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Waste or Raw Material? Perlite Concrete as Part of a Sustainable Materials Management Process in the Construction Sector

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Abstract: Recent advancements in sustainable building practices include the integration of waste materials from various industries into construction materials. This approach is currently being evaluated, allowing us to view recycled material not as waste but as a valuable resource and raw material. Such an approach involves viewing this material as a separate resource with its own distinctive properties. This article investigates the use and environmental safety of perlite-based concrete. The research focuses on the properties of immobilizing potentially toxic elements (PTEs) in soil and plants, and it examines the impact of adding activated carbon to different types of perlite concrete on these properties. Initial tests varied the content of perlite concrete (3%, 5%, and 10%) to better understand the immobilization process in soil, roots, and aboveground plant parts. The results after adding 10% activated carbon provide insights into the nature and direction of the immobilization process and in determining the optimal amount of perlite concrete to enhance this process. The soil analysis revealed that the application of PPC at a rate of 10% led to a notable elevation in soil zinc content, reaching 96.6 mg/kg—a considerable 304% increase. Similarly, the amendment of PBFC at a rate of 10% resulted in a significant enhancement in copper content, reaching 21.7 mg/kg—an 112% increase. This study also evaluates the environmental safety of using perlite concrete and activated carbon in construction projects, such as earthworks and road subbases, where the materials interact with the water–soil environment. The novelty of this research lies in its examination of the remediation potential and environmental safety of modified perlite aggregate, offering a fresh perspective on the impacts of these modifications on previously studied materials. By applying varying concentrations of the amendments, the research provides a deeper understanding of their effects, yielding significant findings that support the advancement of sustainable construction practices.

Keywords: perlite concrete rubble; expanded perlite; activated carbon; immobilization; aggregates

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1. Introduction

Expanded perlite (EP) was first discovered in 1939 in Arizona, USA, by Lee Boyer. Perlite, a siliceous volcanic glass, expands significantly when heated above 870 °C, increasing its volume by 4–20 times and forming a highly porous structure with high water absorption capacity [1–3]. It is extensively used in various industries, including the construction, agriculture, medical, and chemical sectors. The construction industry's increasing demand for energy-efficient buildings and materials has spurred a growing interest in perlite [4,5]. The global production of perlite is rising, driven by increasing demand and the pursuit of ecofriendly building materials to mitigate the environmental impact of cement production. As the global population grows and the demand for building materials increases, the traditional production of materials like Portland cement presents significant environmental challenges due to high energy consumption and CO_2 emissions. This has led to a growing interest in ecofriendly alternatives, including perlite, in construction. Global perlite production is increasing steadily, with major producers including China, Greece, the USA, and Turkey [6]. The continuous growth in demand and new capacity introductions suggest that perlite's popularity will likely persist and expand in the coming years. With its lightweight and insulating properties, perlite can contribute to developing more sustainable and energy-efficient buildings, offering a viable alternative to traditional materials. As the construction industry seeks ecofriendly solutions, perlite utilization is expected to play a significant role in meeting the demand for more environmentally responsible building materials [2,4,7–9].

The expansion process of perlite creates a frothy microstructure, endowing it with excellent insulation properties, low density, and high porosity, making it a popular choice for lightweight mineral fillers [10,11]. Lightweight concrete incorporating expanded perlite as an aggregate is well-suited for thermal insulation, although its properties differ from those of conventional concrete [12,13]. Studies have shown that powdered perlite can significantly influence the properties of both hardened and fresh concrete when used as a cement replacement [14]. This influence is particularly evident in the improvement in concrete durability, as perlite powder has been found to reduce water absorption, sorptivity, shrinkage, and susceptibility to acid attack [4]. Furthermore, the incorporation of perlite powder and nanosilica into mortar formulations has been demonstrated to enhance compressive strength and transport properties, highlighting its potential for improving mechanical properties [15]. Perlite's unique properties make it ideal for applications requiring lightweight, thermally insulating, and fire-resistant characteristics. Its expansion process, which forms a cellular structure, enhances its insulation properties, making it suitable for use in construction materials aimed at reducing heat loss and energy consumption in buildings [7,8,16,17]. The methods and applications of perlite in various economic sectors have been described above, while perlite concrete offers reduced environmental impact, excellent thermal insulation, and increased resistance to cracking [18–22]. It also shows potential for high compressive strength and durability, making it suitable for structural use. However, challenges remain in creating ecofriendly pervious concrete and ensuring high-strength and highly permeable concrete for various construction applications [12,23,24].

In light of the considerable interest in this material and the increasing number of construction companies utilizing perlite concrete blocks as their primary building material, it is imperative to consider the growing demand for methods to dispose of demolition aggregate from this material in the forthcoming years. Currently, the design of building materials often incorporates components or elements that are waste from other economic sectors. These materials have been the focus of numerous scientific studies in recent years. An approach that maximizes the use of available resources, in line with the strategy of sustainable development, is a stage in circular construction. This method is one way materials can be managed in their subsequent application cycles [25,26].

Evaluations of waste perlite powders in self-compacting concrete (SCC) have demonstrated several benefits, including increased compressive strength, improved water permeability, reduced carbonation, and improved resistance to chloride ion migration and freeze–thaw cycles [27]. Studies on the mechanical properties of perlite concrete rubble have demonstrated that partial replacement of perlite with up to 15% fine aggregate can achieve the desired strength while reducing the overall density [28]. This finding suggests that perlite concrete rubble can be effectively used for soil stabilization, providing both mechanical and environmental benefits.

Although direct research on the effects of activated carbon on the mechanical properties of perlite concrete is limited, the proven benefits of activated carbon in contaminant immobilization suggest potential synergies. Incorporating activated carbon into perlite concrete formulations could improve both environmental and structural properties. Studies of soil stabilization practices incorporating activated carbon have shown promising results in the immobilization of potentially toxic elements (PTEs). Research indicates that a combination of blending agents and a chelating agent (TJ400) can effectively stabilize contaminants, such as Cd, Pb, and As, within a short period of time [29]. Understanding the impact of PTEs on soil stabilization requires a thorough understanding of their mobility and speciation, which is critical for a comprehensive risk assessment [30].

However, there remains a paucity of research on the disposal methods of concrete manufactured with perlite. Although several studies focus on concrete reuse in construction, studies on perlite concrete are scarce. Defining disposal methods for various building materials is essential for a sustainable construction process, as this ultimately influences efficient use and enables the full potential of the material to be realized.

