

# Screening and Ranking Methodology Applied to Biochars Aimed at Acidic and Calcareous Sandy Soil Improvement

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## Abstract

The application of biochar (the by-product of biomass pyrolysis), as a soil amendment has been accepted as a sustainable solution to improve soil quality. The current study aims to establish a decision support tool for characterizing, ranking, and selecting biochars of different origins for soil improvement, thereby contributing to the development of a systematic approach, which lacks in the existing literature.

The development of a Multi-Criteria Decision Support Approach applying a banded and weighted rating and scoring system allowed the selection and ranking of various biochars suitable for improving sandy soils before application. First, 14 selected, different biochar products (produced from industrial by-products, herbaceous, wood-based and manure-based feedstocks) were characterized with several physicochemical, biological and ecotoxicological methods taking into account both the technological and the environmental efficiency aspects of biochar utilization. Then, a system for the assessment and ranking of biochars for acidic, and calcareous neutral sandy soil improvement was developed, which could be flexibly adapted to different soil problems as well. Based on their performance in the tests, scores from (–5) to (+5) were assigned to each biochar. As a result, the grain husks and paper fiber sludge biochar was ranked as the most suitable for both acidic and neutral calcareous sandy soil improvement, with 55 and 43 scores, respectively (from the maximum 100). The applicability of this innovative multicriteria scoring-ranking system, as a tool for potential biochar users, was verified in microcosms and field-scale experiments, demonstrating the positive influence of this biochar on the acidic sandy soil.

## Keywords

biochar, soil amelioration, multi-criteria analysis, decision support tool, acidic sandy soil, calcareous sandy soil

## 1 Introduction

Biochar, the solid product of organic material pyrolysis is a highly heterogeneous material with chemical composition and physical properties that vary depending on feedstock and pyrolysis conditions [1, 2]. Many studies have shown that biochar applied to soil positively influences soil physico-chemical properties and improves soil functions, such as water and nutrient holding capacity [3–7], enhances resilience to drought and certain diseases and contributes to climate change mitigation by building soil carbon sinks [8]. Due to these characteristics, biochar, applied alone or combined with other organic amendments (e.g. compost, manure etc.), may potentially improve crop yield [9, 10]. So, in rehabilitating soils

with low fertility and agronomic performance, biochar application can be an excellent alternative to traditional soil-improvement methods.

Although the biochar application in various environmental technologies has numerous benefits, its use has some limitations. The fact that the raw materials (feedstocks) and also the biochar product may contain high concentrations of organic and inorganic contaminants imposes the environmental and human risk assessment to provide information for a safe biochar application [2, 5, 11]. Connected to this topic, there are also gaps in the ecotoxicity assessment of biochars, although several studies have been performed on this issue [5, 9, 11]. Furthermore,

environmental factors may also influence the efficiency of biochar products applied in soil. However, auxiliary data sets, such as information concerning environmental parameters, are incomplete in the scientific literature [12].

To predict whether applying a particular biochar on a particular soil will result in positive, negative or neutral agronomic and environmental responses, a systems-level understanding of soil-crop-climate-biochar interactions is needed [13]. Quality assessment of various biochar types requires, in addition to the physicochemical criteria, consideration also of the ecological aspects [12–14]. It has been recognized [5, 15] that in order to understand the ecological and physicochemical effects of biochars when applied to various soils, biochars should be investigated on a "char by char basis". Thus, determining what type of biochar to apply to optimize environmental and agronomic outcomes is very challenging.

As Meyer et al. [16] recommended, there is a need for systematic research to use suitable biochar quality grades for different soil application purposes.

For the sustainable use and application of biochar Glaser et al. [17] pointed out the need to standardize analytical biochar characterization, to match biochar types with its intended use and to harmonize the related legislation.

The production and application of biochar are still not regulated adequately at national and international levels. Voluntary biochar quality standards have been established in Europe, such as the European Biochar Certificate, the Biochar Quality Mandate in the UK and the IBI Standard in the USA which are intended to be used internationally [18–20]. A recent expert assessment performed by Tammeorg et al. [13] on the key priorities in biochar research has confirmed the previous findings, that biochar should be characterized prior to its addition to soil using established methodologies [18–20] and biochar characterization should be complemented by effect-based approaches in soils that are reflective of possible risks.

Studies applying a scoring procedure supported by a guidance matrix, as a basis for assessing the effects of various biochar types on soil, have not been identified in our literature search, except a previous study conducted by the authors [21]. To assess the sustainability of contaminated land remediation, as part of a multi-criteria decision analysis approach, a semi-quantitative scoring method was developed and applied by Rosén et al. [22]. They scored the effects of remediation based on available data, expert judgment, interviews. Harvey et al. [23] developed a comprehensive framework for evaluating the quality or carbon

credits of different biochars, before land application, establishing a new recalcitrance index (R50) for quantifying biochar recalcitrance.

This paper's authors have published in a previous article [21] a preliminary screening study focusing mainly on the ecotoxicity of 13 biochars to assess their future applicability as soil ameliorant, based on a scoring system. Since the effect of a particular biochar on a particular soil depends on several indicators characterizing soil-biochar-biota interactions [5–7, 13, 14], this study complemented the previous biochar pre-screening methodology [19] with additional physico-chemical and ecotoxicity parameters.

