



Article

Improving Chernozem Fertility and Barley Yield Through Combined Application of Phosphorus Fertilizer and Ash–Carbon Amendment

Abilzhan Khussainov ¹, Anara Sarsenova ², Anar Ayapbergenova ¹, Gulmira Kyzdarbekova ³ and Ekaterina Bazilevskaya ^{4,*} 

- ¹ Regional Institute of Applied Research and Innovation Projects, Shokan Ualikhanov Kokshetau University, 76 Abai St, Kokshetau 020000, Kazakhstan; abil_token@mail.ru (A.K.); anar_03_19@mail.ru (A.A.)
² Agrotechnical Institute, Ualikhanov Kokshetau University, Kokshetau 020000, Kazakhstan; anab76@mail.ru
³ Department of Biology, Ualikhanov Kokshetau University, Kokshetau 020000, Kazakhstan; gulmira.kyzdarbekova.80@mail.ru
⁴ Department of Ecosystem Science and Management, The Pennsylvania State University, University Park, PA 16802, USA
* Correspondence: eab204@psu.edu

Abstract

Phosphorus deficiency and declining organic matter limit crop productivity in Northern Kazakhstan's chernozem soils. This study evaluates whether the combined application of phosphorus fertilizer and an ash-carbon amendment from industrial by-products can improve soil fertility and barley yield. In a three-year field experiment (2018–2020), four P rates (1/10, 1/5, 1/2, and the full recommended dose, Prec) were tested with 100 kg ha^{−1} of ash-carbon product ("Agrobionov"). Across growth stages, we measured cellulolytic microbial activity, water-stable soil aggregates (%WSA), and grain yield. Relative to the control, P + ash-carbon increased microbial activity by up to 57.6% and %WSA by up to 76%. The highest yield (1.32 t ha^{−1}) occurred with Agrobionov + ½ Prec, a 51.7% increase over the control. These results indicate that pairing moderate P rates with an ash-carbon amendment enhances soil biological and physical properties and improves yield in P-deficient chernozems, supporting the sustainable use of industrial by-products as cost-effective soil amendments. Future work should assess long-term effects on C sequestration, nutrient cycling, and economic feasibility.

Keywords: chernozem; phosphorus fertilizer; ash-carbon amendment; microbial activity; water-stable aggregates; barley yield



Academic Editors: José L. S. Pereira and Vítor João Pereira Domingues Martinho

Received: 6 May 2025

Revised: 19 September 2025

Accepted: 20 September 2025

Published: 16 October 2025

Citation: Khussainov, A.; Sarsenova, A.; Ayapbergenova, A.; Kyzdarbekova, G.; Bazilevskaya, E. Improving Chernozem Fertility and Barley Yield Through Combined Application of Phosphorus Fertilizer and Ash–Carbon Amendment. *Soil Syst.* **2025**, *9*, 114. <https://doi.org/10.3390/soilsystems9040114>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Soil dehumification is a global environmental concern [1–4]. This process is particularly severe in the north regions of the Republic of Kazakhstan (RoK), where the development of virgin lands since 1953 has led to a 20–25% decline in humus content in chernozem soils a trend that continues today [5–7]. Dehumidification is primarily caused by the low availability of essential macronutrients in the soil, especially, available phosphorus. For example, 47.2% of arable land in Northern Kazakhstan is classified as low in available phosphorus [8,9]. Despite Kazakhstan's strong agricultural potential and its export of grain to 44 countries, average grain yields remain low, ranging from 1.0 to 1.2 t ha^{−1}, largely due to limited access to mineral fertilizers [10,11]. On average, only 5–6 kg ha^{−1} of fertilizers are applied annually, far below application rates in the USA (140 kg ha^{−1}), EU (130 kg ha^{−1}),

Latin America (90 kg ha^{-1}), and Russia (49 kg ha^{-1}). [6,7,12,13]. Of all fertilizers applied in Kazakhstan, phosphorus fertilizers account for only $3.5\text{--}4.2 \text{ kg ha}^{-1}$ of P_2O_5 . This means that in the soils of Northern Kazakhstan, the lack of phosphorus—essential for root system development and nutrient transport—further limits the growth of agricultural crops [7,14].

With rising phosphorus fertilizer costs [13,15], an alternative solution is to utilize industrial by-products such as ash and slag waste (ASW), which are already repurposed for soil applications in countries like England, Germany, the USA (70% usage), Poland, and China (80%). Kazakhstan has accumulated more than 500 million tons of ASW, 370.5 million tons of which are located in the northern region, with an additional 19 million tons generated annually [11]. Although ASW poses environmental risks through dust and leachate emissions [16,17], its application as a soil amendment offers clear advantages, including improved soil structure, increased nutrient availability and microbial activity, and reduced fertilizer costs [18–21]. Recent research further suggests that combining carbon-rich organic materials with inorganic fertilizers can yield synergistic benefits for soil fertility, nutrient use efficiency, and crop performance. Materials such as fly ash, compost, biochar, and others enhance soil pH, cation exchange capacity (CEC), and moisture retention, which are especially beneficial in degraded or nutrient-depleted soils [22–26]. When applied with mineral fertilizers, these carbon-rich amendments improve nutrient retention, benefit seedlings' emergence, reduce leaching losses, and stimulate beneficial microbial activity, especially under phosphorus and nitrogen fertilization regimes [27–30].

Building on these findings, the present study investigates the potential of Agrobionov, an ash–carbon soil amendment derived from local industrial by-products, to enhance phosphorus fertilization efficiency in degraded chernozem soils. The amendment is a powder comprising fly ash and technical carbon (~2:1). Fly ash supplies SiO_2 , Al_2O_3 , and Fe_2O_3 , which can aid structure and nutrient retention; technical carbon (from tire pyrolysis) was included ($\leq 6\%$) to improve aeration and support microbial activity [31].

Although prior work has been carried out to optimize Agrobionov application rates for enhancing nitrogen uptake in barley and to examine its effects on soil hydrophysical properties, oil flax yield, environmental safety, and microflora activity in chernozem soils [32–34], no studies have assessed its combined application with phosphorus fertilizer for barley production on Kazakhstan's chernozem soils.

It has been proven that the application of ash and slag increases soil fertility and crop yields. These materials improve the soil's physical properties, such as soil structure and water holding capacity, as well as agrochemical balance, and biological activity, thereby enhancing the yield of cereal crops. [27,30,35]. They also provide plants with essential macro- and micronutrients in available forms, enriching the soil's nutrient profile, improving its physical and chemical properties, and supporting the adoption of environmentally sustainable agricultural practices. Research also shows that the addition of ash and slag can enhance the soil's microbial composition and nutrient dynamics, leading to increased crop yields [21].

