilized for the production of sorbents. Additionally, it seeks to enhance soil quality without relying on synthetic chemical additives, thereby aligning with sustainable agricultural practices. The study addresses pressing environmental challenges by integrating circular economy concepts into agricultural and industrial processes. Using lignite as a resource provides a pathway to affordable humates and ensures minimal environmental impact through comprehensive utilization of by-products. Reducing CO_2 emissions associated with biomass decomposition further supports global efforts to mitigate climate change. Moreover, the research highlights the potential of replacing synthetic fertilizers with natural soil amendments, contributing to the development of sustainable farming systems. The dual focus on environmental sustainability and cost-effectiveness makes this study highly relevant for regions seeking to balance agricultural productivity with ecological preservation, particularly in areas with abundant lignite reserves and agricultural waste.

MATERIALS AND METHODS

Materials and characterisation. This study aimed to investigate the effects of various humic extracts derived from lignite and biochar from agricultural residues on the morphometric parameters and yield of lettuce, emphasizing their potential use as organic fertilizers. Every year, 5 million tonnes of straw is generated in Latvia, and unfortunately, it is laid on to the fields. This activity pollutes the environment through the release of

CO_2. To combat this issue, this research considered three products, wheat straw (KV) and barley straw (MZ), as raw materials to evaluate the potential of biochar production fully. Wheat and barley straw were taken from the fields of the research center in Stende, Institute of Agricultural Resources and Economics, Talsi district, Latvia. Using an experimental setup, lignite for humate production was sourced from the Dnipro Coal Basin and processed at Kharkiv Technical University.

Determination of the amount of wood fiber (F). This test was performed per ISO 5498:1981 (2021) standard on an equipment FT 121 Fibertec Labtec line (Foss, Denmark). After boiling the sample in the solvent, filtering and evaporating the residual solvent, the sample was weighed, and the amount of wood fiber was calculated:

$$F(\%) = \frac{m1}{m2} \times 100 \tag{1}$$

where: $m1$ is the mass after test (g); $m2$ is the mass before test (g).

Extraction with organic solvents. It was carried out in the Soxhlet extractor. The extracted content was determined by weighing the raw material and the extract's dry residue after the solvent's evaporation. 5 g of the raw material was put into a filter paper cartridge which was placed in the extractor. The extraction was carried out for 6–8 hours with the solvent under vigorous boiling. The amount of extractives was determined using the following formula:

$$\mathrm{Extracts}(\%) = \frac{\mathrm{G}^0 - \mathrm{G}^1}{\mathrm{G}^0} \times 100 \tag{2}$$

where G^0 is the dry mass of the test sample (g), and G^1 is the mass of the sample extracted (g).

Lignin determination (L). Approximately 1 g of extracted air-dry raw material was transferred into a 100 mL flask with a ground glass stopper at 25 °C. The material was quantitatively transferred to a 500 mL Erlenmeyer flask using 200 mL of H_2O and boiled under reflux for 1 hour. The mixture was allowed to cool, enabling the lignin to precipitate. For optimal results, lignin filtration was performed the following day. The filter containing lignin was dried at 105 °C to a constant weight. The lignin content of the sample was calculated using the following formula:

$$\mathrm{L}(\%) = \frac{\mathrm{B} - \mathrm{C}}{\mathrm{G_W} \times (1 - \frac{\mathrm{W_r}}{100})} \times 100 \tag{3}$$

where B is the filter mass with lignin (g); C is the filter mass (g); $\mathrm{G_W}$ is the mass of dry air raw materials (g); $\mathrm{W_r}$ is the relative moisture of raw materials (g).

Cellulose, Holocellulose and Hemicellulose determination. A mixture of 5 mL HNO_3 and 20 mL EtOH was added to a conical flask containing the sample (1 ± 0.002 g). A reflux condenser was attached to the flask, which was placed in a water bath and heated for 1 hour. The flask was then removed from the bath, and its contents were cooled. The solution was carefully passed through a pre-weighed porous glass filter. The filter was rinsed back into the flask with 25 mL of freshly prepared HNO_3-EtOH mixture, and the contents were boiled under reflux for 1 hour. This procedure was repeated 3–4 times. Delignification was considered complete when a small strand of delignified wood no longer exhibited a pink coloration. After the final treatment, the cellulose was filtered, washed with 10 mL of the HNO_3-EtOH mixture, and subsequently with hot H_2O until neutral. The filter containing cellulose was dried at 105 °C to a constant weight. The cellulose content in the sample was calculated using the following formula:

$$\mathrm{C}(\%) = \frac{\mathrm{B} - \mathrm{C}}{\mathrm{G_W} \times (1 - \frac{\mathrm{W_r}}{100})} \times 100 \tag{4}$$

where B is the filter + cellulose weight (g); $\mathrm{G_W}$ is the mass of dried air raw materials (g); $\mathrm{W_r}$ is the relative moisture of raw materials (g).