The main aim of the work was to select the best performing biochars from several biochar products based on the integrated effects on a particular soil prior to field application. This objective was achieved by the developed preliminary screening methodology, which combined the effects on soil physico-chemical properties, soil biota and plant growth.

Our hypothesis was that the applied scoring system would support the selection of the most suitable biochar products as soil-improving additive both for the acidic and the calcareous sandy soils. The best performing biochars could be recommended as soil ameliorant based on an aggregated score. The system could be adapted to various soil types in finding a suitable biochar product for soil amelioration.

## 2 Materials and methods

### 2.1 Biochar properties

The feedstocks of the tested biochars and their pyrolysis conditions are given in Table 1.

### 2.2 Multicriteria scoring system and the scoring criteria

A scoring-ranking system was developed to assess and rank certain biochar products in terms of their suitability for risk-based soil amendment. As a first step, the classification system of the Multi-Criteria Decision Support System was set up covering a point range from –5 to +5. Since soil is subject to a series of degradation processes and threats, in selecting the scoring criteria, we focused on soil parameters requiring improvement for potentially being affected by a relevant degradation process. In developing the Multi-Criteria Decision Support System, we focused on solving or at least mitigating soil degradation problems (acidification, wind and water erosion, decline in organic matter, decline in biodiversity) associated with sandy soils applying biochar as a soil amendment in agricultural land use.

**Table 1** Properties of the selected biochars

Biochar code	Biomass	Pyrolysis temperature (°C)	Pyrolysis residence time (min)	Pyrolysis system
BC1-PFS	Grain husk and paper fiber sludge	500 °C	20	PYREG®
BC2-PFSA	Grain husk and paper fiber sludge, N-enriched biochar, post treated with stone powder and compost	500 °C	20	PYREG®
BC3-BCM	Grain husk and paper fiber sludge, post treated with digestate, minerals	450 °C	20	PYREG®
BC4-BCMO	Grain husk and paper fiber sludge, post treated with digestate, minerals and organic liquid	450°C	20	PYREG®
BC5-W	Wood-screenings	600–700 °C	20	PYREG®
BC6-V	Vine shoots (pruning)	600–700 °C	15	PYREG®
BC7-BC	Black cherry wood chips	600–700 °C	15	PYREG®
BC8-S	Wheat straw	600–700 °C	15	PYREG®
BC9-MP	Miscellaneous meadow plants (after mowing)	600–700 °C	15	PYREG®
BC10-NB	Natural biomass (herbs pomace)	700 °C	15	PYREG®
BC11-WSD	Wood sawdust	600–700 °C	20	PYREG®
BC12-SP	Spelts mixed with paper (2:1)	600–700 °C	15	PYREG®
BC13-CM	Cow manure	650–750 °C	n.a.	Super Stone Clean®
BC14-M	Miscanthus	600–700 °C	15	PYREG®

Consequently, the parameters included into the evaluation system aimed at characterizing the following problems relevant to degradation of sandy soils: poor water regime, nutrient deficiency, low organic matter content, pH drop (acidification), low biodiversity.

Sandy soils are often considered to have easy to define physical properties: weak structure or no structure, poor water retention properties, high permeability, high sensitivity to compaction with many adverse consequences. The mostly studied key physical properties of sandy soils from an agronomic point of view include grain size distribution (texture) and water-holding capacity [5, 24, 25]. These parameters influence the movement and retention of water, air and solutes in the soil [26].

The key soil chemical properties to be improved include pH [27–29], cation exchange capacity (CEC), organic matter content [30] and available nutrient content (NPK) [31, 32].

Most soil chemical properties are associated with the colloid fraction and affect nutrient availability, biota growing conditions, and, in some cases, soil physical properties [26]. The key soil biological parameters requiring improvement in a sandy soil include microbial activity and biomass [33, 34].

Biological properties in the soil contribute to soil aggregation, structure and porosity, as well as soil organic matter (SOM) decomposition [26]. Soil biological properties are interconnected with other soil physicochemical properties and affect the activity of microorganisms [26].

Assigning scores to the limit values of certain criteria was based on the scientific literature, recommendations and guidelines of the EBC and the IBI. Our aim was to create a scoring system adequately fitting both to the characteristics of the degraded soil and the soil improvement goals taking into account the technological and environmental efficiency. The environmental efficiency parameters provide information on the toxicity, the potential environmental risk of biochar products. Based on XRF measurements performed on several biochar products and on literature data we found that the limit value was mostly exceeded in case of the following toxic metals: Co, Cu, Cr, Ni, Zn. Thus, these metals were considered in our system. Ecotoxicity tests applying plant and animal test organisms also had an important role besides the toxic element content.

### 2.3 Methodology for the characterization and ranking of biochars

The biochars were tested with a wide range of methods taking into account both the technological and the environmental efficiency aspects.

From the technological efficiency point of view, the biochars' pH was determined in a 1:2.5 soil suspension according to the Hungarian Standard MSZ 21470-2:1981 [35] and water holding capacity (WHC) according to Öhlinger [36]. Ash content was measured based on Sluiter et al. [37]. BET specific surface area (SA) and total micropore volume was measured by low temperature (–196 °C) nitrogen vapour

adsorption by BET model based on Brunauer et al. [38]. The total organic carbon was determined using the modified Walkley-Black method [39].

