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POSSIBILITIES FOR THE RECOVERY OF AGRICULTURAL VEGETABLE WASTE

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Abstract

Agricultural activities generate substantial volumes of waste and by-products annually, primarily of plant origin, which are either underutilized or not utilized at all. Through partial pyrolysis, these waste materials can be transformed into a product known as "biochar (BCH)," which has potential applications in both agriculture and innovative construction materials. This paper presents a comparative study examining the impact of BCH utilization in these two fields. Research findings demonstrated beneficial effects on soil quality and crop yield improvement. Additionally, studies conducted on cementitious composites incorporating 5-15% biochar revealed reduced density, increased open porosity, maintained mechanical strength parameters, and thermal conductivity values that suggest the possibility of developing innovative mortars with enhanced thermal resistance or suitable for manufacturing paving elements. Through this dual approach, this paper aims to highlight the potential of transforming agricultural waste into valuable materials that benefit both agriculture and the development of new, innovative, and environmentally friendly construction materials.

***Key words**: agricultural sub-products, benefits for agriculture, biochar, innovative cementitious composites.*

INTRODUCTION

Globally, there is an ongoing transition from the linear economic model of "EXTRACT – PRODUCE – CONSUME – DISPOSE", now considered obsolete, to a circular model. This new approach focuses on reintegrating industrial and agricultural waste and/or by-products into the production cycle, emphasizing increased product durability and extended operational lifespans (Ricciardi et al., 2020; Kebaili et al., 2022). This transition addresses two key challenges: first, the need to find valorization solutions for the large volume of biomass generated by agricultural activities, and second, the necessity to develop new, innovative, and environmentally friendly sustainable materials and technologies to reduce the construction industry's environmental impact (Androutsopoulos et al., 2020). Using agro-industrial waste, which would otherwise be destined for landfills or incineration (Madurwar et al., 2013), presents an opportunity to prevent increased greenhouse gas emissions. The International Biochar Initiative (IBI) defines biochar (BCH) as "a solid material obtained by biomass carbonization" (Cha et al., 2016). Specifically, BCH is a sterile vegetable charcoal produced through thermochemical biomass processing – pyrolysis at 400-900ºC under limited oxygen conditions – which could address both identified challenges. BCH contains 75-90% carbon and is characterized by extremely high porosity and superior adsorption capacity. Its applications include use as an agricultural soil amendment to enhance fertility, an additive in animal feed, and a filtering medium for air, gases, and water (Chan et al., 2007).

Currently, researchers are investigating BCH's potential in developing carbon-neutral concrete, leveraging its ability to store atmospheric CO_2 (Winters et al., 2022; Gupta & Kua, 2018a; Choi et al., 2012; Zhao et al., 2019; Cuthbertson et al., 2019; Gupta & Kua, 2017).

Some research shows that the rich pore structure of BCH causes it to absorb a large amount of water during the concrete preparation stage, which it then releases during the cement hydration-hydrolysis stage. This process promotes the secondary hydration reaction and additional hardening, thereby increasing the mechanical performance of cementitious composites (Maljaee et al., 2021; Gupta et al., 2018b; Chen et al., 2022a).

However, international research results remain controversial.

Generally, it is reported that the beneficial effect of biochar-type materials in cementitious composites is optimal at a maximum addition of 5% in the composition, with higher quantities hurting the composite's performance (Song et al., 2023).

Some studies limit the mass percentage of BCH addition in cementitious composites to 2% (Maljaee et al., 2021), while others suggest that it's possible to partially substitute up to 10% of cement with BCH while maintaining the physical-mechanical performance indicators of both the cementitious composite (Hylton et al., 2024) and cement-based agglomerated boards (Chen et al., 2022b).

Regarding the effect of using BCH in agricultural soils, studies have shown that poor nutrient content and accelerated mineralization of soil organic matter are the two major constraints currently encountered in sustainable agriculture (Zheng et al., 2010).

In recent years, there has been much evidence that BCH is not only more stable than other soil amendments but also that soil nutrient content is higher compared to the effects of other fertilizers (Lehmann & Joseph, 2009).