Cruz-Paredes et al. [16] demonstrated that incorporating ash and slag at a 5% concentration significantly increased microbial activity during a single growing season. Similarly, Mandpe et al. [21] found that the addition of fly ash improved microbial and enzymatic activity during composting processes. According to a review by Jambhulkar et al. [35], microelements derived from ash and slag can supplement nutrient-poor Indian soils, contributing to improved soil biology and plant growth. Ram and Masto [23] also emphasized the benefits of combining ash and slag with materials such as lime, gypsum, sludge, poultry manure, vermicompost, and biochar. These blended amendments not only enhance nutrient availability but also stimulate microbiological processes critical for long-term soil productivity.

Therefore, the objective of this study is to identify optimal phosphorus fertilizer rates in combination with the Agrobionov ash–carbon amendment to improve soil fertility and spring barley yields in Northern Kazakhstan. Specifically, this study evaluates the effects of these treatments on the agrophysical, agrochemical, and biological properties of chernozem soils, as well as crop performance. We hypothesized that there exists an optimal combination of Agrobionov and phosphorus fertilizer dose that produces a synergistic effect, resulting in greater improvements in soil quality and crop yield than either amendment applied alone.

2. Materials and Methods

The study was conducted from 2018 to 2020 in the experimental field at Ualikhanov Kokshetau University (KU) in Northern Kazakhstan. The region has a continental climate, characterized by cold winters and hot summers [36]. The average monthly temperature in July ranges from +19 °C to +21 °C (occasionally reaching up to +35 °C), while in January it ranges from −17 °C to −19 °C (with extreme lows down to −35 °C). The average annual precipitation is approximately 350 mm, with 150–200 mm falling during the growing season. The hydrothermal coefficient (HTC), according to Selyaninov, ranges from 0.8 to 1.0, which is the ratio of precipitation during the growing season to the sum of active temperatures. Overall, the agroclimatic conditions are favorable for cultivating spring barley. However, successful production requires water-saving technologies, minimal tillage, proper selection of crop varieties, and appropriate fertilizer management. The region is considered a zone of risk-prone agriculture and is particularly vulnerable to climate change [37].

Agrometeorological conditions during the study period varied significantly. According to the Zerenda hydrometeorological station, the 2018 growing season experienced 279 mm of rainfall, 105 mm above the long-term average of 174 mm. In contrast, 2019 and 2020 were marked by drought, receiving 112 mm and 114 mm of rainfall, 62 mm and 60 mm below the long-term average, respectively.

The experimental plot soil was an ordinary chernozem—shallow, medium humus, heavy loam, classified by World Reference Base for Soil Resources (WRB) [38] as a haplic chernozem (aric, loamic). Under the USDA Soil Taxonomy, it is classified as a Mollisol in the Ustolls suborder and, at the subgroup level, as a Typic Haplustoll. Organic matter was 4.2%, pH (water) 7.5, calcium occupied 90% of the exchange complex, and the cation-exchange capacity was 27 mol kg^{−1}, indicating good suitability for cereal crops. However, due to extensive arable use, the soil supply of easily hydrolyzable nitrogen and available phosphorus was very low (5.6 and 4.8 mg kg^{−1}, respectively), whereas exchangeable potassium was high (550 mg kg^{−1}).

Field experiments were conducted to assess the impact of different phosphorus fertilizer doses in combination with the Agrobionov (AGB) ash–carbon amendment on soil fertility and barley yield. Designed for enhancing soil fertility, improving water retention, and stabilizing degraded soils, the AGB amendment represents a sustainable solution that repurposes industrial by-products into a valuable agricultural resource. The chemical composition of AGB is 30% carbon, 44. % SiO₂, 18.5% Al₂O₃, 4.45% Fe₂O₃, along with other trace elements. The X-ray fluorescence analysis revealed insignificant levels of trace metals (Appendix A.1), much lower than the background levels in non-contaminated soils in Kazakhstan [39]. The ash–carbon product we used is marketed under the trade name Agrobionov.

The experiment included six treatments. There were a control without fertilizer or amendment, an AGB-only treatment with 100 kg ha^{−1}, and four treatments combining 100 kg ha^{−1} of AGB with different phosphorus fertilizer rates: AGB+1/10Prec, AGB+1/5Prec, AGB+1/2Prec, and also Prec, which was the full calculated recommended

dose without AGB. The full recommended phosphorus fertilizer dose was calculated based on the expected yield of spring barley (2.5 t ha^{-1}), taking into account phosphorus removal by the crop and the soil's available phosphorus content, 4.8 mg kg^{-1} . The field experiment was conducted over three years, each year on new plots following spring wheat as the preceding crop. Each plot measured 125 m^2 , with a registration area of 85 m^2 , and the experiment was repeated four times on chernozem soil characterized by low nitrogen and phosphorus levels but high potassium availability. Soil samples were collected from 0–20 cm and 20–40 cm depths in spring, summer, and autumn to evaluate changes in soil structure, nutrient content, microbial activity, and crop performance. The study analyzed soil aggregate composition, water-stable soil aggregates (%WSA), bacterial activity, and barley yield. Potential heavy-metal contamination from the AGB amendment was assessed by testing the amendment material, soil, and grain.

Water-stable aggregates (%WSA) were determined by wet sieving under bench-top conditions [40] (Kemper and Rosenau, 1986) which evaluates the resistance of aggregates to dispersion under water through controlled immersion and mechanical agitation. Microbiological activity was analyzed by an accredited laboratory, to which soil samples were submitted for certified testing and reporting. Cellulolytic bacterial activity was measured using the method of E.N. Mishustin (1979) [41], wherein cellulose strips were buried at a depth of 0–20 cm and retrieved at three key phenological stages—May (after sowing), July (barley heading), and August (prior to harvest)—with three replicates per sampling period to assess microbial decomposition rates. To determine heavy-metal content in spring barley grain, 1 kg composite samples were collected from the overall lot, taking into account the yield of each treatment, in accordance with Interstate Standard GOST 13586.3-2019 [42]. Heavy metals in the grain were determined by stripping voltammetry in accordance with GOST 50686-94 and GOST 50683-94. Heavy metals in the Agrobionov amendment were determined using a portable X-ray fluorescence spectrometer [43].

Pairwise correlation was calculated using EXCEL, while ANOVA + Tukey HSD analysis of yield data was conducted in Statistika software, version 10 [44] applying the Fisher method [45] and R studio [46] with a significance level of $\alpha \leq 0.05$. We report LSD_{05} (least significant difference at $\alpha = 0.05$) from one-way ANOVA and Pearson's r between P rate and response within each month.