The total N content was measured by the Kjeldahl method [39, 40]. From the measured total organic C and Sum N values, the C/N ratio was calculated. The plant-available P and K concentrations were determined in ammonium-acetate lactate (AL) extract, as described by Egnér et al. [41].

From the environmental efficiency point of view, the Co, Cr, Cu Ni, Zn content of the biochars was measured by XRF (NITON XRF XL3t 600). The Viability Index was created by adding up the determined cultivable heterotrophic bacteria and fungi cell counts. Aerobic heterotrophic living bacteria and fungi were determined as described by Ujaczki et al. [27] based on the method originally described by Benedetti et al. [42]. Meat and malt media was used for the cultivation of bacteria and fungi, respectively. After 48 h incubation the developed colonies (Colony Forming Units — CFU) were counted, and the results were given in CFU/g biochar.

Ecotoxicity tests were also carried out: root and shoot elongation test with white mustard (*Sinapis alba*) and common wheat (*Triticum aestivum*) according to the HS 21976-17:1993 [43]. The standard was modified to direct contact by Leitgib et al. [44] and was carried out according to Molnár et al. [5]. 5 g dry biochar sample was measured into a glass Petri-dish (10 cm in diameter, 2 cm height) and was wetted to 70 % of their WHC with tap water. Onto each sample, 20–20 *Sinapis alba* seeds or 16–16 *Triticum aestivum* seeds (with over 90 % germination ability) were placed, and the Petri dishes were incubated for 72 hours in darkness at  $23 \pm 1$  °C. The lengths of the seedlings' shoot and roots were measured, and the average was calculated.

As an animal ecotoxicological test organism, a soil-dwelling hexapod from the class of springtails (Collembola), the *Folsomia candida* was used in a 7-day mortality test. The test was carried out based on the modified version of [45] and [46]. 10 g dry biochar was measured into 375 mL glass test vessels and wetted to 70 % of their WHC with tap water. Ten animals (14 days old, from a synchronized culture) were transferred into each test vessel, and 2 mg dry yeast was added as food for the animals. The glass containers were incubated for 7 days at room temperature in the dark. After the incubation period, the number of surviving animals was determined after flooding the test vessels with tap water by counting the floating, live animals.

## 2.4 Statistical analysis

The statistical evaluation of the datasets was carried out with TIBCO Statistica™ 13.4. software. One-way analysis of variance (ANOVA) was performed to investigate whether the biochar type had any effect on the examined parameter ( $p < 0.05$ ).

Tukey's honestly significant difference test was applied to compare the effects of the different biochars. Pearson Product Moment Correlation Analysis was also carried out to map the relationship between the examined biochar parameters. The level of significance was  $p < 0.05$ . The correlation was considered strong in the cases when the Pearson's correlation coefficient ( $r$ ) was higher than 0.60 and very strong at  $r > 0.85$ .

## 3 Results and discussion

### 3.1 Results of biochar characterization

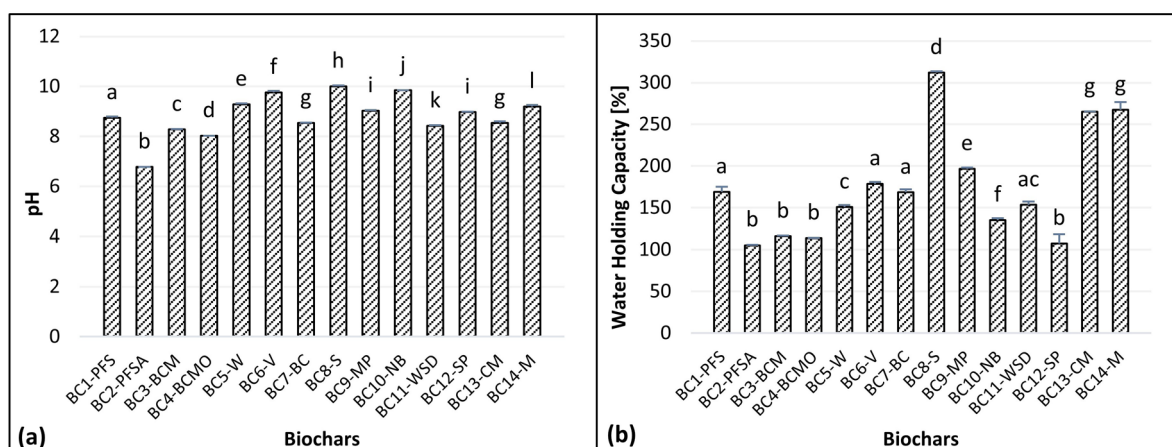
The biochars were tested with a wide range of methods taking into account both the technological and the environmental efficiency aspects.

#### 3.1.1 Characterization and evaluation of biochars in terms of technological efficiency

From the technological efficiency point of view, the pH, WHC, total organic carbon (TOC), total nitrogen content (Sum N), C/N ratio, available (ammonium-lactate-acetate soluble) P and K, ash content, total pore volume and BET surface area of the biochars were measured. Table 6 in the Appendix summarizes the results of the conducted tests, and selected significant properties are shown in separate diagrams (Fig. 1 and Fig. 2).

All of the examined biochars have alkaline pH (Fig. 1 (a)), except the BC2-PFSA biochar (grain husk and paper fiber sludge, post-treated), which has the lowest pH (6.8), probably due to the compost and stone powder post-treatment and N-enrichment. Nonetheless, the pH of the other biochars is above 8; furthermore, it can be seen, that the biochars produced at higher temperature feature a higher pH (biochars from BC5 to BC14) which is in line with the literature [47, 48].