Numerous studies have reported improvements in water capacity and retention when a rate of 0.5% BCH was applied, modifying porosity and facilitating the formation of bonds and complexes of cations and anions with metals and elements in the soil, which improves nutrient retention capacity (Suarau et al., 2016), while reducing soil density (Mukherjee & Lal, 2013). The increase in soil fertility also results from the fact that the basic cations contained in BCH are discharged into the soil, replacing Al and H+ and thus improving the cation exchange capacity (CEC) of the soil (Cha et al., 2016), but also through the influence on the dynamics of Soil Organic Carbon (SOC), inhibiting the degradation process and increasing the mean residence time (MRT) in which organic carbon remains in the soil, respectively, increasing the processes of stabilization and retention of SOC (Suarau et al., 2016). At the same time, studies have reported an increase, from 50% to 72%, of biological nitrogen fixation in the soil and increases in the yield of agricultural crops (Suarau et al., 2016).

A recent statistical meta-analysis of global results (Hartley et al., 2016; Zhang et al., 2016) indicates a significant positive effect on agricultural production yield, namely an increase of 12%, simultaneously showing a significant impact on soil performance indicators (Schmidt et al., 2016).

For example, an analysis carried out on the use of inorganic fertilizers in the cultivation systems of small farmers in Africa shows that they often become ineffective due to increased sensitivity to fertilizer application.

The use of BCH, alone or in combination with classical fertilizers (urea or di-ammonium phosphate), had no effects on macrofauna, such as beetles, centipedes, millipedes, termites and ants, but attracted earthworms and led to taxonomic enrichment of species as well as increased corn production yield in the first 2 growing seasons, with no subsequent significant effects in seasons 3 and 4 (Kamau et al., 2019).

Other studies (Mikajlo et al., 2024; Kammann et al., 2016) indicate that good results were obtained for soil treatment intended for lettuce growth. Thus, it is shown that BCH applied by simply spreading on the surface does not necessarily lead to an improvement in soil quality, but composted BCH, or BCH applied in a mixture with compost, can lead to 3-6 times higher growth of lettuce plants compared to untreated soil. The study also indicates more obvious results in soils with lower iron content.

Therefore, in recent years the use of BCH in agriculture has become increasingly common, as evidenced by countries such as Portugal, Spain, Germany, Austria and Switzerland (Calotescu, 2016; Zmaranda, 2019; Schmidt et al., 2016), where very large quantities of biochar are used to replace chemical fertilizers and pesticides. Countries such as Belize, Cameroon, Chile, Costa Rica, Egypt, India, Kenya, Mongolia, and Vietnam are implementing similar projects as discussed at the Biochar 2018 conference (IBI, 2018).

In this context, the purpose of this paper is to present a parallel study on the possibilities of using BCH in two apparently unrelated fields which, in this case, have in common the possibility of implementing circular economy principles on biomass residues.

MATERIALS AND METHODS

The research methodology followed two parallel directions. Thus, on one hand, cementitious composites with BCH addition were prepared, and on the other hand, the development of three plant species was monitored: radish (*Raphanus sativus*), spinach (*Spinacia oleracea*), and garden lettuce (*Lactuca sativa*) on a plot of land located in Sălaj County, where the soil was enriched with BCH. The BCH used was obtained from vegetable waste, produced by Explocom GK through the slow pyrolysis process (temperature of 500ºC, residence time of 15 minutes) and is characterized by the following parameters: granulation 0-20 mm, pH 9, carbon content 70-76%, volatile substances content 8-19%, ash content 3-6%, and water content max. 12%. To analyze the influence of BCH addition on the performance of cementitious composites, 4 compositions were prepared: one control and three compositions with BCH addition, using Portland cement CEM I 52.5 R, water, and standardized polygranular sand (Table 1).