The objective of this article is to present the effect of using concrete made of perlite on the immobilization of potentially toxic elements (PTEs), serving as a potential method of disposal for this material. The investigation examines the immobilization properties of potentially toxic elements (PTEs) in plants and soil, assesses the impact of different types of perlite concrete on the immobilization of PTEs, and evaluates the effect of adding activated carbon to various types of perlite concrete on PTE immobilization. Moreover, the study aims to evaluate the environmental safety of employing these materials in construction applications, such as earth structures and road foundations, where they interact with the water–soil environment. Initial tests were conducted with varying perlite concrete contents to gain insight into the immobilization process in soil, roots, and aboveground parts. By comparing the results after the addition of activated carbon, the study was able to gain a comprehensive understanding of the nature and direction of the immobilization process, as well as determine the impact of this adsorbent on process efficiency.

A novel aspect of this article is the environmental safety assessment of the disposal of aggregate from perlite concrete addressing current needs and future utilization possibilities in sustainable material management. As perlite concrete becomes more prevalent in construction, significant quantities of demolition waste are expected, necessitating the early identification of suitable disposal methods to prevent landfill creation. The study also explores the modification of aggregates with activated carbon to evaluate its effects on plants and soil. Varying concentrations of modified aggregate were used to better understand its impact on the immobilization of potentially toxic elements (PTEs). To analyze the microstructural changes and elemental distribution in modified perlite concrete, advanced techniques such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) were employed. These methods provide insights into the interactions between the modified aggregate, soil, and plant systems, contributing to our understanding of the environmental impact and applications of this material in sustainable construction.

2. Materials and Methods

2.1. Material

2.1.1. Perlite Concrete

In the study, perlite-based concrete was crushed into 0–2 mm fractions and used at various concentrations. The blocks utilized in the study were procured from a Polish manufacturer who asserts that their production is conducted under uniform conditions. The following two types of base perlite concrete material were used Figure 1: (PPC) with the addition of CEM I 52.5R cement and (PBFC) with the addition of CEM III 42.5R cement. In the second phase of the research, activated carbon was utilized.

The results of the analyses of the chemical compositions of the three materials are shown in Figure 2. CEM I 52.5R (PC), CEM III 42.5R (BFC), and expanded perlite (EP) show diverse chemical properties. For CEM I 52.5R, the main components are calcium and oxygen, accounting for 45.5% and 42.64% of the total mass, respectively. Silicon also plays a significant role with an 8.79% share, while smaller amounts of sulfur, aluminum, magnesium, iron, and sodium complete the composition.

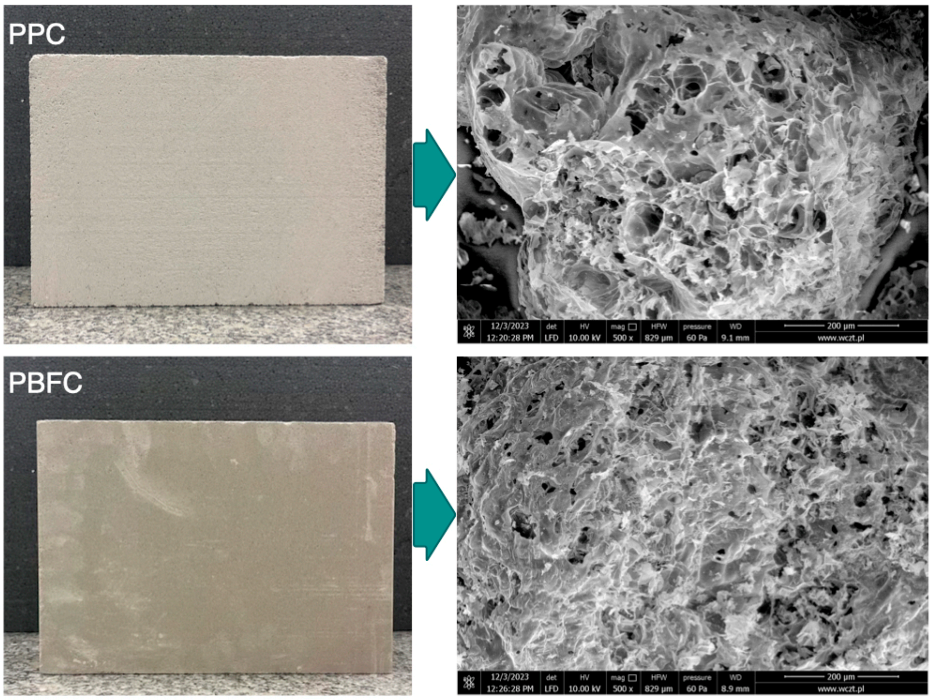

Figure 1. Overview photos of the two types of base perlite concrete materials used in the study: (PPC) with the addition of CEM I 52.5R cement and (PBFC) with the addition of CEM III 42.5R cement.