BC8-S (wheat straw), BC10-NB (natural biomass) and BC6-V (vine shoots) show high pH values (10.0, 9.9, 9.8, respectively). According to the ANOVA analysis, only the BC7 and BC13, as well the BC9 and BC12, can be grouped based on similar pH values. The remaining biochars are statistically different from each other in light of their pH. In terms of improving acidic sandy soil, the higher pH biochars are favoured.



**Fig. 1** (a) pH values and (b) Water Holding Capacity of the examined biochars. Data represent averages of three replicates and error bars are standard deviation. Letters on the columns indicate significant differences ( $p < 0.05$ )

Increased ash content contributes to the increased pH of the biochars produced under high-temperature pyrolysis conditions, due to the higher volatilization of organic compounds, therefore ash content influences biochar pH [49], which in turn affects the mineral nutrition for plants and microorganisms among various other soil properties. As a tendency, the biochars produced from grain husk and paper fiber sludge (BC1-BC4) exhibit higher ash content than the plant-based biochars, probably due to the high mineral content of the feedstock.

According to Laghari et al. [51], the evolution of the ash content is more sensitive to the feedstock than to the pyrolysis conditions. Feedstocks with relatively higher mineral content (e.g., manure) result in a biochar product with higher ash content than feedstocks with lower mineral content (e.g., crop residues). For acidic soils, additional alkalinity is welcome due to the treatment with high-ash biochars, but additional liming may lead to poor crop performance for high pH soils. However, low ash content makes biochar more amenable to transportation and incorporation into soils [52].

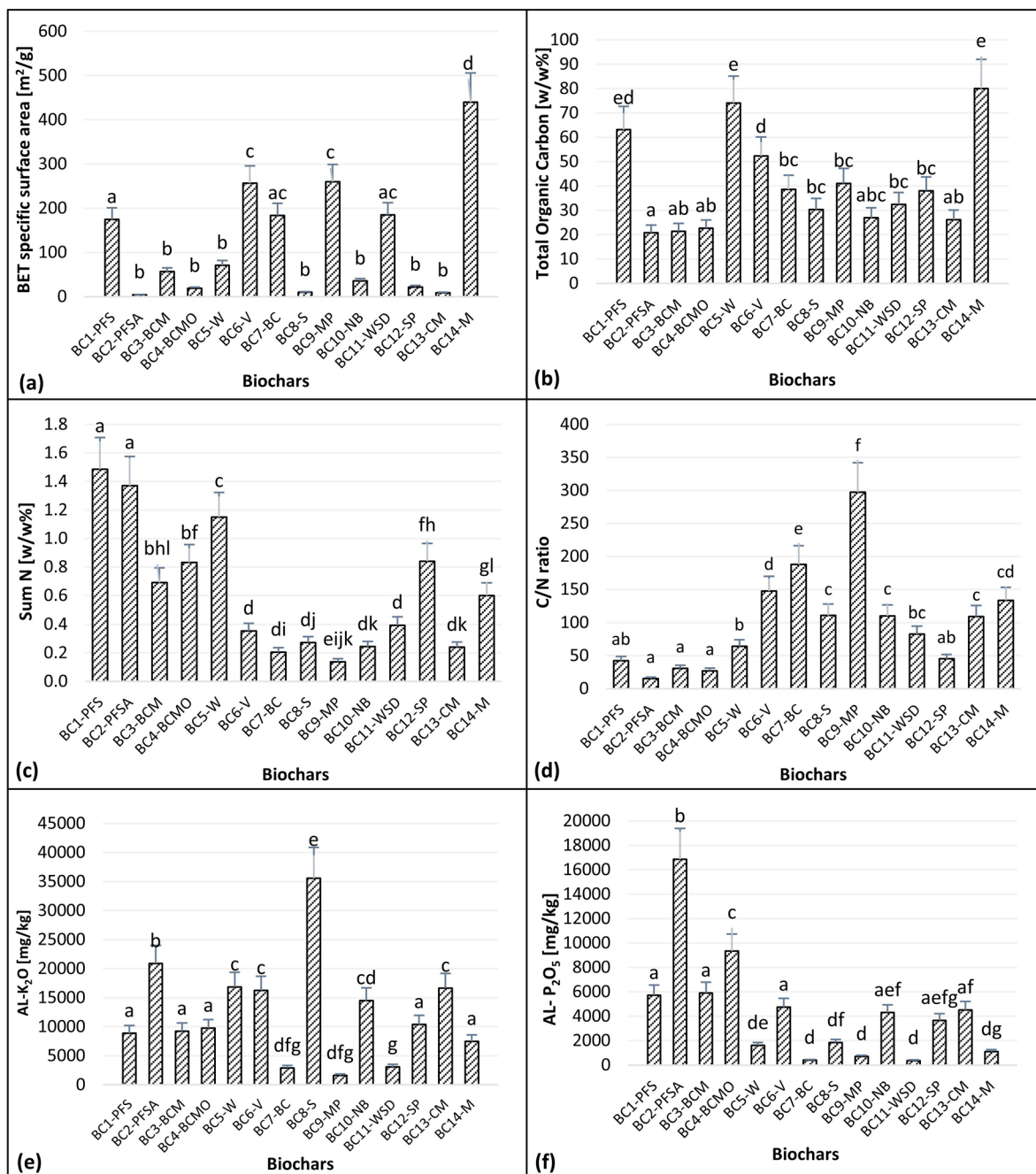
Due to their high water holding capacity, which may originate from their porous structure and high specific surface area, biochars can improve the water holding capacity and hydraulic properties of coarse-textured soils [47]. In our study, the WHC of the examined biochars (Fig. 1 (b)) ranges widely, in general, between 100 % and 200 % with some outliers. According to Chen et al. [53], with the increasing pyrolysis temperature, the degree of aromatization and hydrophobicity of biochar is enhanced, the number of functional groups containing O and N is decreased, and the water-holding capacity of biochar declines.