3. Results

3.1. Cellulose-Decomposing Microbial Activity

Over the three-year study, the activity of cellulose-decomposing bacteria in the control plots averaged 21.77%, while in fertilized variants, it increased significantly to 32.30–34.30%, depending on the phosphorus fertilizer dose. The highest microbial activity was observed in the AGB+1/2Prec (34.30%) and AGB+1/5Prec (33.62%) treatments, representing a 57.6% and 54.4% increase over the control, respectively. This enhancement in cellulose-decomposing bacterial activity suggests an improvement in soil microbial function due to the combined effect of phosphorus fertilization and the Agrobionov amendment. A moderate positive correlation ($r = 0.50$) was established between phosphorus fertilizer doses and bacterial activity, indicating that higher phosphorus availability supported microbial decomposition processes in the soil (Figure 1).

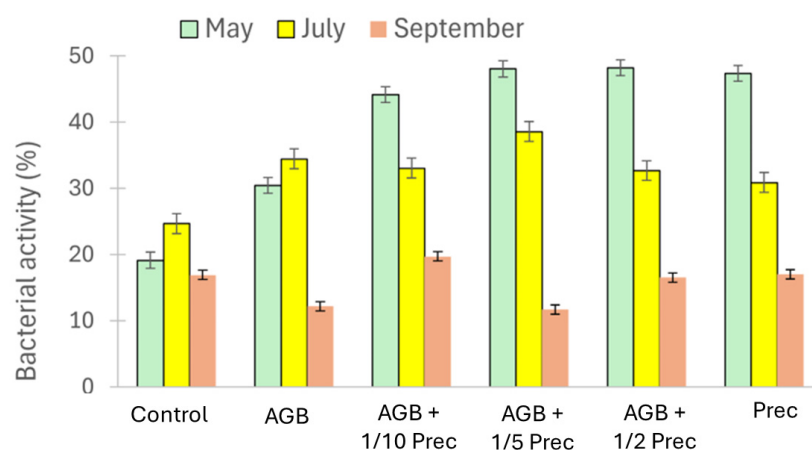


Figure 1. The effect of phosphorus fertilizer doses in combination with the Agrobionov amendment on cellulose-decomposing bacterial activity in ordinary chernozem during the cultivation of spring barley in the 0–20 cm soil layer in 2018. LSD_{05} and Pearson's r (correlation between phosphorous application rate and cellulose-decomposing activity): May—1.50 and 0.54; July—1.50 and 0.09; September—0.70 and 0.02; mean—1.40 and 0.45.

Figure 1 indicates that microbial activity varied across different months, with measurable differences in response to phosphorus application. The least significant difference (LSD_{05}) and correlation coefficient (r) values suggest variations in microbial response depending on the time of measurement. In May, microbial activity showed a stronger correlation with phosphorus application ($r = 0.54$) and an LSD_{05} value of 1.50, indicating significant differences between treatments. By July, the correlation weakened ($r = 0.09$), while the LSD_{05} remained at 1.50, suggesting that microbial activity had stabilized. In September, the correlation was minimal ($r = 0.02$), with an LSD_{05} value of 0.70, indicating fewer statistically significant changes among treatments. On average, across all months, the LSD_{05} was 1.40, with a moderate overall correlation of $r = 0.45$, reinforcing that phosphorus application in combination with the Agrobionov amendment influenced microbial activity, particularly in the early stages of barley growth.

3.2. Water-Stable Soil Aggregates (%WSA)

The soil aggregate stability (%WSA) showed no significant overall changes; however, a notable improvement in water-stable aggregates was observed in the top 20 cm layer of treated plots, particularly in the AGB+1/5Prec, AGB+1/2Prec, and Prec variants. The water resistance of soil aggregates increased from 29% in the control to 34.0–51.3% in treated plots, indicating that the combination of ASW-based materials and phosphorus fertilizer contributed to enhancing soil physical properties. The highest water stability was recorded in AGB+1/5Prec (51.3%), AGB+1/2Prec (46.0%), and Prec (46.3%) (Figure 2), suggesting that these amendments reinforced soil structure and aggregation. A weak but positive correlation ($r = 0.46$) was found between the water stability of soil aggregates and phosphorus fertilizer doses.

In the 20–40 cm soil layer, %WSA also increased in fertilized plots, ranging from 29% to 44%, compared to 15% in the control. The most significant improvements were observed with the AGB+1/5Prec (44.0%) and Prec (36.7%) treatments. These results suggest that the application of Agrobionov amendment and phosphorus fertilizers contributed to greater soil stability and resilience, particularly in the topsoil, where organic matter and microbial activity play a crucial role in soil aggregation and structure formation.

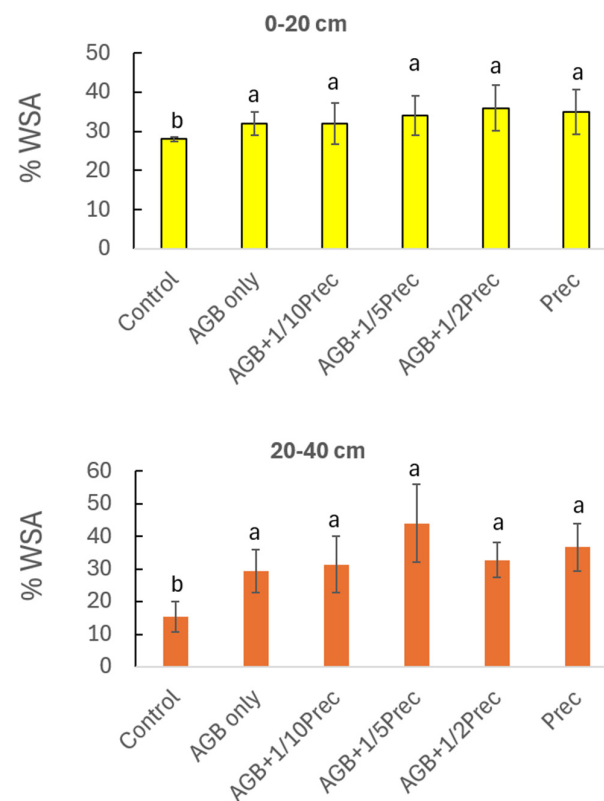


Figure 2. % water stable aggregates in soil layers 0–20 cm and 20–40 cm. LSD_{05} (0–20 cm) = 9.9, LSD_{05} (20–40 cm) = 14.2. At both depths, all amended treatments exceed the control (letters: control = b, all amendments = a; $\alpha = 0.05$). Differences among amended treatments are not statistically separable (shared a), though AGB+1/2 Prec shows the highest mean at each depth. Subsoil %WSA is lower than at the surface, yet amendments still yield significant gains over the control.

3.3. Barley Crop Yields

Spring barley yields in treated plots significantly exceeded those in the control, ranging from 1.11 to 1.32 t ha⁻¹. The highest yield (1.32 t ha⁻¹) was observed in AGB+1/2Prec plots, representing a 51.7% increase compared to the control (Table 1). This substantial yield improvement suggests that the combination of Agrobionov amendment and phosphorus fertilization played a critical role in enhancing soil fertility and plant productivity.