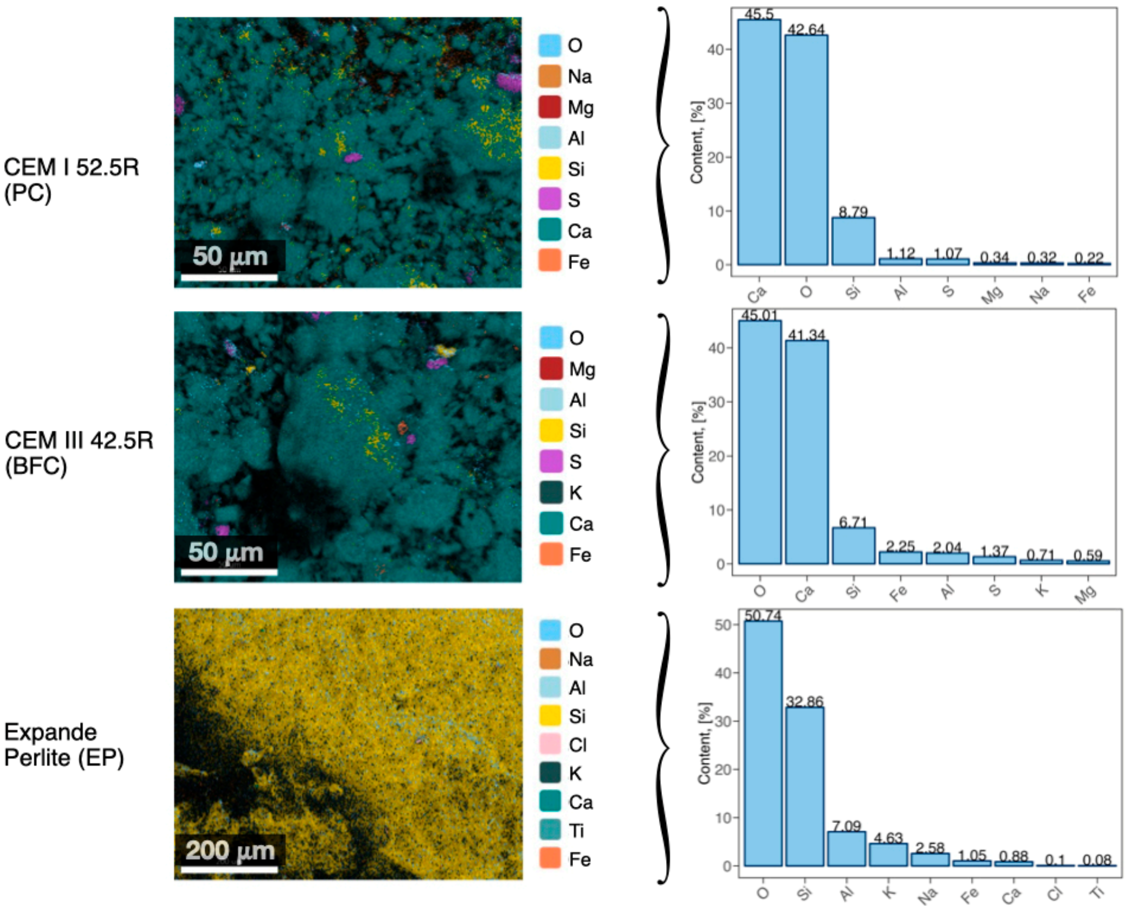

Figure 2. Maps of the distributions of elements in the samples using the EDS technique and detailed chemical compositions of the main components of the perlite concrete blocks.

In the case of CEM III 42.5R, the dominant elements are oxygen and calcium, with respective concentrations of 45.01% and 41.34%. Silicon is present at 6.71%, while iron, aluminum, magnesium, potassium, and sulfur occur in smaller proportions, indicating a complex chemical composition of this material.

Expanded perlite is characterized by high oxygen and silicon contents, representing 50.74% and 32.86% of the mass, respectively. Aluminum is the third most common component, comprising 7.09% of the material, while potassium, sodium, iron, calcium, titanium, and chlorine are present in smaller quantities. These analyses elucidate the distinctive attributes of each component, which may inform their utilization in diverse construction applications.

Elemental distribution maps of the samples were made using the EDS technique, and detailed chemical compositions of the main components of both perlite concretes are shown in Figure 2.

2.1.2. Activated Carbon's Characteristics

Activated carbon possesses a substantial internal surface area and high adsorption capacity, which aids in the reduction in contaminants in perlite concrete. The incorporation of activated carbon enhances the porosity of the mixture, thereby influencing its permeability and water filtration capabilities. The synergistic use of activated carbon and perlite concrete can be applied in structures that require lightness, insulation, and filtration while also enhancing soil stability. The environmental impacts include soil remediation, whereby the activated carbon within perlite concrete can adsorb toxins and heavy metals, thereby improving soil quality. It follows that this is a direction worth considering when analyzing the impact of perlite concrete's application on the ground.

In the experiment (Figure 3), activated carbon (AC) produced from a range of deciduous tree species was utilized. The specific density of the AC was determined to be 2.04 g/cm^3, indicative of its compactness at the molecular level, while its bulk density was found to be 411 kg/m^3, reflecting its overall mass per unit volume in a loose form. Furthermore, the AC exhibited a pH value of 6.1, suggestive of its slightly acidic nature.

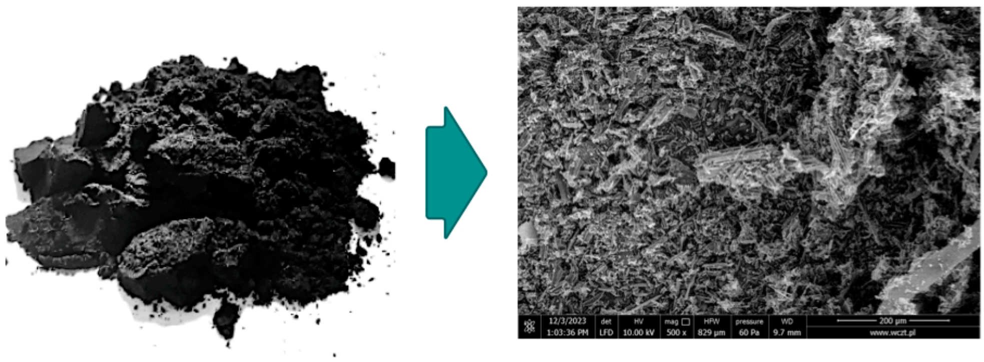

Figure 3. Overview photo of the activated carbon used in the study and SEM image of its structure at approximately 200 µm.

The analysis of the chemical composition of the activated carbon reveals that the predominant element is carbon, comprising 91.92% of the material. Oxygen is present at 6.18%. Potassium and calcium are found in trace amounts. The elemental distribution map for the activated carbon, made using the EDS technique, and detailed chemical composition are presented in Figure 4.

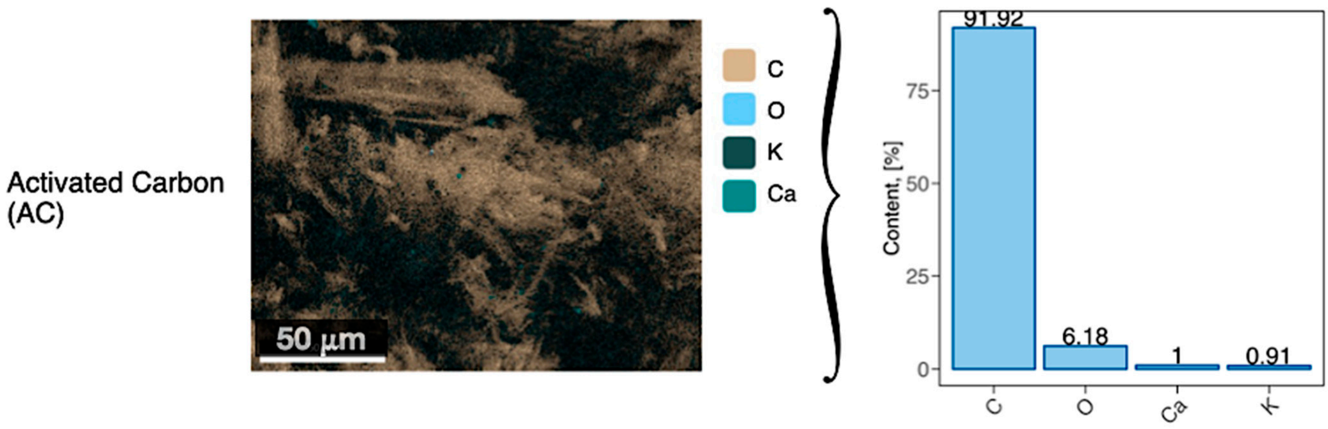

Figure 4. Elemental distribution map for activated carbon, made using the EDS technique, and detailed chemical composition.