In our case, the biochars produced at low temperatures (BC1, BC2, BC3, BC4) featured lower WHCs supporting Laghari et al.'s [51] findings, whereby in most cases, higher temperature biochars had higher WHCs, due to their honeycomb-like structure and less hydrophobic properties. The post-treated versions of the grain husk and paper fiber sludge-based biochar (BC1-PFS), namely BC2-PFSA (post-treated with stone powder and compost), BC3-BCM (post-treated with digestate, minerals) and BC4-BCMO (post-treated with digestate, minerals, and organic liquid) furthermore the BC12-SP (spelts mixed with paper (2:1)) biochar were not statistically different from each other (based on the ANOVA analysis) and had the lowest WHC. Besides pyrolysis temperature, the applied post-treatments could also influence the WHC, blocking the pores of biochar and thereby reducing water retention.

However, 3 of the remaining biochars, namely BC8-S (straw), BC13-CM (cow manure), and BC14-M (miscanthus), have extremely high WHC, 312 %, 265 % and 268 %, respectively. Basso et al. [31] confirmed that biochar increased the water holding capacity of sandy loam soils, and the availability of some nutrients.

In relation to the WHC, the evolution of BET surface area (Fig. 2 (a)) and pore volumes (Table 6 in the Appendix) also need to be evaluated. These parameters play an important role in improving degraded soil's hydraulic conditions as well as nutrient retention. According to Chen et al. [53], the biochars' specific surface area is usually in the range of 1.5–500 m<sup>2</sup>/g, which is similar to our experience (Fig. 2 (a)), and it increases with the pyrolysis temperature within a certain range. Once the temperature exceeds the critical value, the specific surface area decreases with increasing





**Fig. 2** Differences in the physicochemical properties of the biochars: (a) BET specific surface area, (b) total organic carbon content, (c) sum nitrogen content, (d) C/N ratio, (e) ammonium-lactate-acetate soluble K<sub>2</sub>O, (f) P<sub>2</sub>O<sub>5</sub>. Data represent averages of three replicates and error bars are standard deviation. Letters on the columns indicate significant differences (*p* < 0.05)

temperature, probably as a consequence of the destruction of the microporous structure [53]. However, in our case, there is no apparent trend considering the pyrolysis temperature. Some of the biochars, namely BC1-PFS (grain husk and paper fiber sludge), BC6-V (vine shoots), BC7-BC (black cherry), BC9-MP (meadow plants), BC11-WSD (wood sawdust), BC14-M (miscanthus) have an exceptionally high specific surface area exceeding 150 m<sup>2</sup>/g, which is the value recommended by the International Biochar

Initiative (IBI). Among these, the biochar produced from miscanthus (BC14-M) has the greatest specific surface area, 440 m<sup>2</sup>/g (which differs from the others significantly), and it can be stated that BC6, BC7, BC9, and BC11 are statistically not different from each other.

The other biochars with low BET values not mentioned so far cannot be statistically separated.

Extremely low values were measured in the case of BC2-PFSA (4.6 m<sup>2</sup>/g), BC8-S (9.9 m<sup>2</sup>/g), and BC13-CM (8.7 m<sup>2</sup>/g).

The residual non-combustible component content usually depends on the feedstock and influences the surface area, besides it correlates with the moisture and ash content.

The inorganic material (ash) that partially fills or blocks the micropores may also contribute to the lower surface area of biochars [52].

The biochars' total pore volume also varies greatly, and no distinct tendency can be observed (Table 6 in the Appendix). Exceptionally high values can be observed for the BC1-PFS, BC6-V, BC7-BC, and BC9-MP and BC14-M biochars. Comparing these values with the BET surface area results, it can be seen that all of these biochars have a high specific surface area as well.

Each biochar feedstock contains a large amount of cellulose, which decomposes at 500 °C, resulting in a honeycomb-like structure with large pores. The biochar product is suitable for improving the nutrient retention and WHC of coarse-textured soils [51].

In the case of the Total Organic Carbon (TOC) content (Fig. 2 (b)), only the grain husk and paper fiber sludge-based (BC1-PFS, 63.2 %), woodscreenings- (BC5-W, 74.1) and miscanthus-based (BC14-M, 80 %) biochars have very high TOC content compared to the others, and their similarity was also proved statistically. As opposed to this, similarly to the WHC, the post-treated versions of the BC1-PFS biochar had low TOC values: BC2-PFSA, BC3-BCM, BC4-MO resulted in 20.8, 21.4, 22.6 % TOC content, respectively, probably due to their post-treatment, which reduced the amount of carbon per unit mass of biochar. Except for BC2 and BC6, the remaining biochars belong to the same group, as they are not different statistically. Soil total organic carbon content is a significant indicator of healthy soil to support various soil functions. Several authors described a significant increase in the soil organic carbon content following incorporation of biochar pyrolyzed at 300 and 500 °C; others reported significant increases in soil labile organic carbon and humic fractions following biochar application [54]. These findings indicate that biochar can largely contribute to enhancing the organic carbon stocks in soil and improving soil quality.