Table 1. Effect of doses of phosphorus fertilizer in combination with the Agrobionov (AGB) amendment on the yield of spring barley.

Option	Productivity by Year, t ha ⁻¹				Increase Over Control	
	2018	2019	2020	Mean	t ha ⁻¹	%
Control	0.77	0.75	1.08	0.87	-	-
AGB * only	0.82	0.87	1.20	0.96	0.09	10.3
AGB+1/10Prec **	1.16	0.91	1.37	1.15	0.28	32.1
AGB+1/5Prec	1.00	0.94	1.39	1.11	0.24	27.6
AGB+1/2Prec	1.44	1.06	1.46	1.32	0.45	51.7
Prec	1.00	0.92	1.40	1.10	0.23	26.4
LSD_{05}	0.07	0.10	0.10	0.09		

* Agrobionov amendment; ** the full calculated recommended dose without AGB.

In 2018, on the treated plots, barley yield increased significantly depending on the phosphorus fertilizer rate by 0.23–0.67 t ha⁻¹ (29.9–87.0%) compared with the control (control yield 0.77 t ha⁻¹). The least significant difference at the 5% level (LSD_{05}) was

0.07 t ha⁻¹. The highest yield, 1.44 t ha⁻¹, was obtained with the AGB+1/2 of the calculated dose of available phosphorus. The exception was the AGB 100 t ha⁻¹ treatment, where the yield increase was not significant (yield 0.82 t ha⁻¹). In 2019, all treated variants produced a significant yield gain of 0.12–0.31 t ha⁻¹ (16.0–41.3%) (LSD₀₅ = 0.10 t ha⁻¹). In 2020, the yield increase was 0.12–0.38 t ha⁻¹ (11.1–35.2%). On average, in 2018–2020, barley yield from the treated variants was 0.96–1.32 t ha⁻¹, exceeding the control by 0.45–0.90 t ha⁻¹ (10.3–51.7%) (LSD₀₅ = 0.09 t ha⁻¹). The maximum average yield was achieved with AGB+1/2 of the calculated dose of available phosphorus—1.32 t ha⁻¹, which was 0.45 t ha⁻¹ (51.70%) above the control (Figure 3).

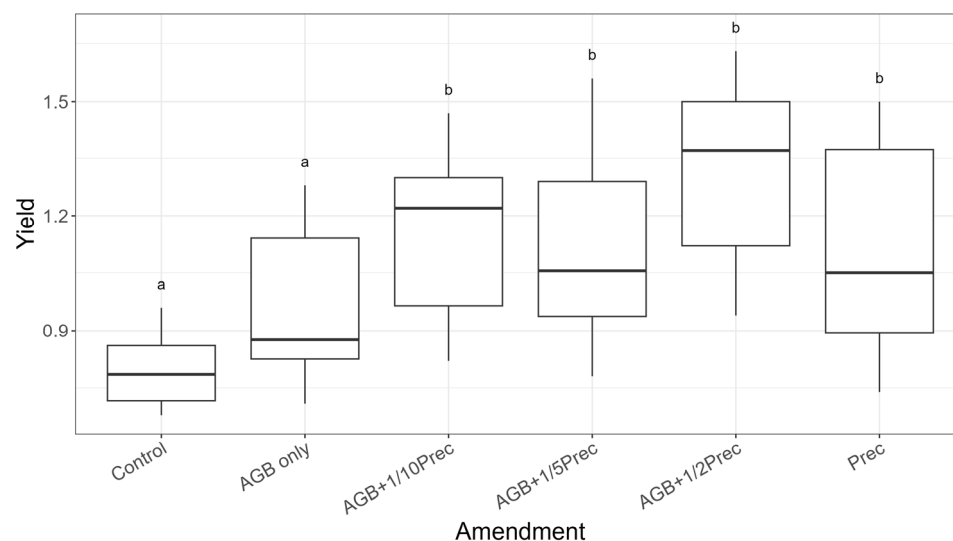


Figure 3. Barley grain yield (t ha⁻¹) across all years by amendment treatment. Boxplots show median (line), interquartile range (box), and 1.5 × IQR whiskers. Letters denote groups from Dunn's post-hoc test at $\alpha = 0.05$; treatments sharing a letter do not differ. Single-year results are provided in Appendix A.2 (Figure A1).

These results align with previous studies demonstrating that ash and slag waste (ASW) applications contribute to soil fertility improvements and yield increases by enhancing soil physical, chemical, and biological properties [16,23,24,47]. The integration of ASW with phosphorus fertilization has been shown to stimulate beneficial soil microflora, increase microbial activity, and improve nutrient availability, leading to better root development and plant growth. These findings reinforce the potential of ASW-based amendments as a sustainable agricultural practice, supporting long-term soil health, nutrient efficiency, and improved crop productivity.

Application of the ash–carbon product in combination with a phosphorus fertilizer increased the copper content to 0.14–2.01 mg kg⁻¹ (vs. 0.10 mg kg⁻¹ in the control), which is far below the maximum permissible concentration (MPC) of 33 mg kg⁻¹. Zinc did not exceed the control concentration (1.6 mg kg⁻¹) and ranged from 1.0 to 2.3 mg kg⁻¹. Lead in spring barley grain increased to 0.30–0.43 mg kg⁻¹ in the fertilized treatments (vs. 0.25 mg kg⁻¹ in the control) but remained well below the MPC of 32 mg kg⁻¹ [48]. From an environmental safety standpoint, the most favorable options were treatments with ½ of the calculated P-fertilizer rate combined with the Agrobionov product at 100 kg ha⁻¹, since granular double superphosphate contains lead compounds. In contrast, no detectable Pb was observed in the Agrobionov amendment. Cadmium, arsenic, and mercury levels in the barley grain were below detection limits.

4. Discussion

The application of ash and slag has been shown to enhance soil fertility and crop productivity. These materials improve stability of soil aggregates, water holding capacity, agrochemical balance, and biological activity in the soil, thereby increasing grain crop yields [23,49]. They also contribute essential macro- and micronutrients in plant-available forms, enriching the soil's nutrient profile, enhancing physical and chemical characteristics, and promoting environmentally sustainable agricultural practices. Studies further indicate that the addition of ash and slag can improve soil microbial composition and nutrient dynamics, resulting in increased crop yields [21].

The combined application of phosphorus fertilizer and the Agrobionov (AGB) amendment significantly improved soil physical and biological properties, as evidenced by increased water-stable aggregate formation, microbial activity, and spring barley yield. These improvements were consistent across both topsoil (0–20 cm) and subsoil (20–40 cm) layers, indicating a broad impact on soil structure and function. Similar synergistic effects have been reported when organic or industrial by-product amendments have been combined with mineral fertilizers to enhance soil fertility and crop performance [23,27,49,50].