Table 1. Ratio of raw materials for the preparation of cementitious compositions

Sample code	Cement (g)	Ratio water/ cement	Polygranular sand (g)	BCH (% based on cement quantity)
R-M	450	0.5	860	0
R-5BCH				5
R-10BCH				10
R-15BCH				15

The indicators for quantifying the influence of BCH on the performance of cementitious composites were: density in the hardened state, according to EN 1015-10:2002+A1:2007; water absorption according to EN 1339:2004+AC:2006; compressive strength and flexural tensile strength determined according to EN 1015-11:2020; and wear resistance (EN 1339:2004+AC:2006). At the same time, an analysis of the influence of BCH on the durability of cementitious composites was carried out, namely an analysis in terms of behavior after 25 freeze-thaw cycles (EN 1339:2004+AC:2006) and 25 wet-dry cycles (a wet-dry conditioning cycle was performed by completing 8 h of air conditioning at a temperature of 21±2°C and 16 h of immersion in 3% NaCl solution at a temperature of 21±2°C). All tests were performed under laboratory conditions, on sets of 3 prismatic specimens 40x40x160 mm each, made by casting in metal molds. After casting, the samples were kept for 24 h in high humidity conditions (90%), at room temperature (23°C), then demolded, deburred, and kept under controlled temperature and humidity conditions in the climatic chamber until reaching the age of 28 days from casting. Finally, the influence of BCH on the thermal performance of cementitious composites was evaluated by following the variation of the thermal conductivity coefficient λ (W/m·K). For this purpose, 300x300x20 mm plates made by casting from cementitious composites and conditioned under conditions similar to the prismatic specimens were used. Using the hot plate method, a FOX 314 conductivity meter was used for testing at a temperature difference between the plates of 10°C, according to EN 12667:2002.

The research conducted to identify the influence of BCH on plant growth performance was carried out using soil collected from an agricultural area in Sângeorgiu de Meseș locality, Buciumi commune, Sălaj county. The soil falls into the class of clinohydromorphic black soils, with a concave appearance, having a high humus content, a dark brown to black color, and being slightly stony. This soil was prepared for planting seeds of radish (*Raphanus sativus*), spinach (*Spinacia oleracea*), and garden lettuce (*Lactuca sativa*), by adding 5%, 10%, 15%, and 20% BCH (mass percentages in relation to the amount of soil). BCH was used in the soil in combination with Bio-pyrolytic condensate - a biopyrolytic distilled product, representing a solution of organic fertilizer (pyrolinic acid - humic acid), a commercially purchased nutrient intended for use on all soil types, dosed at 1ml/l water/container, applied in odd weeks of growth. An experimental greenhouse-type stand was built in which containers with a capacity of 1l were placed, 3 for each type of plant and each type of soil sample, with a set of 3 containers for each type of plant being filled with soil without the addition of BCH and considered as control. In each container, purchased commercially, 5 seeds of the same type were planted and watered with 100 ml of water. Subsequently, at equal intervals of 2 days, each sample was watered with 50 ml of water, continuously monitoring the temperature in the greenhouse, which was kept constant at 25±2ºC, and the degree of sunlight was ensured equally for all samples by their location. Plant growth monitoring was carried out for 9 weeks from planting until they reached a degree of development that no longer allowed cultivation in the containers used. The quantifiable monitoring indicator was the height of the plants, measured using a graduated ruler with a minimum division of 1 mm, reporting average values of all plants of a species developed in the 3 pots with the same type of soil. The samples were assigned codes (Table 2).

Table 2. Sample coding system for plants grown with different BCH concentrations

	BCH 0%	BCH 5%	BCH 10%	BCH 15%	BCH 20%
Radish	CR	R5	R10	R15	R20
Spinach	CS	S5	S10	S15	S20
Garden lettuce	CSV	SV5	SV10	SV15	SV20

RESULTS AND DISCUSSIONS

Regarding the influence of BCH addition on the performance indicators of cementitious composites, the experimental results indicate a progressive reduction in apparent density, with an increase in the amount of BCH, by 4.8%-5.8% compared to the control sample.
Based on these results, a first benefit of using BCH can be identified: reducing the mortar density (Figure 1) therefore, in the case of its use as a construction material, reducing the load on the construction's resistance structure.