To estimate holocellulose, a solution of CH_3COOH was prepared in a conical flask placed in an ice-water bath. The solution was cooled to 0–2 °C, and 30% H_2O_2 was added in small portions. An equal volume of acetic anhydride was subsequently added to maintain the temperature in the flask below 2 °C. The flask was sealed and left to stand for two days. During this period, the concentration of peracetic acid reached 14–15%, after which it began to decrease due to slow decomposition. A 1 mL sample was transferred to a 100 mL volumetric flask and diluted with distilled water to the mark. An aliquot of 15 mL was taken, mixed with 10 mL of H_2SO_4, and titrated with 0.1 M $KMnO_4$ until a pink color appeared. The reaction is represented as follows:

$5H_2O_2+2KMnO_4+3H_2SO_4 \rightarrow 2MnSO_4+K_2SO_4+5O_2+8H_2O$

Next, 15 mL of a 2% KI solution was added to the titrated sample, and the released iodine was titrated with 0.1 M $Na_2S_2O_3$ until a faint yellow color appeared. A few drops of starch solution were added, and the titration was completed when the solution turned from dark blue to colorless.

The mass percentages of peroxide and peracetic acid in the solution were calculated using the following formulas:

$$\mathrm{H_2O_2}(\%) = \frac{\mathrm{V_1} \times 0.0017 \times 100}{15} \times 100 \tag{5}$$

$$\mathrm{CH_3COOH}(\%) = \frac{\mathrm{V_2} \times 0.0038 \times 100}{15} \times 100 \tag{6}$$

where 0.0017 was the weight 1 mL 0.1 M $KMnO_4$ (g); 0.0038 was the weight 1 mL 0.1 M $Na_2S_2O_3$ (g).

The total hemicellulose content was calculated as follows:

$$\mathrm{HC}(\%) = \mathrm{H} - \mathrm{C} \tag{7}$$

where H is holocellulose content (%); C is cellulose content (%).

Determination of elements in the raw materials. The Kjeldahl nitrogen and protein content in the raw material were analyzed by LVS EN ISO 20483:2014 and ASTM D3590-17 standards. Biomass samples were subjected to digestion at 320 °C using H_2SO_4 in a SpeedDigester K-439 unit (BUCHI, Flawil, Switzerland). Following digestion and cooling, the samples were titrated using a KjelFlex K-360 apparatus (BUCHI, Switzerland). The nitrogen content was calculated using the following formula:

$$\mathrm{N}(\%) = \frac{1.4 \times \mathrm{C} \times (\mathrm{V_1} - \mathrm{V_2})}{\mathrm{m}} \times 100 \tag{8}$$

where 1.4 is the coefficient; C is the HCl concentration; $\mathrm{V_1}$ is the volume of HCl used to titrate the sample; $\mathrm{V_2}$ is the volume of HCl used for idle titration; m was the sample mass (g).

To determine the trace elements in lignite, the following methods were employed TGA701 Thermogravimetric Analyzer (LECO Corporation, USA). The determination of carbon and nitrogen in pyrolyzed granules was conducted using a FlashSmart™ Elemental Analyzer (Thermo Fisher Scientific (Bremen) GmbH, Germany) analyzer by LVS ISO 10694:2006 and LVS ISO 13878:1998 (LVS_ISO_10694_2006_A_L, n.d.; LVS_ISO_13878_1998, n.d.)

Granulation. The raw materials were initially pre-crushed using a VIKING GE 250 S apparatus (Viking GmbH, Kufstein, Germany), followed by secondary grinding in a disintegrator. Granulometric analysis revealed that the degree of grinding performed on the disintegrator Veb Nosser Maschinenbau 8255 (Nossen, Germany) did not significantly influence the characteristics or distribution of the resulting fractions. After each stage of comminution, the material was sieved using a set of sieves with mesh sizes of 0.01, 0.2, 0.25, 1.00, and 1.77 mm.