Phosphorus fertilization contributed to soil structural improvement by stimulating root growth and enhancing the secretion of polysaccharides, which are natural biopolymers that bind soil particles and promote aggregate formation [51–53]. In tandem, components of the Agrobionov amendment—particularly, fly ash—supplied silica and alumina, which reinforced soil cohesion and mechanical strength [54]. The presence of technical carbon and alkaline binding agents is likely to have further enhanced aggregate stability by promoting cementation processes. Fly ash, rich in SiO_2 , Al_2O_3 , and Fe_2O_3 , has been shown to improve soil aggregation and water-holding capacity when applied at appropriate rates [55].

Enhanced microbial respiration and enzymatic activity stimulated by the mineral and carbonaceous components of Agrobionov can play a key role in nutrient cycling and long-term soil function [47]. These biological responses are particularly pronounced in phosphorus-deficient soils, where fertilization alleviates nutrient stress and encourages root exudation, microbial proliferation, and extracellular polysaccharide production [56]. A moderate positive correlation ($r = 0.46$) between phosphorus application rate and aggregate stability supports the involvement of these biological mechanisms in soil structure development [57].

The observed increase in water-stable aggregates (2.3–6.5%) reflects the synergistic effects of Agrobionov's mineral and carbon inputs, which improved the physical structure of the soil while fostering a favorable environment for microbial activity. Root-induced changes in the rhizosphere, combined with microbial enzyme production, probably created a positive feedback loop that sustained aggregate formation and enhanced nutrient retention.

Spring barley productivity was particularly responsive to moderate phosphorus inputs in combination with AGB. The AGB+1/2Prec treatment produced the highest yield (1.32 t ha^{-1}), representing a 51.7% increase over the control. This result demonstrates a notable improvement in nutrient use efficiency, as similar or superior outcomes were achieved with lower fertilizer input compared to the highest phosphorus-only treatment (P68). These findings highlight the potential for nutrient savings and reduced environmental loading when AGB is integrated into fertilization regimes.

Beyond their agronomic benefits, Agrobionov amendments offer a sustainable approach to soil fertility management by repurposing industrial by-products such as fly ash and technical carbon derived from waste tires. Tire pyrolysis char (TPC), which shares similarities with biochar, has gained interest as an agricultural amendment due to its high porosity and carbon content, and its potential to improve soil aeration and water retention

and stimulate microbial activity [51–53]. However, TPC and similar materials must be used cautiously due to potential contamination by trace metals and polyaromatic hydrocarbons [53]. Pre-treatment methods such as acid washing have been shown to reduce toxicity and improve safety for agricultural use [16]. In this study, chemical analyses confirmed that the AGB amendment contained only trace concentrations of metals, well below background levels [39], supporting its suitability as a safe and effective soil amendment.

Overall, the integration of Agrobionov with phosphorus fertilization significantly enhanced soil aggregate stability, microbial function, and barley productivity, particularly in the biologically active topsoil layer. These improvements are attributed to a combination of organic binding agents, root exudation, and microbial stimulation.

5. Conclusions

Microbial activity, as measured by flax cloth decomposition, increased by 54–58% in AGB+1/5Prec and AGB+1/2Prec treatments. Aggregate stability in the 0–20 cm soil rose from 29% (control) to 46–51% in the AGB+1/5Prec, AGB+1/2Prec, and Prec treatments. Spring barley yield increased from 0.87 t ha^{−1} in the control to 1.11–1.32 t ha^{−1} in treated plots, with the highest yield observed in AGB+1/2Prec (a 51.7% increase).

These results demonstrate the effectiveness of Agrobionov–phosphorus combinations in improving microbial function, soil structure, and crop yield. The amendment also reduced the need for high phosphorus doses while maintaining yield performance, highlighting its role in enhancing nutrient use efficiency.

Composed of fly ash and technical carbon, Agrobionov repurposes industrial by-products in line with circular economy principles. Given its low trace-metal content, the Agrobionov product aligns with circular-economy principles and appears safe at the tested rate; multi-year monitoring of C stocks and nutrient dynamics is warranted.

Author Contributions: Conceptualization, A.K.; methodology, A.S. and G.K.; validation, G.K. and E.B.; formal analysis, A.A.; investigation, A.A.; resources, A.S.; data curation, G.K.; writing—original draft preparation, A.K. and A.A.; writing—review and editing, E.B.; visualization, A.A. and E.B.; supervision, A.K.; project administration, A.K.; funding acquisition, A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Grant No. AR05131092, Agreement No. 213 dated 19 March 2018 for the project titled “*Ecological and agrochemical assessment of the application of ash and slag-based and nanocarbon-based preparations as fertilizers for chernozem soils cultivated with agricultural crops*”. This research was funded by Grant No. AR05131092 (Agreement No. 213, 19 March 2018) for the project “*Ecological and agrochemical assessment of the application of ash- and slag-based and nanocarbon-based preparations as fertilizers for chernozem soils cultivated with agricultural crops*”, through grant financing of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original (raw) data are provided in the Appendix A.3.

Acknowledgments: The authors thank all project participants and laboratory staff for their support and contributions. The authors gratefully acknowledge the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan for supporting this research through grant funding (Grant No. AR05131092, Agreement No. 213 dated 19 March 2018) for the project titled “*Ecological and agrochemical assessment of the application of ash and slag-based and nanocarbon-based preparations as fertilizers for chernozem soils cultivated with agricultural crops*”.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AGB	Agrobionov amendment
ASW	Ash and slag waste
IQR	Interquartile range
KU	Ualikhanov Kokshetau University
LSD ₀₅	Least significant difference at the 5% probability level ($\alpha = 0.05$)
MPC	Maximum permissible concentration

Appendix A

Appendix A.1

Table A1. X-ray fluorescence analysis (XRF) of trace metals in the Agrobionov amendment. <LOD—below detection limit. LODs for trace metals of Olympus Vanta XRF on the order of few ppm are reported in [58].