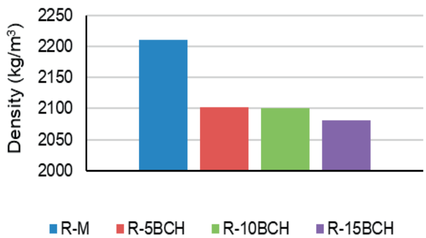


Figure 1. Hardened bulk density of cementitious composites

Regarding water absorption (Figure 2), the results indicate increases in this indicator following the addition of BCH, without being able to identify a direct correlation with the amount of BCH added to the composite.

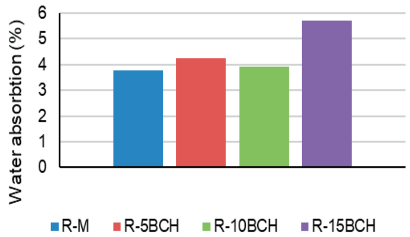


Figure 2. Water absorption of cementitious composites

However, correlating this information with the variation of apparent density in the hardened state, it can be concluded that both directions provide indications leading to the hypothesis of increased open porosity in mortars with the introduction of BCH in the composition.
On the other hand, correlating the experimentally obtained results with the references in standards EN 1338, EN 1339, and EN 1340, which indicate a maximum water absorption of 6% for prefabricated elements such as tiles, pavers, and curbs, it can be noted that, from this point of view, the analyzed mortars successfully satisfy the condition of resistance and durability to climatic factors required for use in the production of such elements.
These results correlate with the literature which indicates the possibility of increasing the total water absorption by up to 28% compared to the control samples (Song et al., 2023).
From the point of view of BCH addition's influence on the mechanical strengths of cementitious composites (Figure 3) the results indicate reductions of 30-40% in tensile bending strength (from 10.4 N/mm² to min. 6.2 N/mm²), and 26-47% in compressive strength (from 71.3 N/mm² to min. 37.9 N/mm²), while maintaining sufficient performance to be classified as M35 or M50 masonry mortars according to EN 998-2 specifications.
Comparing the experimental results with other findings reported in the literature (30-50 N/mm²) (Roychand et al., 2023), it can be said that they are consistent, with some cases where the compressive strength of the laboratory-tested cementitious composite is even better.

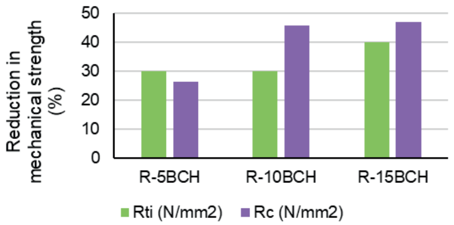


Figure 3. Reduction in mechanical strength of cementitious composites with BCH, compared to the control sample

Although negative influences of BCH addition on mechanical strength are identified under laboratory conditions when cementitious composites are subjected to freeze-thaw cycles (Figure 4), a first beneficial effect is observed: the reduction in mechanical strength following freeze-thaw action occurs only in the control composition, while composites with BCH show slight increases in strength indicators. This behavior suggests the possibility of improving the durability of cementitious composites through BCH addition.

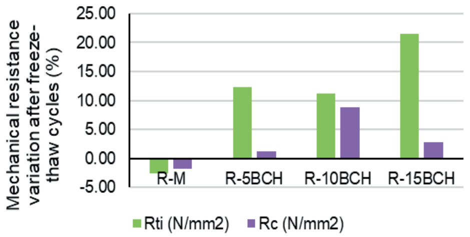


Figure 4. Increase in mechanical strength of control and BCH cementitious composites after 25 freeze-thaw cycles