The complete technological process for biochar production comprises four stages:

1. Preparation of raw materials, including grinding of barley straw (MZ), wheat straw (KV), and homogenization of bran (MZGA).
2. Preparation of a homogeneous wet mixture.
3. Granulation process using a pelletizer.
4. Pyrolysis process.

For further experiments, the optimal composition, based on mechanical strength criteria, consisted of 90% plant material and 10% bran (MZGA).

Pyrolysis. The pyrolysis of raw materials was performed in a metal pyrolyzer equipped with an inert gas (argon) supply to facilitate the removal of volatile substances. The pyrolyzer containing the granules was placed in a muffle furnace (LE 05111, LAC, Czech Republic) and heated under an argon atmosphere to a final temperature of 500 °C at a heating rate of 5 $°C\cdot min^{-1}$, following the principles of slow pyrolysis. The inert gas flow rate was maintained at 20 $mL\cdot min^{-1}$, with the material held at the final temperature for 1 hour. The yield of the final product was calculated using the following formula:

$$\text{Yield (\%)} = \frac{m_2}{m_1} \times 100 \tag{9}$$

where: m_1 is the mass before pyrolysis (g); m_2 is the mass after pyrolysis (g).

Technology for Producing Humates from Lignite. Lignite for humate production was obtained from the Dnipro Lignite Coal Basin of Ukraine. A 100 g portion of air-dried lignite is ground to a particle size of 200 μm and soaked in a 1% NaOH solution at a coal-to-solution ratio of 1:10. The mixture is then maintained at 50 °C for 5 hours with periodic stirring. The resulting humate solution is allowed to settle and then centrifuged LMC-4200R (BioSan, Latvia) for 15 min at 5,000 rev min^{-1}. The obtained solution is dried at 90 °C to produce a dry humate powder (Memmert GmbH +Co. KG, Germany). A humate solution of the desired concentration is subsequently prepared from this powder.

Tests in real plantation conditions. The experiments were conducted under real conditions in Latvia, using pot trials to grow lettuce (*Lactuca sativa*). Planting pots with a volume of 6 liters were equipped with SOIL SCOUT soil moisture sensors (Lapinlahdenkatu, Helsinki, Finland). The average soil temperature in the pots during the experiment was maintained at 22–28 °C. Sensor readings were recorded and monitored daily. Pure peat and peat with perlite served as the control sample for comparison. Data processing was performed with a Microsoft Excel for Windows 2013 program package using a single-factor variance analysis with 2 repetitions. The calculation was performed separately for each indicator (LSD 0.05). The pH was analyzed according to LVS EN ISO 10390:2022, Ministry of Defense Procedure No. 1 of January 4, 2022 (Annex 5, Method 1) was used to determine the organic matter, Egner-Riem method (Ministry of the Interior Order No. 1 of January 4, 2022 (Annex 5, Method 3)) was used to determine mobile phosphorus and potassium, total nitrogen in substrates was determined according to LVS EN ISO 11261:2002L.

RESULTS AND DISCUSSIONS

Characterization of the raw materials

The characterization of raw materials for biochar production is presented in (Table 2).

Table 2. The characterization of raw materials for biochar production

Content of parameter, wt.%						
Samp. abbr.	Wood fibre content	Extr. sol. in acetone	Lignin	Cellulose	Holocell.	Hemicell.
KV	47.44 ± 0.06	2.50 ± 0.12	22.42 ± 0.18	42.73 ± 0.08	71.13 ± 0.11	28.4 ± 0.06
MZ	55.86 ± 0.08	2.09 ± 0.16	20.53 ± 0.12	46.60 ± 0.14	72.52 ± 0.08	25.92 ± 0.06

The wood fiber content in barley straw is 17.74% higher than in wheat straw, while the cellulose content exceeds 8.3%. Based on these findings, it can be hypothesized that the porous surface of granules derived from barley straw will be more developed than those produced from wheat straw. This characteristic is expected to enhance the substrate's water retention capacity and positively impact plant growth (Papadimitriou et al., 2024). After pyrolysis, the yield of the resulting biochar and the carbon and nitrogen content were determined. The results of the study are presented in (Table 3).