As shown in Fig. 2 (c), the majority of biochars have relatively low nitrogen content (Sum N). However, BC1-PFS, BC2-PFSA and BC5-W with 1.49 %, 1.37 %, and 1.15 %, respectively, which are the multiple of the average total N content, are highly exceeding the rest.

The composition of biochars varies depending on the feedstock type and pyrolysis operating conditions [15, 55]. For this reason, the total and available nutrient content of

biochars varies largely. According to Chan and Xu's [56] review, the total N content of biochars ranges from 1.8 g/kg to 56.4 g/kg. For example, the total N content of biochars from sewage sludge (64 g/kg) [57] and soybean cake (78.2 g/kg) [58] was much higher than that from green wastes (1.7 g/kg) [59].

On the other hand, despite the high total N content, the mineral N was < 2 mg/kg for the green waste and poultry manure char compared to the total N of 1.7 g/kg and 20 g/kg, respectively [56]. 1 t/ha biochar may approximately supply 1–20 kg N to the soil [60]; however, this nitrogen will become available for plants only after mineralization [61].

The calculated C/N ratio of the biochars (Fig. 2 (d)) ranges between 15 (BC2-PFSA) and 297 (BC9-MP). The grain husk and paper fiber sludge-based biochar (BC1-BC) and the BC12-SP had similarly low C/N ratio (< 50), which could also be supported by statistics. Besides the extremely high C/N value (297) of the meadow plants biochar (BC9-MP), the C/N ratios of the rest of the biochars range between 64 and 188. According to the literature, the C/N ratio of biochars is highly variable between 7 and 400, with a mean of 64. The C/N of biochar influences various other processes and can be an indicator of the bioavailability of organic compounds [62]. Several authors stated that microbial consumption of volatile biochar components with greater C:N ratios resulted in N immobilization [63, 64]; therefore, the high C/N ratio is unfavorable in case of nutrient-depleted soils. According to Hamer et al. [65], biochar stability is strongly correlated to its C:N ratio, which is influenced by the pyrolysis temperature and by the chemical structure of the feedstock used. In a study conducted by Gao et al. [66], biochar C/N ratio and biochar feedstock strongly influenced the soil's P availability response to biochar, where inorganic N was mostly influenced by the biochar C/N ratio and soil pH. Biochars made from manure or other low C/N ratio materials, generated at low temperatures, or applied at high rates were generally more effective at enhancing soil available P.

Fig. 2 (e) shows that three biochars made from feedstocks of high lignin content have remarkably low ammonium acetate-lactate soluble K<sub>2</sub>O content: BC7-BC (black cherry), BC9-MP (meadow plants), and BC11-WSD (wood sawdust) contains 2887 mg/kg, 1622 mg/kg and 3084 mg/kg AL-K<sub>2</sub>O, respectively and their similarity is also supported by ANOVA analysis. On the other hand, BC8-S (wheat straw) biochar has the highest K<sub>2</sub>O content, 35570 mg/kg, while most biochars feature K<sub>2</sub>O contents

between 7500 mg/kg and 21000 mg/kg. According to Chan and Xu's [56] review, the total K level of biochars ranges between 1.0 g/kg to 58 g/kg, and in contrast to N, the available K in biochars is typically high.

Also, an increased K uptake has been frequently reported as a result of biochar application [59, 61]. As reported previously [67] biochar at 10–25 t/ha rate may result in significant K content elevation in the soils.

There are large differences in the phosphorus content of the studied biochars (Fig. 2 (f)). The post-treated and N-enriched grain husk and paper fiber sludge biochar (BC2-PFSA) provides the highest  $P_2O_5$  content (16871 mg/kg). Besides this, all of the grain husk and paper fiber sludge-based biochars (BC1, BC3, BC4) feature higher  $P_2O_5$  content than the others. Similarly to the previously discussed  $K_2O$  content, the lowest values were measured in the wood sawdust (BC11-WSD, 373 mg/kg), followed by the black cherry (BC7-BC, 403 mg/kg) and meadow plants (BC9-MP, 703 mg/kg) biochars. According to the literature, in the case of total P, higher contents were found in biochars produced from feedstocks of animal origin than those from plants and significantly higher levels of available P were found in biochars produced from poultry litter than those from plant biomass [56]. The phosphorous content of biochar may range between 0.2–25 kg [60].

### 3.1.2 Evaluation of biochars in terms of environmental efficiency

Although the biochar application in various environmental technologies has numerous benefits, its use has some limitations. When using biochar as a soil amendment, the primary consideration is to avoid introducing into the soil the elements and compounds that are harmful to its condition, which can significantly contaminate the soil, or deteriorate the groundwater or surface water. For this reason, the biochar feedstocks have to be tested by biological and ecotoxicological methodology. From the environmental efficiency point of view, the toxic element content, the viability index and the ecotoxicity to plant and animal test organisms were measured.