2.1.3. Experimental Soil

The experiments were carried out in 5.0 kg polyethylene pots using soil samples collected from the top layer (0–30 cm) of an urban site located in Central Poland. The soil was found to have a pH level of 8.4, as determined by standard laboratory methods. *Festuca rubra* L., commonly known as red fescue, was chosen as the test plant. Red fescue seeds (5 g) were sown in the pots, and germination was observed within 11 to 14 days. The plants were irrigated every other day with deionized water until the soil reached its maximum water-holding capacity. The experiment lasted approximately 40 days from the initial sowing of the seeds. At the end of this period, the plants were harvested, weighed, and divided into aboveground and root portions for analysis. The soil used in the experiments contained potentially toxic elements, with zinc concentrations of 125.42 mg/kg and copper concentrations of 48.91 mg/kg.

2.1.4. Tested Samples

In the initial phase of the study, various concentrations of perlite concrete rubble (PPC and PBFC) of 3.0%, 5.0%, and 10.0% were mixed with the experimental soil, with each concentration tested in three replicates. A control group, consisting of soil without any perlite concrete rubble, was also established, similarly in three replicates. The contents of potentially toxic elements (PTEs) in the soil, roots, and aboveground parts of the plants were subsequently measured.

In the second phase of the study, activated carbon was incorporated at a 10.0% concentration into soil already containing a 10% concentration of perlite concrete rubble. The PTE contents in the soil, roots, and aboveground plant parts were again measured. Each experimental setup was conducted in triplicate, totaling 27 pots.

2.2. Methods

2.2.1. Research Methodology of Plant Material and Soil

The plants were carefully extracted from the pots to minimize root damage. The *Festuca rubra* L. samples were then rinsed with ultrapure water and air-dried at room temperature for two weeks. After drying, the samples were ground into a fine powder using an analytical mill (Retsch type ZM300, Haan, Germany) and stored at ambient temperature in clean, light-protected containers for subsequent chemical analysis.

The roots and aboveground parts were subjected to oven drying at 55 °C until a consistent weight was achieved, after which the dry biomass was recorded. Representative samples underwent mineralization in nitric acid (65% *w*/*w*, POCH, Gliwice, Poland) utilizing a microwave digestion system (Milestone Start D, Milan, Italy). Postdigestion, the samples were filtered and diluted to a final volume of 100 mL with deionized water. These extracts were then analyzed for their total potentially toxic element (PTEs) concentrations.

Zinc and copper concentrations were determined using flame atomic absorption spectrometry (FAAS) with an iCE-3000 spectrophotometer (Thermo Scientific, Waltham, MA, USA). A five-point calibration curve was established using standard solutions, and each sample was analyzed in triplicate to ensure accuracy and reproducibility. This meticulous process allowed for precise quantification of PTEs in the plant samples, contributing valuable data to the study's overall assessment of soil and plant contamination levels.

2.2.2. Statistical Analysis

A comprehensive statistical analysis of the experimental results was conducted using the R Studio software (version 2022.12.0+353). The primary method of analysis was a one-way analysis of variance (ANOVA), which was employed to ascertain the significance of differences among the treatment groups. In cases where the assumptions for ANOVA were not met, the nonparametric Kruskal–Wallis test by ranks was employed as an alternative statistical method. To identify and quantify significant differences among specific variables, a Tukey's honest significant difference (HSD) test was employed. This rigorous statistical approach ensured the data were interpreted in a robust and reliable manner, thereby facilitating a detailed understanding of the effects of different amendments on the measured outcomes.

3. Results

3.1. Effect of Various Concentrations of Perlite Concrete Rubble (PPC and PBFC) and Activated Carbon on the Biomass of Festuca rubra L.

Figure 5 shows the analysis of the biomass of red fescue (*Festuca rubra* L.) grown on soil mixed with different concentrations of perlite concrete rubble (PPC and PBFC) and activated carbon (AC). The goal was to understand how these mixtures affect plant growth at concentrations of 3%, 5%, and 10%, with and without the addition of activated carbon.

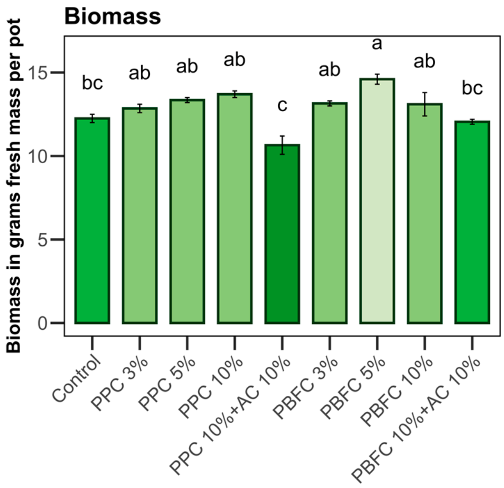

Figure 5. Amount of resulting biomass of *Festuca rubra* L. grown on soil mixed with different concentrations of perlite concrete rubble (PPC and PBFC) and activated carbon. Significance test results are denoted by letters (one-way ANOVA and subsequently Tukey's test).

The control group, without any amendments, exhibited a biomass of around 12 g, serving as a baseline for comparison. The addition of PPC at concentrations of 3%, 5%, and 10% did not result in statistically significant differences in biomasses compared to the control. This suggests that perlite concrete rubble with Portland cement does not substantially affect plant growth at these concentrations. However, the addition of PPC 10% with activated carbon (PPC 10% + AC 10%) resulted in a significant decrease in biomass to about 8 g. This decrease indicates that activated carbon may negatively affect plant growth by adsorbing essential nutrients from the soil. In contrast, the addition of PBFC at concentrations of 3% and 5% resulted in increases in biomass, with the PBFC 5%

amendment reaching the highest biomass of approximately 15 g. This suggests that perlite concrete rubble with blast furnace cement enhances plant growth at these concentrations. The addition of PBFC 10% with activated carbon (PBFC 10% + AC 10%) showed a slight decrease in biomass compared to the PBFC 10% amendment, though the effect was not as pronounced as in the PPC 10% + AC 10% amendment.

3.2. Immobilization Properties of PTEs in Plants and Soil for Various Concentrations of Perlite Concrete Rubble (PPC and PBFC)

Figure 6 presents the concentrations of zinc and copper in the aboveground parts of *Festuca rubra* L. when grown in soil mixed with various concentrations of perlite concrete rubble (PPC and PBFC) and activated carbon. The concentrations are given in milligrams per kilogram (mg/kg).