Table 3. Characteristics of granules after pyrolysis

Sample	Content of parameter, wt.%		
abbrev.	Yield	C	N
KV	45 ± 0.06	51.4 ± 0.02	0.72 ± 0.03
MZ	55 ± 0.26	56.8 ± 0.07	0.58 ± 0.02

Although barley straw and wheat straw are classified as the same type of biomass, the composition of granules after pyrolysis shows slight differences. The biochar yield from barley straw is 22%higher than that from wheat straw, which can be attributed to its higher wood fiber content. Visually, the granules derived from barley straw appear denser and heavier. Additionally, the total carbon content in barley straw granules exceeds that of wheat straw granules by 9.5%. However, the nitrogen content is 24.4% higher in the granules produced from wheat straw. This difference could significantly impact the primary experiment involving lettuce cultivation, depending on the rate and duration of biostimulant decomposition in the soil and the migration speed of nitrogen from the biochar into the soil (K.T. Wang et al., 2024).

The characteristics of lignite and the resulting humates are presented in (Table 4).

The lignite used for humate production has a higher sulfur content than coal from other deposits (Zheng et al., 2015). The nitrogen content in the humates is three times lower than in similar studies (Wan et al., 2022). The sulfur and oxygen content are higher by 83% and 27.7%, respectively. These factors may reduce the effectiveness of biostimulants;

however, the low cost of raw materials and the need for such additives to improve soil quality in Ukraine after the military conflict maintain the necessity for this stimulant.

Table 4. Characteristics of lignite and the resulting humates

Sample abbrev.	Content of parameter, wt.%				
	S	C	H	N	O
Lignite	4.76 ± 0.06	68.07 ± 0.03	5.92 ± 0.04	0.64 ± 0.02	20.61 ± 0.02
Humic acids	4.63 ± 0.08	64.51 ± 0.12	4.82 ± 0.18	0.46 ± 0.06	25.58 ± 0.06

Six distinct soil mixtures incorporating different humic components were evaluated for comparison, as shown in (Table 5).

Table 5. Types of soil mixtures for comparison

Number in order	Name of the soil mixture	Composition
1	KV+MZGA	wheat straw (90%) + bran (10%)
2	MZ+MZGA	barley straw (90%) + bran (10%)
3	KP	peat + perlite
4	P	peat
5	PH 3%	peat + 3% humic extract from lignite
6	PH 9%	peat + 9% humic extract from lignite

Lettuce (*Lactuca sativa*) was selected as the test object for this study. On June 14, lettuce seeds were sown in pots containing various soil substrates. In the experimental variant utilizing humic substances derived from lignite, seeds were sown in peat, followed by the addition of 150 mL of 3% and 9% aqueous solutions of humic substances. Substrates containing biochar were prepared by mixing biochar with peat in a 1:10 ratio by weight (Fig. 1).

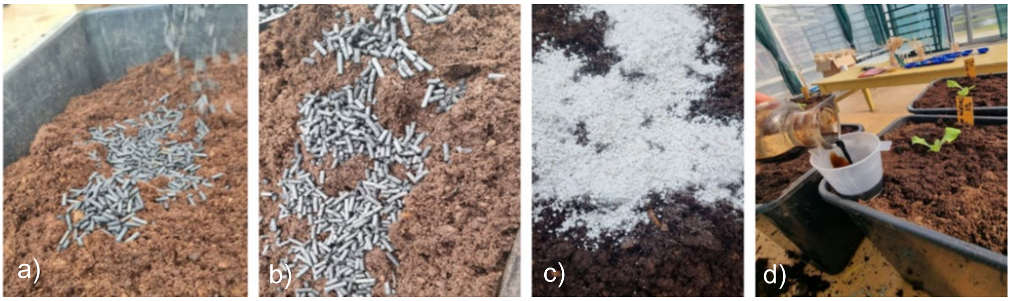

Figure 1. Appearance of soil mixtures: a) KV+MZGA; b) MZ+MZGA; c) KP; d) PH.

Seedlings emerged on day 6 after sowing in the variant treated with the 3% solution of humic substances, whereas in other variants, seedlings appeared on day 7. On days 10, 15, and 20 after sowing, the variants treated with humic substances were irrigated with 100 mL of 3% or 9% aqueous solutions of humic substances. Other variants were irrigated with 100 mL of water. The lettuce (*Lactuca sativa*) plants were cultivated in pots for 35 days (Fig. 2; Fig. 3). At the time of harvesting, the diameter of the lettuce leaf rosettes was measured. Additionally, the fresh weight of the aboveground and underground parts of the plants was recorded.