Table 7 in the Appendix summarizes the results of the conducted tests, and the most important properties are shown in separate diagrams (Fig. 3). The concentrations of some potentially toxic elements (Co, Cr, Cu Ni, Zn) as one of the environmental efficiency factors were considered.

Based on the XRF measurements performed on the biochar products and according to literature data, we found that the limit value was mostly exceeded in the case of the

following toxic metals: Co, Cu, Cr, Ni, Zn. Thus, we considered only these metals in our system, despite the over 30 elements determined by the XRF method. The limit values set by the International Biochar Initiative recommendation for the above metals were exceeded in the following biochars: Co in BC3-BCM, Cu, in BC13-CM, Ni in BC3-BCM, Zn in BC3-BCM, BC4-BCMO and BC13-CM. As opposed to these metals, the limit value for Cr was not exceeded in any of the studied biochars (Table 7).

The effect of biochar on soil microbial communities is diverse, depending on both the biochar and soil type. The viability index may be a good indicator and predictor for biochar-microorganism interactions, for example, colonization.

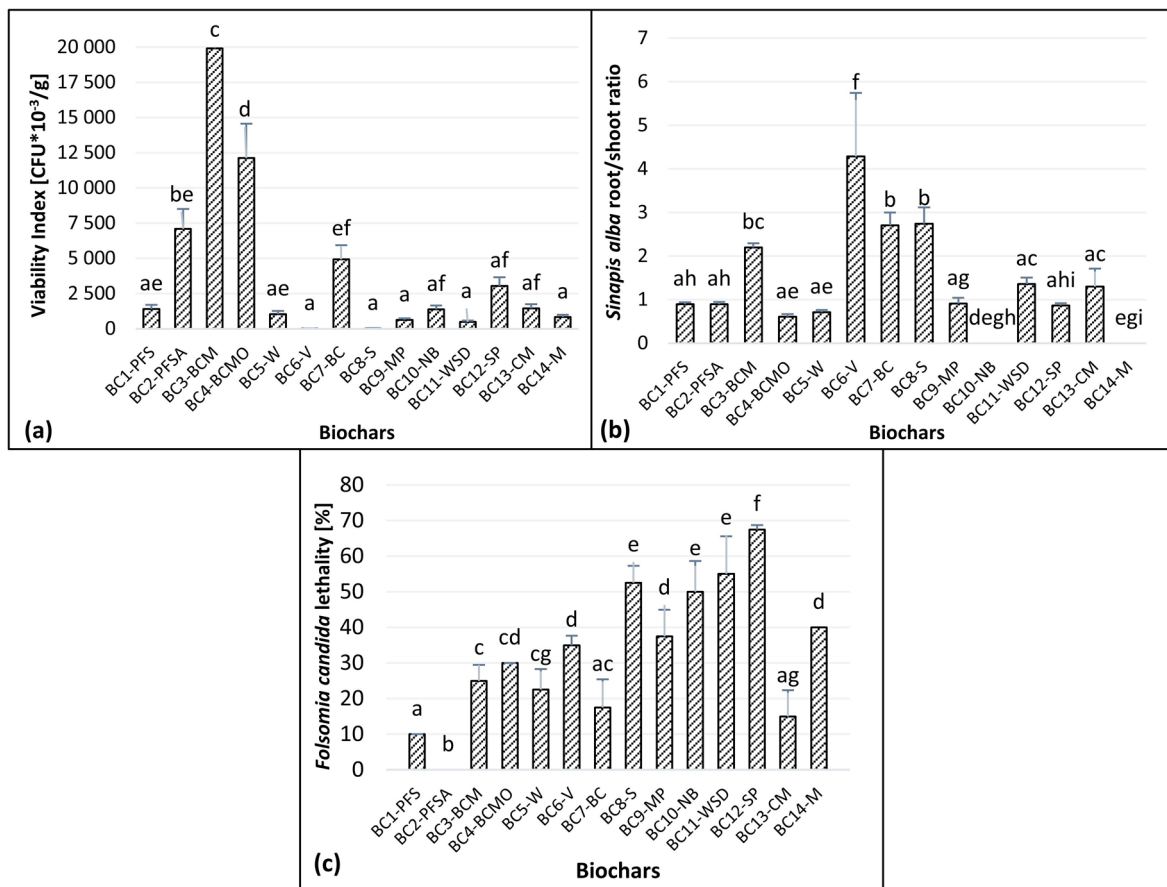
Although the biochars mostly have low bacteria and fungi counts, in a few cases, very high viability indexes were calculated (Fig. 3 (a)).

Fig. 3 (a) shows the calculated Viability Indexes. BC3-BCM and BC4-BCMO grain husk and paper fiber sludge-based biochars, both post-treated with digestate and minerals, had high cell counts (19 914 and 12 132 CFU/g biochar, respectively), probably due to the organic compound-rich digestate post-treatment. BC6-V (vine) and BC8-S (straw) biochars, statistically similar to each other, had the lowest viability indexes ( $< 10$ ). Furthermore, the rest of biochars with low cell counts (BC1, BC5, BC6, BC8, BC9, BC10, BC11, BC12, BC13, and BC14) could not be distinguished from each other.

The root/shoot ratio ( $R/S$ ) of the mustard seedlings is an important indicator of the ecotoxicity of the biochars (Fig. 3).