Ti, wt%	Fe, wt%	Mn, wt %	Zr, ppm	As, ppm	Cu, ppm	Ni, ppm	Co, ppm	Pb, ppm
0.60 ± 0.008	4.31 ± 0.1	0.98 ± 0.01	168 ± 4.7	14 ± 1	<LOD	<LOD	<LOD	<LOD

Appendix A.2

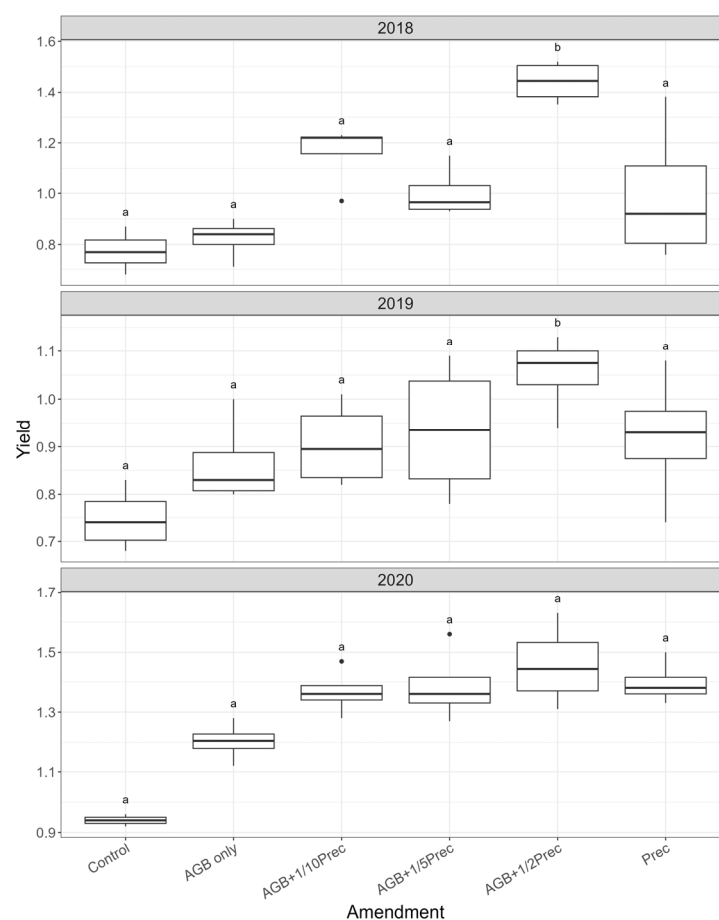


Figure A1. Barley grain yield (t ha⁻¹) by amendment for 2018, 2019, and 2020. Boxplots show the median (line), interquartile range (box), and $1.5 \times$ IQR whiskers; points denote outliers. Letters above

boxes indicate groups from Dunn's post-hoc test at $\alpha = 0.05$, with comparisons made within each year (treatments sharing a letter do not differ). In 2018, AGB+1/2Prec produced the highest yield and was significantly greater (b) than all other treatments (a); the same pattern persisted in 2019, with AGB+1/2Prec outperforming the rest (b vs. a). In 2020, no pairwise differences were detected (all treatments a), although AGB+1/2Prec still showed the highest central tendency. Across years, P-containing treatments generally exceeded the control and AGB-only, with AGB+1/2Prec consistently among the top-yielding treatments.

Appendix A.3

Table A2. % water stable aggregates in soil layers 0–20 cm and 20–40 cm (replicates).

Soil Depth	Control	AGB Only	AGB+1/10Prec	AGB+1/5Prec	AGB+1/2Prec	Prec
0–20 cm	28	32	32	34	36	35
0–20 cm	30	40	48	60	56	52
0–20 cm	30	30	48	60	46	52
20–40 cm	6	16	14	20	22	22
20–40 cm	20	36	40	56	38	44
20–40 cm	20	36	40	56	38	44

Table A3. Crop yield data (replicates).

Year	Control	AGB Only	AGB+1/10Prec	AGB+1/5Prec	AGB+1/2Prec	Prec
2018	0.87	0.85	0.97	0.94	1.35	0.76
2018	0.68	0.71	1.23	1.15	1.52	1.02
2018	0.8	0.9	1.22	0.99	1.5	1.38
2018	0.74	0.83	1.22	0.93	1.39	0.82
2019	0.83	1	1.01	1.02	1.06	1.08
2019	0.77	0.85	0.95	1.09	1.13	0.94
2019	0.71	0.8	0.82	0.78	1.09	0.92
2019	0.68	0.81	0.84	0.85	0.94	0.74
2020	1.19	1.28	1.47	1.56	1.63	1.5
2020	0.96	1.12	1.28	1.35	1.39	1.37
2020	0.92	1.2	1.36	1.27	1.31	1.33
2020	1.08	1.21	1.36	1.37	1.5	1.39

References

1. Gebremedhin, M.; Coyne, M.S.; Sistani, K.R. How Much Margin Is Left for Degrading Agricultural Soils? The Coming Soil Crises. *Soil Syst.* **2022**, *6*, 22. [\[CrossRef\]](#)
2. Kenenbaev, S. Preserving Soil Fertility Is the Most Important Problem of Agriculture. *Bull. Agric. Sci. Kazakhstan* **2003**, *12*, 25–26.
3. Prăvălie, R. Exploring the Multiple Land Degradation Pathways across the Planet. *Earth-Sci. Rev.* **2021**, *220*, 103689. [\[CrossRef\]](#)
4. Yumagulova, A. *Soil Fertility, Ways of Its Regulation*; Yumagulova, A.N., Ed.; Kainar University: Almaty, Kazakhstan, 1986.
5. Kireev, A. Increasing Soil Fertility and Grain Yield through Biologization of Rain-Fed Farming. *Bull. Agric. Sci. Kazakhstan* **2000**, *3*, 29–32.
6. Paramonova, T.; Shynbergenov, Y.; Botavin, D.; Golosov, V. Assessment of Soil Pollution and Erosion Processes in the Republic of Kazakhstan According to Literature Data. *Eurasian Soil Sci.* **2025**, *58*, 11. [\[CrossRef\]](#)
7. Sarapov, A. Ways to Increase the Productivity of Agricultural Crops and Soil Fertility in Market Conditions. *Bull. Agric. Sci. Kazakhstan* **2002**, *8*, 27–29.
8. Akhzanov, Z. Analytical Note on the Trends in the Development of Soil Science. *Soil Sci. Agrochem.* **2008**, *2008*, 6–13.