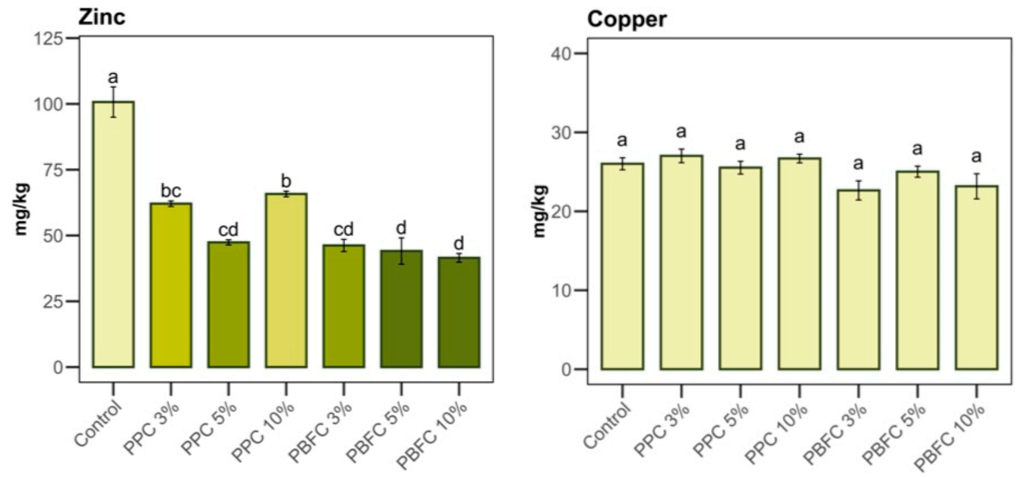

Figure 6. Zinc and copper contents in aboveground parts of *Festuca rubra* L. grown in soil mixed with different concentrations of perlite concrete rubble (PPC and PBFC). Significance test results are denoted by letters (one-way ANOVA and subsequently Tukey's test).

In the zinc analysis, the control group showed the highest zinc concentration at approximately 100.7 mg/kg. For the PPC amendments, PPC 3% resulted in a significant decrease in the zinc concentration to 62.9 mg/kg, PPC 5% further reduced the zinc concentration to 47.4 mg/kg, and PPC 10% increased the zinc concentration slightly to 65.8 mg/kg. For the PBFC amendments, PBFC 3% resulted in a zinc concentration of 46.2 mg/kg, PBFC 5% reduced the zinc concentration to 44.1 mg/kg, and PBFC 10% showed the lowest concentration, at around 41.5 mg/kg. The copper concentrations remained relatively stable across all amendments, ranging between 22 and 27 mg/kg, with no significant differences among the control and PPC and PBFC amendments.

The results indicate a significant reductions in the zinc concentrations in the aboveground parts of the plants for both the PPC and PBFC amendments. The most substantial decrease (67%) was observed with PBFC 10% compared to the control. PPC 5% resulted in a 50% reduction in the zinc concentration, indicating effective zinc immobilization at this concentration.

Figure 7 shows the analysis of the zinc and copper concentrations in the roots of *Festuca rubra* L. grown in soil, which for the control group shows zinc concentrations of 50.2 mg/kg. In the PPC amendments, the zinc concentration increased with PPC 3%, resulting in 72.5 mg/kg, PPC 5% maintained a concentration of 63.9 mg/kg, and PPC 10% showed the highest concentration among the PPC amendments, at 74.5 mg/kg. Conversely, the PBFC amendments resulted in decreases in the zinc concentrations, as follows: PBFC 3% at 53.8 mg/kg, PBFC 5% at around 42 mg/kg, and PBFC 10%, showing the lowest concentration, at 28.4 mg/kg.

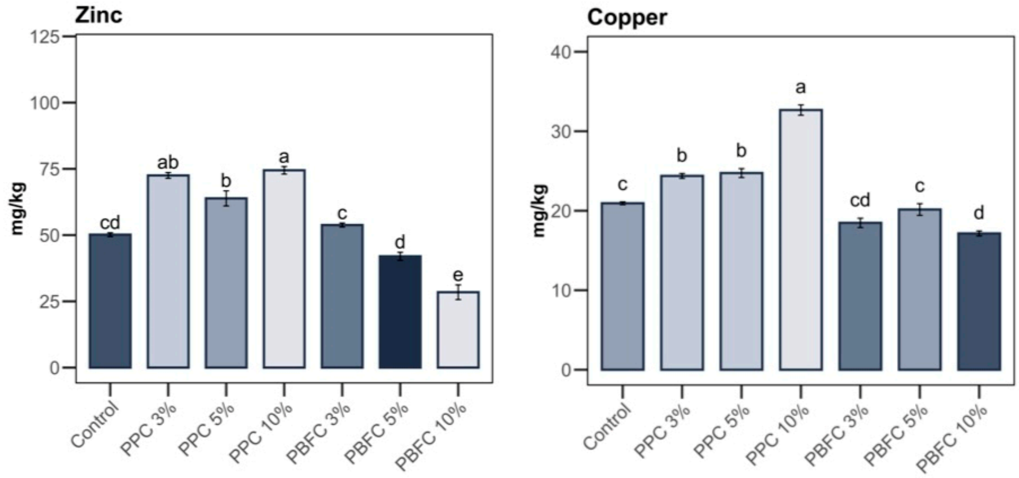

Figure 7. Zinc and copper contents of the roots of *Festuca rubra* L. grown in soil mixed with different concentrations of perlite concrete rubble (PPC and PBFC). Significance test results are denoted by letters (one-way ANOVA and subsequently Tukey's test).

For copper, the control group had a concentration of 20.9 mg/kg. The PPC amendments increased the copper concentrations, with PPC 3% and PPC 5% reaching around 24.5 mg/kg, and PPC 10% resulting in the highest concentration, at 62.7 mg/kg. The PBFC amendments exhibited slight decreases, as follows: PBFC 3% at 18.5 mg/kg; PBFC 5% similar to the control, at 20.2 mg/kg; and PBFC 10% showing a slight decrease to around 17.1 mg/kg.

The results indicate that the PPC amendments significantly increased the zinc concentrations in the roots for all tested concentrations, with PPC 10% showing the highest increase of 48%. In contrast, the PBFC amendments showed a mixed effect, with slight increases at lower concentrations but a decrease of around 44% at PBFC 10%. For copper, the PPC amendments also resulted in significant increases in the root concentrations, with the highest increase of 56% observed at PPC 10%. On the other hand, the PBFC amendments lead to a reduction in copper concentrations, with PBFC 10% showing the highest decrease of 20%.