Similarly, the action of wet-dry alternation cycles combined with the action of chlorine ions in the immersion phase (wet), leads to a reduction in mechanical strength only for the control composition, supporting the possibility of improving durability by using BCH (Figure 5).
According to the literature (Chen et al., 2023), a possible explanation for this phenomenon could be found as a result of several processes that occur when BCH is introduced into the composite matrix:
- the incorporation of biochar into the cementitious composite improves the pore structure, dimensions, and distribution, which leads to a reduction in capillary porosity. At the same time, the macropore structure becomes more independent, providing more space for frozen water (this being the main factor that induces internal stresses in the composite matrix upon freezing), thus reducing the internal stresses in the freezing phase and the loss of mechanical strength (Gupta et al., 2020; Jia et al., 2023; Qin et al., 2016);

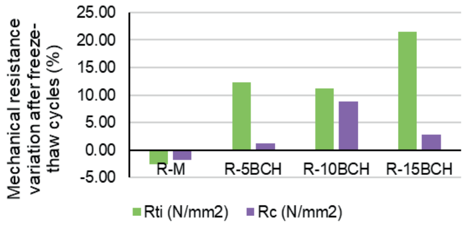


Figure 5. Increase in mechanical strength of control and BCH cementitious composites after 25 wet-dry cycles

- on the other hand, the porous structure of BCH can store and, when necessary, slowly release an amount of water necessary to reduce the self-shrinkage of the cement paste, promoting the hydration reactions of the partially or unreacted cement granules, densifying the material and thus improving long-term properties and durability (Mo et al., 2019). Additionally, it has been shown that the BCH-cement paste transition zone (ITZ) can be superior to that characteristic of sand particles, which increases the yield of hydration product formation (Mrad & Chehab, 2019);
- at the same time, studies have shown that the incorporation of BCH into the composite matrix strongly contributes to increasing the possibilities of storing CO_2 and forming stable calcium carbonate precipitates through rapid reaction with the main compounds of non-hydrated cement, tricalcium silicate (C_3S) and calcium hydrogen silicate (C-S-H) inside the cement matrix, while promoting the process through its function as a nucleating agent. Subsequently, through the precipitation of calcium carbonate, BCH will cause the filling of pores and the reduction of the carbonation depth (Liu et al., 2022), a similar effect being probably possible on the penetration of liquids in the freeze-thaw or wet-dry process in the presence of chloride. This CO_2 absorption capability could also improve indoor air quality, as recent

studies have shown that CO2 levels in multifamily buildings often exceed recommended thresholds for a health-safe indoor environment (Magurean & Petran, 2023). The mass loss due to abrasion stresses is reduced by modifying the mortar composition as a result of the addition of organic waste subjected to thermal treatments (mass loss of 13.6-17.2% for samples with BCH, compared to 19.6% for the control sample). However, given that the addition of organic waste subjected to thermal treatments results in a reduction in the density of the material, it is considered that this indicator is inconclusive and could lead to an erroneous conclusion indicating an increase in wear resistance. Therefore, two other indicators were analyzed: the height loss of the sample and its volume loss (Figure 6).

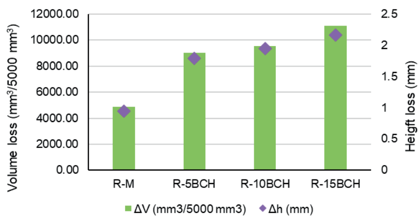


Figure 6. Height/volume loss of specimens subjected to abrasion stress

It is thus demonstrated that with the addition of BCH, the wear resistance of the mortars decreases, increasing the height losses and volume losses of the specimens. However, analyzing the experimentally obtained results in correlation with the series of standards EN 1338, EN 1339, and EN 1340, specific to prefabricated elements such as tiles, pavers, and curbs, it can be said that mortars with the addition of BCH meet the acceptability criteria in terms of wear resistance, with maximum height and volume loss limits being 2 mm and 11080 mm^3 / 5000 mm^3, respectively.