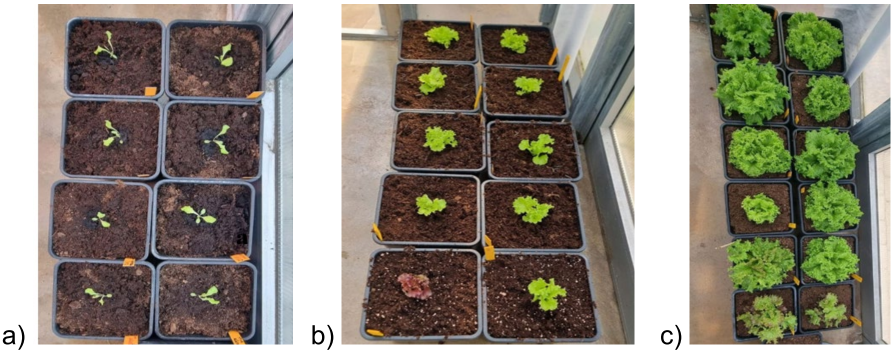

Figure 2. General view of lettuce plants (*Lactuca sativa var. secalina*): a) 11 days after sowing; b) 23 days after sowin; c) 33 days after sowing.

Figure 3. General view of lettuce plants (*Lactuca sativa var. secalina*) on the 35th day after sowing.

The analysis of lettuce rosette diameter revealed that the largest value, measuring 335 mm, was observed in the variant treated with a 3% aqueous solution of humic substances. Slightly smaller diameters were recorded in other variants utilizing different soil substrate (Fig. 4).

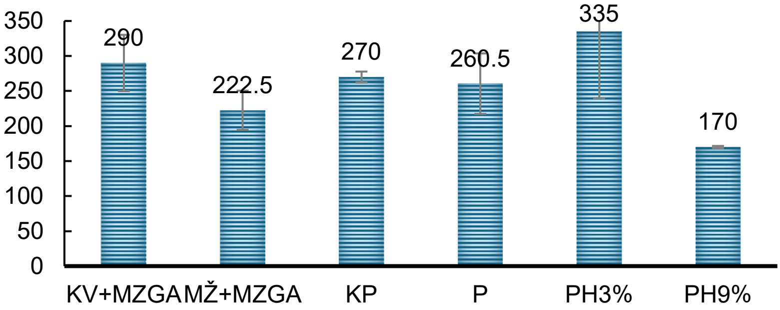

Figure 4. The effect of soil mixtures of fertilizer variants on the diameter of the leaf rosette of lettuce plants.

The smallest leaf rosette diameter was observed in the variant treated with a 9% aqueous solution of humic substances, suggesting a negative impact of this concentration on plant development.

The analysis of the weight of the aerial part of the lettuce (*Lactuca sativa*) revealed that the highest value, 135.77 g, was achieved in the variant treated with a 3% aqueous solution of humic substances. The positive effects of using humates have also been confirmed by other studies (Mridha et al., 2021). Slightly lower weights were recorded in variants with different soil mixtures (Fig. 6).

The smallest weight of the aboveground part, measuring only 37.36 g, was observed in the variant treated with a 9% aqueous solution of humic substances (Fig. 5).

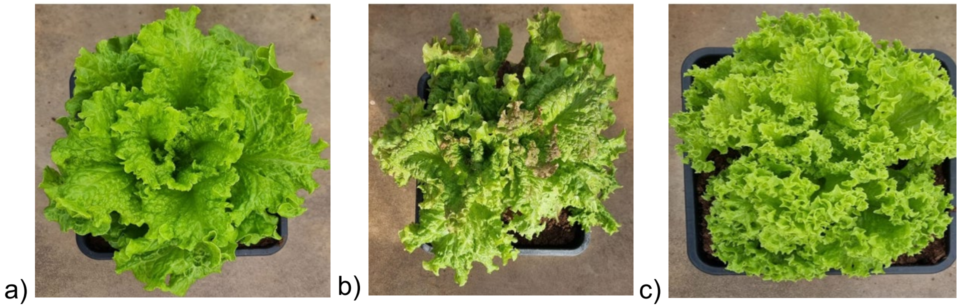

Figure 5. The effect of soil mixtures of fertilizer variants on the diameter of the leaf rosette of lettuce plants: a) PH3%; b) PH9%; c) KV+MZGA.

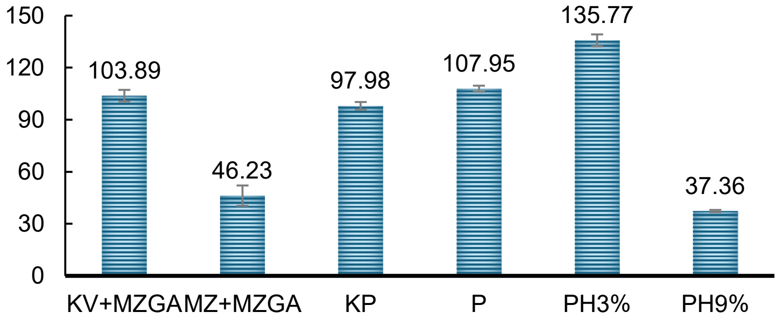

Figure 6. Effect of soil mixtures and fertilizer on the weight of the aerial part of lettuce plants.