9. Karbozova–Saljnikov, E.; Funakawa, S.; Akhmetov, K.; Kosaki, T. Soil organic matter status of Chernozem soil in North Kazakhstan: Effects of summer fallow. *Soil Biol. Biochem.* **2004**, *36*, 1373–1381. [\[CrossRef\]](#)
10. Kenenbaev, S.; Ramazanov, S.; Gusev, V. State and Prospects of Mineral Fertilizers Use in Agriculture of Kazakhstan. *SABRAO J. Breed. Genet.* **2023**, *55*, 886–895. [\[CrossRef\]](#)
11. Khussainov, A.; Seydalina, K. Agroecological Conditions of Chernozem Soils of Northern Kazakhstan: Monograph. 2011; p. 120.
12. Lu, C.; Tian, H. Global Nitrogen and Phosphorus Fertilizer Use for Agriculture Production in the Past Half Century: Shifted Hot Spots and Nutrient Imbalance. *Earth Syst. Sci. Data* **2017**, *9*, 181–192. [\[CrossRef\]](#)
13. Zou, T.; Zhang, X.; Davidson, E. Global Trends of Cropland Phosphorus Use and Sustainability Challenges. *Nature* **2022**, *611*, 81–87. [\[CrossRef\]](#)
14. Makenova, S.; Alipbeki, O.; Tatarintsev, V.; Inkarov, D.; Asanova, G.; Muzyka, O. Issue on Land Degradation in Kazakhstan. *Her. Sci. Seifullin Kazakh Agrotech. Univ. Multidiscip.* **2023**, *2*, 261–272. [\[CrossRef\]](#)
15. Ludemann, C.I.; Gruere, A.; Heffer, P.; Dobermann, A. Global Data on Fertilizer Use by Crop and by Country. *Sci. Data* **2022**, *9*, 501. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Cruz-Paredes, C.; López-García, Á.; Rubæk, G.H.; Hovmand, M.F.; Sørensen, P.; Kjølner, R. Risk Assessment of Replacing Conventional P Fertilizers with Biomass Ash: Residual Effects on Plant Yield, Nutrition, Cadmium Accumulation and Mycorrhizal Status. *Sci. Total Environ.* **2017**, *575*, 1168–1176. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Mayer, E.; Eichermüller, J.; Endriss, F.; Baumgarten, B.; Kirchhof, R.; Tejada, J.; Kappler, A.; Thorwarth, H. Utilization and Recycling of Wood Ashes from Industrial Heat and Power Plants Regarding Fertilizer Use. *Waste Manag.* **2022**, *141*, 92–103. [\[CrossRef\]](#)
18. Almuaythir, S.; Zaini, M.S.I.; Hasan, M.; Hoque, M.I. Sustainable Soil Stabilization Using Industrial Waste Ash: Enhancing Expansive Clay Properties. *Heliyon* **2024**, *10*, e39124. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Dhadse, S. Utilization of Fly Ash in Agriculture: Perspectives and Challenges. *J. Mater. Environ. Sci.* **2024**, *15*, 1038–1050.
20. Jangde, V.; Choubey, S.; Markam, D.K. Sustainable Circular Economy: Transforming Fly Ash into Valuable Compost. *J. Environ. Nanotechnol.* **2024**, *13*, 470–476. [\[CrossRef\]](#)
21. Mandpe, A.; Paliya, S.; Kumar, S.; Kumar, R. Fly Ash as an Additive for Enhancing Microbial and Enzymatic Activities in In-Vessel Composting of Organic Wastes. *Bioresour. Technol.* **2019**, *293*, 122047. [\[CrossRef\]](#)
22. Faloye, O.; Alatisé, M.; Ajayi, A.; Ewulo, B. Synergistic Effects of Biochar and Inorganic Fertiliser on Maize (*Zea mays*) Yield in an Alfisol under Drip Irrigation. *Soil Tillage Res.* **2017**, *174*, 214–220. [\[CrossRef\]](#)
23. Ram, L.; Mastro, R. Fly Ash for Soil Amelioration: A Review on the Influence of Ash Blending with Inorganic and Organic Amendments. *Earth-Sci. Rev.* **2014**, *128*, 52–74. [\[CrossRef\]](#)
24. Shaheen, S.M.; Shams, M.S.; Khalifa, M.R.; El-Dali, M.A.; Rinklebe, J. Various Soil Amendments and Environmental Wastes Affect the (Im) Mobilization and Phytoavailability of Potentially Toxic Elements in a Sewage Effluent Irrigated Sandy Soil. *Ecotoxicol. Environ. Saf.* **2017**, *142*, 375–387. [\[CrossRef\]](#)
25. Thapa, R.B.; Budhathoki, S.; Shilpakar, C.; Panday, D.; Alsunuse, B.; Tang, S.X.; Stahl, P.D. Enhancing Corn Yield and Soil Quality in Irrigated Semiarid Region with Coal Char and Biochar Amendments. *Soil Syst.* **2024**, *8*, 82. [\[CrossRef\]](#)
26. Oueriemmi, H.; Zoghalmi, R.I.; Le Guyader, E.; Mekki, F.; Suidi, Y.; Bennour, A.; Moussa, M.; Sbihi, M.; Saidi, S.; Morvan, X.; et al. Addressing Soil Fertility Challenges in Arid Agriculture: A Two-Year Evaluation of Combined Soil Organic Amendments Under Saline Irrigation. *Soil Syst.* **2025**, *9*, 16. [\[CrossRef\]](#)
27. Bazilevskaya, E.; Robbins, M.; Colestock, A.; SamieiFard, R. The Synergistic Effect of Biochar and Inorganic Fertilizer and Compost on Soil Fertility and Plant Growth. In Proceedings of the ASA, CSSA, SSSA International Annual Meeting, St. Louis, MO, USA, 29 October–1 November 2023.
28. Liu, M.; Linna, C.; Ma, S.; Ma, Q.; Song, W.; Shen, M.; Song, L.; Cui, K.; Zhou, Y.; Wang, L. Biochar Combined with Organic and Inorganic Fertilizers Promoted the Rapeseed Nutrient Uptake and Improved the Purple Soil Quality. *Front. Nutr.* **2022**, *9*, 997151. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Thies, J.E.; Rillig, M.C.; Graber, E.R. Biochar Effects on the Abundance, Activity and Diversity of the Soil Biota. In *Biochar for Environmental Management*; Routledge: Oxfordshire, UK, 2015; pp. 327–389.
30. Ghodszad, L.; Reyhanitabar, A.; Oustan, S.; Alidokht, L. Phosphorus Sorption and Desorption Characteristics of Soils as Affected by Biochar. *Soil Tillage Res.* **2022**, *216*, 105251. [\[CrossRef\]](#)
31. Sarsenova, A. Reclamation Preparation for Soil Fertility Increase. 2013. Available online: <https://patents.google.com/patent/RU2494137C2/en?q=Sarsenova+A+A+RU+Patent+No.+2494137+C2.2013+No.+27+Reclamation+preparation+for+soil+fertility+increase.+Google+Scholar> (accessed on 18 September 2025).
32. Khusainov, A.; Kyzdarbekova, G.; Khusainova, R. Influence of the preparation agrobionov on the hydro-physical properties of ordinary black soil and yield capacity of oil flax. *Seriâ Agrar. Nauk.* **2020**, 59.