Figure 8 illustrates the concentration of zinc in the soil in which *Festuca rubra* L. was cultivated. The analysis of the control group revealed a concentration of 23.9 mg/kg. The addition of PPC significantly increased zinc levels in the soil, with PPC 10% showing the most substantial increase of 304%, rising to 96.6 mg/kg. PPC 5% resulted in a 123% increase, while PPC 3% caused a modest 27% increase. In contrast, the PBFC amendments had a less pronounced effect, with PBFC 10% resulting in a 137% increase, PBFC 5% a 27% increase, and PBFC 3% showing no significant change from the control.

For copper, the control group had a concentration of 10.2 mg/kg. The PPC amendments increased the copper concentrations significantly, with PPC 10% showing an 88% increase to 19.2 mg/kg. PPC 5% and PPC 3% resulted in 56% and 26% increases, respectively. The PBFC amendments also raised copper levels, with PBFC 10% showing the highest increase of 112%, doubling the concentration to 21.7 mg/kg. PBFC 3% and 5% resulted in more modest increases of 17% and 21%, respectively.

The PPC amendments resulted in notable increases in both zinc and copper concentrations in the soil, particularly at the highest concentration of 10%. These results underscore the varying impacts of PPC and PBFC on the availability of potentially toxic elements in soil, influenced by the type and concentration of the amendments used.

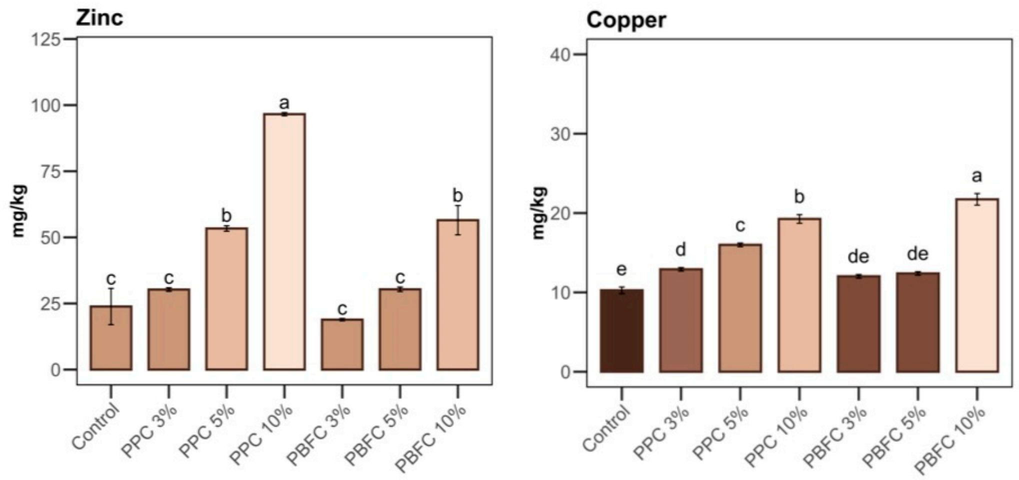

Figure 8. Zinc and copper contents of *Festuca rubra* L. soil mixed with different concentrations of perlite concrete rubble (PPC and PBFC). Significance test results are denoted by letters (one-way ANOVA and subsequently Tukey's test).

3.3. Immobilization Properties of PTEs in Plants and Soil for Various Concentrations of Perlite Concrete Rubble (PPC and PBFC) and Activated Carbon (AC)

This chapter presents an analysis of the zinc and copper concentrations in plants, roots, and soil, with the additions of PPC and PBFC at concentrations of 10% and their combination with 10% activated carbon in the soil. Figure 9 illustrates the concentrations of the analyzed elements in the aboveground parts of *Festuca rubra* L.

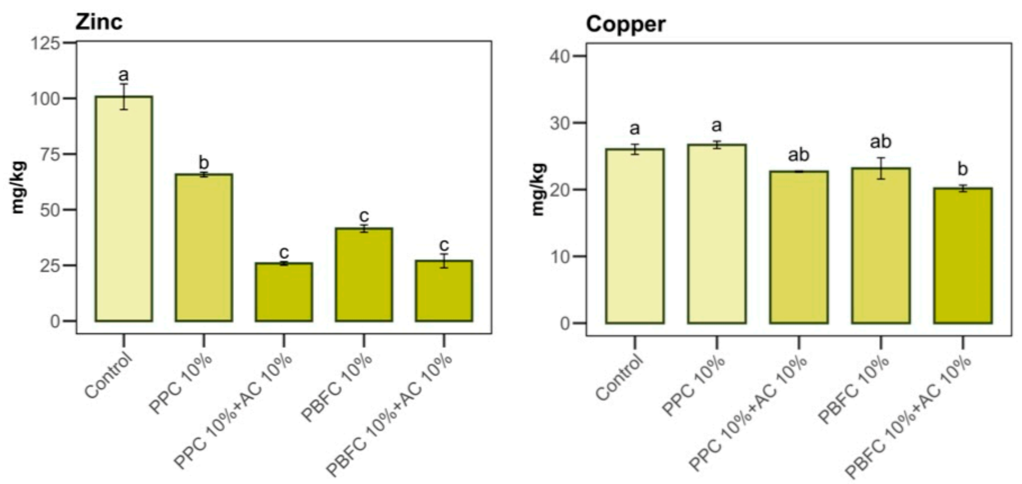

Figure 9. Zinc and copper contents in aboveground parts of *Festuca rubra* L. grown in soil mixed with perlite concrete rubble (PPC and PBFC) and activated carbon (AC). Significance test results are denoted by letters (one-way ANOVA and subsequently Tukey's test).

For zinc, the control group showed a concentration of approximately 100 mg/kg. The addition of PPC 10% resulted in a reduction in the zinc levels by 35% to 65.8 mg/kg. When combined with activated carbon (PPC 10% + AC 10%), the zinc concentration decreased further to 25.9 mg/kg, representing a 74% reduction. PBFC 10% resulted in a 59% decrease in the zinc concentration to 41.5 mg/kg. The addition of activated carbon to PBFC 10% (PBFC 10% + AC 10%) also resulted in a significant reduction, with zinc levels dropping by 73% to approximately 27 mg/kg. For copper, the control group had a concentration of approximately 26 mg/kg. PPC 10% maintained similar copper levels to the control. However, when combined with activated carbon (PPC 10% + AC 10%), the copper concentration decreased by 13% to 22.7 mg/kg. PBFC 10% reduced copper levels by 11% to approximately 23.2 mg/kg. The combination of PBFC 10% with activated carbon (PBFC 10% + AC 10%) resulted in the most significant reduction, with copper levels dropping by 22% to approximately 20.2 mg/kg.