Processing of the results using one-factor analysis with two replications in (Table 6).

Table 6. Analysis of Variance

Samples	Diameter, mm				Weight, g			
	1rep.	2rep.	Average		1rep.	2rep.	Average	
KV+MZGA	279	301	290	20	106.76	101	103.88	5.9
MZ+MZGA	218	227	222.5	-47.5	51.31	41.15	46.23	-51.75
KP	265	275	270	0	99.91	96.05	97.98	0
P	265	256	260.5	-9.5	106.5	109.4	107.95	9.97
PH3%	334.2	335.8	335	65	138.74	132.8	135.77	37.79
PH9%	171.1	168.9	170	-100	37.92	36.8	37.36	-60.62
			$LSD_{0.05}$	29.5			$LSD_{0.05}$	9.901

After the experiment, the quality of the substrates was evaluated after harvesting, and the results are displayed in (Table 7).

Table 7. Substrate analysis after the experiment and harvesting

Samples	Reaction (pH)	Organic substances, %	Mobile phosphorus (P_2O_5), mg·kg^{-1}	Mobile potassium (K_2O), mg·kg^{-1}	Total Nitrogen (N), mg·g^{-1}
KV+MZGA	6.21	81.50	713.76	7,638	12.40
MŽ+MZGA	6.58	79.91	620.84	2,015.5	15.09
KP	5.90	82.93	705.45	1,272	12.79
P	6.20	55.95	541.78	1,074.5	8.25
PH3%	5.94	48.57	590.16	1,120.5	8.73
PH9%	6.24	58.83	568.42	1,082	8.68
P (clean, not used in the experiment)	5.38	84.29	714.57	1,626.5	10.95

The sample KV+MZGA had a positive effect on substrate quality after the experiment. The content of organic matter, mobile phosphorus, and total nitrogen remained at the level of the control sample and pure peat. However, sample PH3% is more effective because it does not increase the content of mobile potassium to a critical level.

CONCLUSIONS

This study evaluated the feasibility of introducing a novel approach to circular agriculture by sustainably producing biochar from various biowaste sources to enhance soil quality and by assessing the effects of humates derived from Ukrainian lignite, applied at different concentrations, on the growth of lettuce (*Lactuca sativa*). The dual focus on biochar production and humate application exemplifies the potential for integrating sustainable practices into modern agriculture. Both approaches demonstrated that utilizing cost-effective raw materials significantly reduces the overall cost of the final product, making it accessible for broader agricultural use. The results revealed that biochar granules produced from wheat straw were the most effective among the tested materials. The use of these granules as a biostimulant increased lettuce weight by an average of 6% and lettuce diameter by 7.5% compared to a substrate containing perlite, which served as the control. This improvement highlights the value of biochar derived from wheat straw as a promising soil amendment. On the other hand, the application of humates at a 9% concentration had a detrimental effect, reducing lettuce biomass weight by 34.61% and lettuce diameter by 34.74%. These findings were consistent with visual observations, where plants appeared weak and unhealthy, likely due to an excessive concentration of micronutrients in the substrate, leading to nutrient imbalance or toxicity. Addressing this issue will form the basis of our future investigations, with a focus on understanding the interaction between high humate concentrations and soil-plant dynamics. In contrast, humates applied at a 3% concentration showed markedly positive effects on lettuce growth. The biomass of lettuce increased by 25.77%, and its diameter expanded by 28.60%, compared to the control substrate. This concentration demonstrated the ability to enhance nutrient availability and promote healthier plant development, establishing it as a viable option for agricultural applications. The findings suggest that lower concentrations of humates are more effective for improving plant growth, likely due to optimal nutrient delivery without the risk of over-saturation. These results underscore the potential of optimizing the use of biochar and humates in agriculture to achieve sustainable productivity. The study demonstrates that the integration of these soil amendments not only enhances crop growth but also contributes to reducing input costs and environmental impact. Future research should focus on scaling these methods for broader implementation and investigating their long-term effects on soil health, crop yield, and ecological sustainability.

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