33. Khusainov, A.; Syrlybayev, M.; Ayapbergenova, A. Environmental Safety and Efficacy of Ordinary Chernozem Fertilization with “Agrobionov” Preparation under Barley Crops. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Omsk, Russia, 4–5 July 2020; Volume 624, p. 012227.
34. Khussainov, A.; Ayapbergenova, A.; Sarsenova, A.; Aishuk, Y.; Khussainova, R. Microflora, Provision of Ordinary Chernozem with Nutrients and Barley Productivity When Inoculating the “Agrobionov” Preparation. *AGRIVITA J. Agric. Sci-Ence* **2020**, *43*, 13–24. [[CrossRef](#)]
35. Jambhulkar, H.P.; Shaikh, S.M.S.; Kumar, M.S. Fly Ash Toxicity, Emerging Issues and Possible Implications for Its Exploitation in Agriculture; Indian Scenario: A Review. *Chemosphere* **2018**, *213*, 333–344. [[CrossRef](#)]
36. World Bank Climate Change Knowledge Portal: Historical Data and Country Profile for Kazakhstan (1991–2020) [Data Set]. 2025. Available online: <https://climateknowledgeportal.worldbank.org/Country/Kazakhstan> (accessed on 18 September 2025).
37. Weather Underground Weather History for Kokshetau, 10 June 2018.
38. FAO. *World Reference Base for Soil Resources*; World Soil Resources Reports 84; FAO: Rome, Italy, 1998.
39. Kakabayev, A.A.; Sharipova, B.U.; Baranovskaya, N.V.; Rodrigo-Ilarri, J.; Rodrigo-Clavero, M.-E.; Lo Papa, G.; Bazilevskaya, E.A.; Muratbekova, S.; Nurmukhanbetova, N.; Durmekbayeva, S.; et al. Impact of Environmental Conditions on Soil Geochemistry in Southern Kazakhstan. *Sustainability* **2024**, *16*, 6361. [[CrossRef](#)]
40. Kemper, W.D.; Rosenau, R.C. Aggregate Stability and Size Distribution. In *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*; American Society of Agronomy (ASA) and Soil Science Society of America (SSSA): Madison, WI, USA, 1986; Volume 5, pp. 425–442.
41. Mishustin, E. Microbial Associations of Soil Types. *Microb. Ecol.* **1975**, *2*, 97–118. [[CrossRef](#)] [[PubMed](#)]
42. GOST 13586.5-2015; Method of Moisture Content Determination. Federal Agency on Technical Regulating and Metrology of the Russian Federation (Rosstandart): Moscow, Russia, 2019.
43. EPA. SW-846 Test Method 6200: Field Portable X-Ray Fluorescence Spectrometry for the Determination of Elemental Concentrations in Soil and Sediment; Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846), Update IVB.; U.S. Environmental Protection Agency (EPA): Washington, DC, USA, 2007.
44. StatSoft, Inc. *STATISTICA (Data Analysis Software System)*, Version 10; StatSoft, Inc.: Tulsa, OK, USA, 2011.
45. Dospekhov, B.A. *Methodology of Field Experimentation*, 5th ed.; Agropromizdat: Moscow, Russia, 1985.
46. RStudio: Integrated Development Environment for R. *Posit Software*; PBC: Boston, MA, USA, 2023.
47. Schönegger, D.; Gómez-Brandón, M.; Mazzier, T.; Insam, H.; Hermanns, R.; Leijenhorst, E.; Bardelli, T.; Juárez, M.F.-D. Phosphorus Fertilising Potential of Fly Ash and Effects on Soil Microbiota and Crop. *Resour. Conserv. Recycl.* **2018**, *134*, 262–270. [[CrossRef](#)]
48. Boluspayeva, L.; Jakubus, M.; Spychalski, W.; Abzhalelov, A.; Bitmanov, Y. Health Risk of Heavy Metals Related to Consumption of Vegetables in Areas of Industrial Impact in the Republic of Kazakhstan—Case Study for Oskemen. *Int. J. Environ. Res. Public Health* **2022**, *20*, 275. [[CrossRef](#)]
49. Shaheen, S.M.; Hooda, P.S.; Tsadilas, C.D. Opportunities and Challenges in the Use of Coal Fly Ash for Soil Improvements—A Review. *J. Environ. Manag.* **2014**, *145*, 249–267. [[CrossRef](#)]
50. Wei, W.; Yan, Y.; Cao, J.; Christie, P.; Zhang, F.; Fan, M. Effects of Combined Application of Organic Amendments and Fertilizers on Crop Yield and Soil Organic Matter: An Integrated Analysis of Long-Term Experiments. *Agric. Ecosyst. Environ.* **2016**, *225*, 86–92. [[CrossRef](#)]
51. Helleur, R.; Popovic, N.; Ikura, M.; Stanculescu, M.; Liu, D. Characterization and Potential Applications of Pyrolytic Char from Ablative Pyrolysis of Used Tires. *J. Anal. Appl. Pyrolysis* **2001**, *58*, 813–824. [[CrossRef](#)]
52. Gao, N.; Wang, F.; Quan, C.; Santamaria, L.; Lopez, G.; Williams, P.T. Tire Pyrolysis Char: Processes, Properties, Upgrading and Applications. *Prog. Energy Combust. Sci.* **2022**, *93*, 101022. [[CrossRef](#)]
53. Burdová, H.; Nebeská, D.P.; Kwoczynski, Z.; Žizková, L.; Neubertová, V.; Snow, J.; Pilnaj, D.; Baka, M.; Al Souki, K.S. A Comprehensive Evaluation of the Environmental and Health Risks Associated with the Potential Utilization of Chars Produced from Tires, Electro-Waste Plastics and Biomass. *Environ. Res.* **2025**, *264*, 120390. [[CrossRef](#)]
54. Firoozi, A.A.; Guney Olgun, C.; Firoozi, A.A.; Baghini, M.S. Fundamentals of Soil Stabilization. *Int. J. Geo-Eng.* **2017**, *8*, 26. [[CrossRef](#)]
55. Skousen, J.; Yang, J.E.; Lee, J.-S.; Ziemkiewicz, P. Review of Fly Ash as a Soil Amendment. *Geosyst. Eng.* **2013**, *16*, 249–256. [[CrossRef](#)]
56. Sher, Y.; Baker, N.R.; Herman, D.; Fossum, C.; Hale, L.; Zhang, X.; Nuccio, E.; Saha, M.; Zhou, J.; Pett-Ridge, J.; et al. Microbial Extracellular Polysaccharide Production and Aggregate Stability Controlled by Switchgrass (*Panicum virgatum*) Root Biomass and Soil Water Potential. *Soil Biol. Biochem.* **2020**, *143*, 107742. [[PubMed](#)]

-
57. Chen, M.; Liu, L.; Song, X.; Zhang, S.; Cheng, B.; Ding, X. How Does Phosphorus Fertilizer Improve the Stability of Soil Aggregates? Evidence from a Decade Fertilization Experiment. *Plant Soil* **2024**, *504*, 643–657. [[CrossRef](#)]
 58. Mendoza, L.; Nolos, R.; Villaflores, O.; Apostol, E.; Senoro, D. Detection of Heavy Metals, Their Distribution in *Tilapia* spp., and Health Risks Assessment. *Toxics* **2023**, *11*, 286. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.