Figure 10 shows the concentrations of zinc and copper in the roots of *Festuca rubra* L. grown in soil amended with different concentrations of perlite concrete rubble (PPC and PBFC) and activated carbon.

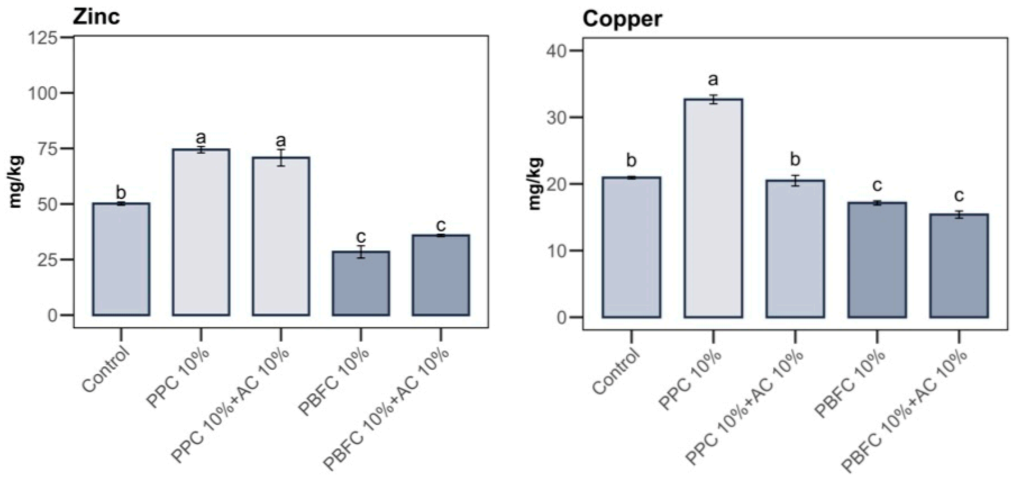

Figure 10. Zinc and copper contents in roots of *Festuca rubra* L. grown in soil mixed with perlite concrete rubble (PPC and PBFC) and activated carbon (AC). Significance test results are denoted by letters (one-way ANOVA and subsequently Tukey's test).

With regard to zinc, the control group exhibited a concentration of 50.2 mg/kg. The addition of PPC 10% resulted in a significant increase in zinc levels, reaching approximately 74.5 mg/kg. This increase was consistent even when activated carbon was added (PPC 10% + AC 10%), maintaining a rise of around 70.7 mg/kg. In contrast, PBFC 10% reduced the zinc concentration by 43% to approximately 28.4 mg/kg. The addition of activated carbon to PBFC 10% (PBFC 10% + AC 10%) resulted in a more modest decrease of 29%, bringing zinc levels to 35.8 mg/kg. For copper, the control group had a concentration of 20.9 mg/kg. PPC 10% increased copper levels by 56% to approximately 32.7 mg/kg. However, when combined with activated carbon (PPC 10% + AC 10%), copper concentrations remained similar to the control. PBFC 10% decreased copper levels by 18% to 17.1 mg/kg, a reduction that was consistent even with the addition of activated carbon (PBFC 10% + AC 10%).

Figure 11 illustrates the concentrations of zinc and copper in soil in which *Festuca rubra* L. was cultivated. The soil was enriched with 10% perlite concrete rubble (PPC and PBFC) and 10% activated carbon.

For zinc, the control group exhibited a concentration of approximately 24 mg/kg. The addition of PPC 10% led to a significant increase in zinc levels, reaching 96.6 mg/kg. This increase was consistent even when activated carbon was added (PPC 10% + AC 10%), maintaining a rise of around 300%. The addition of PBFC 10% resulted in a 137% increase in the zinc concentration, reaching 56.5 mg/kg. The addition of activated carbon (PBFC 10% + AC 10%) led to a slightly lower increase of 81%, with zinc levels at 43.2 mg/kg. For copper, the control group had a concentration of around 10 mg/kg. PPC 10% increased copper levels by 88% to approximately 19 mg/kg. When combined with activated carbon (PPC 10% + AC 10%), copper concentrations rose further to 22.8 mg/kg, representing a 122% increase. The addition of PBFC 10% resulted in an 112% increase in copper levels, reaching 21.7 mg/kg. The combination of PBFC 10% with activated carbon (PBFC 10% + AC 10%) led to a 30% increase, with copper concentrations reaching 13.4 mg/kg.

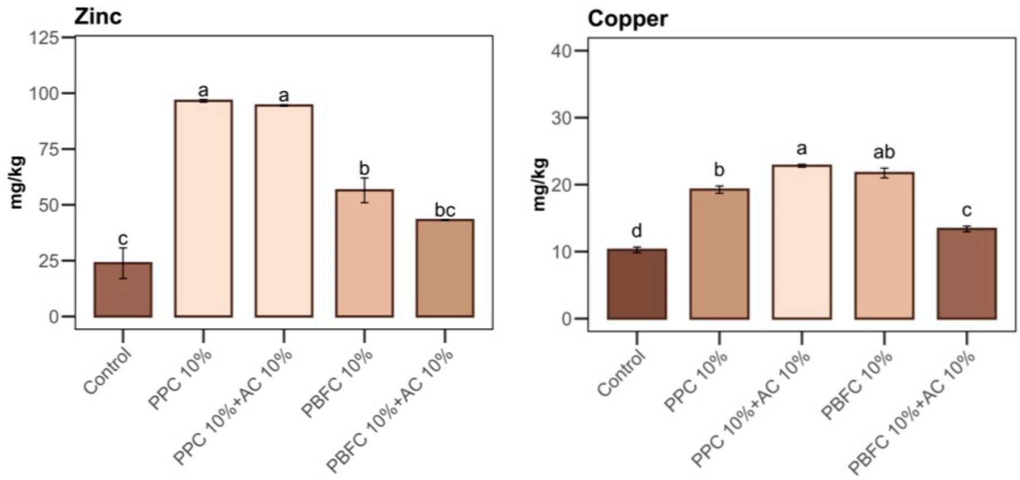

Figure 11. Zinc and copper contents in *Festuca rubra* L. soil mixed with different concentrations of perlite concrete rubble (PPC and PBFC) and activated carbon (AC). Significance test results are denoted by letters (one-way ANOVA and subsequently Tukey's test).

In summary, these findings indicate that both the PPC and PBFC amendments, particularly when combined with activated carbon, significantly increased the concentrations of zinc and copper in the soil. The highest increases for both metals were observed for the PPC 10% and PPC 10% + AC 10% amendments, which highlights the effectiveness of these amendments in altering the availability of potentially toxic elements in soil. The PBFC amendments also increased the metal concentrations, though to a lesser extent than the PPC. The addition of activated carbon further influenced these levels. These findings underscore the varying impacts of PPC and PBFC on soil metal concentrations, which are influenced by the type and combination of amendments used.