It should be noted that the specialized literature restricts the amount of heat-treated organic waste to 1-2%, a maximum 5% mass percentage, and the tests carried out addressed substantially larger amounts of used waste. This approach, assuming the risk of reducing some physical-mechanical performance indicators, allowed demonstrating the achievement of the acceptability criteria specific to a specified field of use, in this case, masonry mortars or compositions intended for the manufacture of paving elements. At the same time, corroborating the indicators relating to the apparent density and water absorption that lead to an increasing porosity with the addition of BCH, with the thermal conductivity coefficient (Figure 7), it is appreciated that the addition of BCH contributes to improving the thermal performance of the composites. Thus, a possibility is foreseen to produce cementitious composites similar to adhesive mortars intended for the production of ETICS thermal insulation systems whose thermal conductivity coefficient generally falls within the range of 0.08-0.11 W/mK. At the same time, for cementitious composites containing BCH, the mechanical strength indicators support this possibility of defining a field of use in the area of adhesive mortars intended for the creation of ETICS thermal insulation systems.

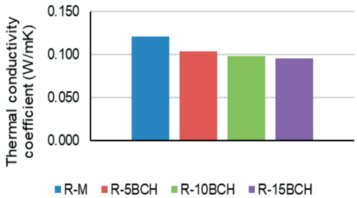


Figure 7. Thermal conductivity of cementitious composites

Regarding the results of the program analyzing the influence of BCH on plant growth, several key elements were highlighted. After the first week following seed planting (Figure 8), it was observed that the control containers showed a germination rate of 60% (3 shoots out of 5 seeds), while in containers with BCH-enriched soil, the germination rate was 80-100% (4-5 shoots out of 5 seeds).

Figure 8. Plant development - week 1

During the 9 weeks of monitoring, more accelerated plant development was recorded, regardless of plant type, in the soil enriched with BCH (Figures 9-11).

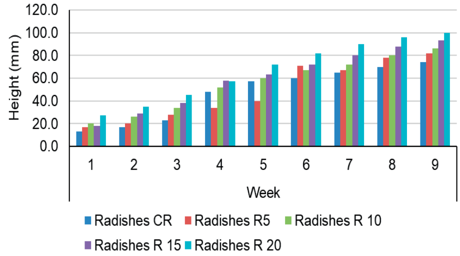
Figure 9. Plant development - week 5

Figure 10. Plant development - week 9

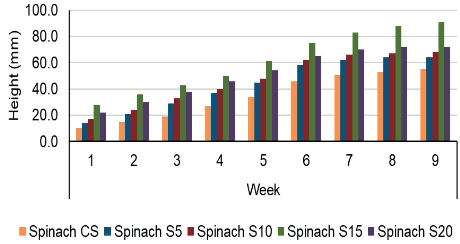
Compared to the control sample, radishes showed a 6-fold more intense growth after 9 weeks with just 5% BCH addition, and for additions of 10-20% BCH in the soil, the height increase was 16.2%, 25.7%, and 35.1% more intense.

In the case of spinach, a Gaussian evolution of the benefit was observed, quantified by the increase in plant height. In the range of 5-15% BCH addition to the soil, after 9 weeks, compared to the control, the plants were taller by 16.4%, 23.6%, and 65.5%, respectively, while for soil with 20% BCH, this indicator was 30.9%. This Gaussian evolution was maintained throughout all weekly measurements, indicating that a 20% BCH addition to the soil is not beneficial, with the limit in the analyzed case being 15% BCH.

A similar evolution to spinach development was also recorded in lettuce plants. For 5-15% BCH, the plant heights were 8.1%, 21%, and 69.4% higher compared to the control after 9 weeks, while for soil with 20% BCH, this indicator was 32.3% higher compared to the control. Again, this Gaussian-type evolution was maintained throughout all 9 weeks, similarly indicating a limitation of 15% for BCH addition to the soil.



a)



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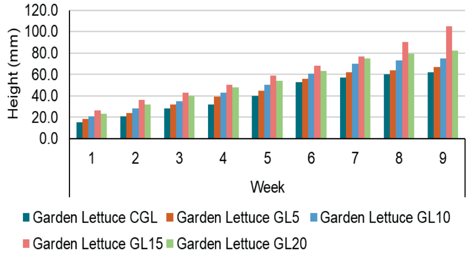

c)

Figure 11. Evolution of plant height during the 9 weeks of analysis, based on the amount of BCH used: a) radishes (R); b) spinach (S); c) garden lettuce

Similar results were also obtained by Goldan E. and Nedefe V. (Goldan & Nedeff, 2020) in their experimental research on winter barley plants in open fields.