4. Discussion

Perlite is a material with a multitude of applications, but the properties of perlite concrete are not as well understood. This research provides detailed insights into managing perlite concrete rubble at the end-of-life stage. The unique properties of perlite, such as low bulk density, high water retention capacity, and high air-filled porosity, make it a valuable additive in green roofs, vertical gardens, and biofilters [31,32]. Furthermore, perlite's ability to sorb metal ions, such as Cd^{2+}, Cu^{2+}, Ni^{2+}, and Pb^{2+}, highlights its potential for immobilizing potentially toxic elements (PTEs) in soil and plants [31]. Expanded perlite, when used as a soil additive, effectively reduces the bioavailability of PTEs through mechanisms including precipitation, complexation, and ion exchange [28,33]. Soil amendments such as biochar and nanomaterials have been identified as effective for removing PTEs from polluted soils [34]. Our research shows that the concentration of zinc in the soil significantly increased with the addition of PPC, particularly at a concentration of 10%. This suggests that PPC can effectively mobilize zinc, making it more available in the soil. Conversely, the concentration of copper in the soil also increased with both PPC and PBFC, with the highest values observed in the presence of PPC at a concentration of 10% in combination with activated carbon (PPC 10% + AC 10%). This indicates that PPC, especially when combined with activated carbon, can also increase the availability of copper in the soil. The use of perlite concrete rubble for soil stabilization can improve its functionality and quality, as indicated by increased soil pH and decreased potential bioavailability of PTEs [35]. Immobilization of PTEs in soil using organic and inorganic amendments has been shown to mitigate PTE toxicity to soil microorganisms, indicating the potential impact of PTEs on soil stabilization [36]. The incorporation of perlite in lightweight concrete enhances thermal resistance and insulation, providing significant environmental benefits [37]. Calcined perlite powder used as a supplementary cementitious material improves concrete's durability, reduces environmental pollution, and increases resistance to chloride ion ingress, making perlite concrete a sustainable option for immobilizing PTEs in soil and plants [38,39]. Integrating waste perlite powders into cement replacement can enhance the properties of hardened and fresh concretes, making it a viable option for sustainable construction practices [14]. Previous experimental studies have shown that stabilization with perlite and lime improves the geotechnical properties of expansive clayey soil, indicating its potential for effective soil stabilization [40,41]. Overall, PPC was found to be more effective than PBFC in immobilizing zinc and copper in the soil and reducing their uptake in the aboveground parts of plants. Consequently, PPC can be used for soil stabilization or as a filtration layer within the ground. It improves geotechnical properties such as compaction, Atterberg limits, swelling, and unconfined compressive strength in expansive clay soils [15]. Studies have shown that a mixture of 30% perlite and 8% lime may be optimal for soil stabilization in terms of strength [15]. The practical applications of these findings in construction are significant. The use of PPC and PBFC in soil stabilization has great potential. They can be utilized to remediate contaminated sites by reducing the availability of heavy metals and mitigating ecological risks. Additionally, these materials can improve soil quality in degraded areas. In civil engineering, PPC and PBFC can stabilize construction soils, improving their mechanical properties and reducing the risk of erosion. This dual benefit of contaminant immobilization and soil stabilization makes PPC and PBFC valuable additions to sustainable construction practices. However, further research on the specific characteristics and long-term stability of perlite concrete rubble is necessary to fully understand its potential applications and environmental impacts. There remains a need to explore various forms and methods of utilizing this material effectively, especially considering its end-of-life stage management.

5. Conclusions

This study provides comprehensive insights into the effects of perlite concrete rubble with Portland cement (PPC) and blast furnace cement (PBFC), along with activated carbon, on the immobilization of potentially toxic elements in plants and soil. The key findings are as follows:

- The addition of PPC at various concentrations did not significantly impact plant biomass, indicating that PPC alone is neutral in its effect on plant growth. However, combining PPC 10% with AC 10% reduced biomass, suggesting that activated carbon, while effective in adsorbing PTEs, may also hinder plant growth by adsorbing essential nutrients. In contrast, PBFC at 3% and 5% concentrations enhanced plant biomass, implying beneficial properties for soil and plant growth.
- The addition of PPC reduced zinc levels in aboveground parts, with the most significant decrease observed with PPC 5%, reducing the zinc content by 50% compared to the control. Similarly, PBFC also reduced the zinc contents, with the largest reduction observed for PBFC 10%, decreasing the zinc level by 67%. In plant roots, adding PPC increased the zinc content by 48% for PPC 10%, while PBFC decreased the zinc level by 44% for PBFC 10%.
- In the soil, zinc contents increased significantly with the PPC addition, peaking at a 304% increase with PPC 10%. PBFC also raised soil zinc contents, with the highest level for PBFC 10%, increasing by 136%. These results suggest that PPC is more effective at immobilizing zinc in soil.
- Adding PPC increased the copper content in the soil by 88% for PPC 10%. PBFC also elevated the soil copper levels, with an increase of 112% for PBFC 10%. In plant roots, the control group's copper content was 20.9 mg/kg. PPC increased the copper content by 48% for PPC 10%, whereas PBFC reduced it by 20% with PBFC 10%.
- The addition of activated carbon to perlite concrete rubble offers a potent method for improving the immobilization of toxic elements in soil. The integration of activated carbon into perlite concrete formulations for soil stabilization presents a promising approach for enhancing the immobilization of PTEs. However, it is crucial to balance the benefits of contaminant immobilization with the potential negative impacts on plant

growth. Further research is needed to optimize the concentrations and application methods of AC to maximize its benefits.

The use of PPC and PBFC in soil stabilization has potential. They can be used to remediate contaminated sites, reducing the availability of heavy metals and the ecological risks. These additives can also improve soil quality in degraded areas. In civil engineering, PPC and PBFC can be used to stabilize construction soils, improving their mechanical properties and reducing the risk of erosion.

Further research should focus on the long-term effects of PPC, PBFC, and AC on heavy metal contents in soil and plants, as well as their effects on other soil and plant parameters, including other heavy metals. A detailed analysis of the mechanisms by which AC affects the adsorption of nutrients and heavy metals in soil is also necessary. In addition, it is worth conducting studies on different types of soils to assess how these modifications work under different soil conditions and with different plant species to see whether the observed effects are specific to *Festuca rubra* L. or are more universal in nature. Analysis of the effects of PPC, PBFC, and AC on the soil microbiome can provide valuable information on soil health and plant growth.

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