CONCLUSIONS

The purpose of this study was to analyze, in parallel, possible directions for using plant waste treated by partial pyrolysis, specifically a biochar-type product, in two independent fields: construction materials and agriculture. Based on the experimental results presented, regarding the influence of BCH addition in cementitious composites, the following can be stated:

- reductions in apparent density in the hardened state were recorded simultaneously with increases in water absorption, which could be considered indicators suggesting an increase in open porosity. Additionally, reductions in mechanical resistance to compressive, flexural, and abrasion stresses were recorded. However, by correlating the obtained results with the specific conformity indicators for tiles, pavers, and curbs specified in the product standards EN 1338, EN 1339 and EN 1340, a preliminary direction for identifying the field of use can be determined, as cementitious composites with BCH addition satisfy these criteria;
- analyzing the durability indicators, namely the loss of mechanical resistance following exposure to freeze-thaw cycles and wet-dry cycles under the action of chlorine ions, the experimental results indicate a performance improvement. More specifically, mechanical resistance increases in cementitious composites with BCH addition, unlike the control sample whose mechanical performance is, as expected, reduced following exposure to the test cycles. Possible explanations can be found in the scientific literature, which identifies a significant influence of BCH on the porosity of cementitious composites, on the hydration-hydrolysis mechanism of cement granules, on the structure of the interfacial transition zone (ITZ) between the cement paste and BCH granules, and the potential for CO_2 storage and formation of stable calcium carbonate precipitate. This precipitate forms through rapid reaction with the main compounds of non-hydrated cement and could fill the pores or even the microcracks that appeared during the stress period of the test cycles;
- regarding the influence of BCH on the thermal conductivity coefficient, this indicator showed improvement compared to the control sample, which, correlated with the reduction in apparent density and sufficient mechanical resistance, can support the identification of a new research direction, namely, the development of adhesive mortars intended for ETICS thermal insulation systems of building facades.

Therefore, although the literature restricts the amount of heat-treated organic waste to 1-2%, with a maximum of 5% mass percentage, the tests carried out addressed substantially larger amounts of waste. This approach, while assuming the risk of reducing some physical-mechanical performance indicators, allowed the demonstration of achieving acceptability criteria specific to a particular field of use, in this case, masonry mortars, compositions intended for the manufacture of paving elements, or even adhesive mortars specific to ETICS thermal insulation systems.

Based on the experimental results presented, regarding the influence of BCH addition to agricultural soil, a positive influence was also identified on the development of some food consumption plants: radish (*Raphanus sativus*), spinach (*Spinacia oleracea*), and garden lettuce (*Lactuca sativa*). The experimental results indicated an increase in germination rate from 60% recorded for the control samples to 80-100% recorded for the soil samples with BCH addition. Additionally, more accelerated plant development was recorded, regardless of plant type, in the soil enriched with BCH, noting that, for the same development time interval, the evolution of plant height depending on the amount of BCH used in the soil can be Gaussian-type, depending on the cultivated plant type. Overall, a maximum limit of 15% BCH amount is recorded, exceeding it (samples with 20% BCH) may lead to reduced benefits in terms of plant development (spinach and lettuce).

In conclusion, based on the experimental results, in addition to several benefits that prove the possibility of valorizing plant waste and using BCH in construction and agriculture, several future research directions can be identified:

- analysis of the influence of introducing BCH into cementitious composite matrices not as an addition but as a raw material substitute;
- identification of maximum acceptable limits for BCH use in cementitious composites, depending on the expected field of use;
- identification of correlations between soil nature and characteristics, plant type, and optimal BCH amount used to obtain maximum benefits.

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