The natural biomass-based BC10-NB and the miscanthus BC14-M biochars inhibited the germination of the mustard seeds; therefore, the  $R/S$  ratios were not calculated. A seedling is considered healthy if this ratio is around 1 (0.85–1.15); therefore, healthy mustard seedlings were developed on the following biochars: BC1-PFS, BC2-PFSA, BC9-MP, BC12-SP, however, the following samples did not differ statistically significantly from the previous ones either: BC4-BCMO, BC5-W, BC11-WSD, BC13-CM. The  $R/S$  ratio was extremely high ( $> 2$ ) in several cases (BC3-BCM, BC6-V, BC7-BC, BC8-S) because the roots of the seedlings were at least twice as long as the shoots. This result could be explained with the escaping behavior of the plant roots from the inappropriate environment established by these biochars. Conversely, when the  $R/S$  ratio was  $< 1$  (in case of BC4-BCMO and BC5-W, 0.6, and 0.71 respectively) indicating that the seedling shoots were longer than the roots, the underdeveloped





**Fig. 3** Evolution of the environmental efficiency parameters: (a) Viability index, (b) *Sinapis alba* root/shoot ratio, and (c) *Folsomia candida* mortality rate. Data represent averages of three replicates and error bars are standard deviation. Letters on the columns indicate significant differences ( $p < 0.05$ )

roots could be the result of a toxic or inappropriate environment as in the previous case.

Due to the feedstock and the pyrolysis process, some biochars might pose a risk to soil biota; therefore, the integrity of soil's habitat function should be checked. BC2-PFSA, the N-enriched, stone powder, and compost post-treated grain husk and paper fiber sludge biochar provided an excellent habitat to the *Folsomia candida* animals, resulting 0 % lethality in the mortality test (Fig. 3 (c)). However, the majority of the biochars induced various degrees of lethality. Among them, BC1-PFS (grain husk and paper fiber sludge), BC7-BC (black cherry), and BC13-CM (cow manure) resulted in only a slight, less than 21 % lethality. The lethality rate was higher in the case of the rest of the tested biochars, reaching the highest value, 67.5 % for the spelts and paper mix (BC12-SP) biochar.

### 3.2 Description of the biochar scoring-ranking system

Studies applying a scoring procedure supported by a guidance matrix as a basis for the assessment of the effects of various biochar types on soil have not been identified

in the scientific literature. During the development of the Multi-Criteria Decision Support System (MCDSS), as a first step, we developed a classification system in the -5 points to +5 points interval.

Table 2 and Table 3 summarize the characterization criteria for technological and environmental efficiency (respectively) and show the parameter ranges and the corresponding scoring. From the technological efficiency point of view – as described earlier - the pH, WHC, TOC, total nitrogen content, C/N ratio, available P and K, ash content, total pore volume and BET surface area of the biochars were considered. As the aim of the research was to develop soil improvement technology for both acidic and neutral soil, two relevant parameters (pH and ash content) were handled separately for both soils during the scoring.

When aiming for acidic sandy soil improvement, the biochars featuring higher pH received a higher score. "0" score was assigned to the 6.1–7 pH range. Below pH 6.1, negative scores were assigned. In the case of neutral sandy soil improvement, the "0" score was assigned to the pH 6.1–8 values interval.

**Table 2** Intervals of the created scoring system to determine scores for the technological efficiency parameters

Score	Characteristics of biochars							Technological efficiency				
	pH <sup>1</sup>	pH <sup>2</sup>	Ash content <sup>1</sup> [%]	Ash content <sup>2</sup> [%]	WHC [%]	BET <sup>3</sup> [m <sup>2</sup> /g]	Sum pore volume [cm <sup>3</sup> /g]	TOC [%]	Sum N [%]	C/N ratio	AL-P [mg/kg]	AL-K [mg/kg]
5	8 <	–	–	–	200 <	150 <	0.16 <	85 <	–	–	15000 <	15000 <
3	7.1–8	–	35 <	–	101–200	101–150	0.13–0.16	71–85	–	10–30	7501–15000	10001–15000
1	–	–	25.1–35	5–15	71–100	81–100	0.10–0.13	61–70	>1	31–49	1501–7500	5001–10000
0	6.1–7	6.1–8	15.1–25	15.1–25	51–70	51–80	0.07–0.10	51–60	0.3–0.99	50–100	1001–1500	3001–5000
–1	–	–	5–15	25 <	31–50	31–50	0.04–0.07	31–50	0–0.29	101–199	501–1000	1000–3000
–3	5–6	8.1–9	<5	–	<30	11–30	0.01–0.04	11–30	–	> 200	< 500	< 1000
–5	< 5	9 <	–	–	–	< 10	–	< 10 %	–	–	–	–

<sup>1</sup> aiming acidic soil improvement,<sup>2</sup> aiming neutral soil improvement,<sup>3</sup> based on the EBC Guideline**Table 3** Intervals of the created scoring system to determine scores for the environmental efficiency parameters

Score	Characteristics of biochars		Environmental efficiency	
	Toxic element concentration <sup>1</sup> Co, Cr, Cu Ni, Zn [mg/kg]	Viability index [CFU 10 <sup>-3</sup> /g]	Plant growth inhibition <sup>2</sup> [%]	<i>F. candida</i> lethality <sup>2</sup> [%]
5	No limit value exceeded	2000 <	< 0 (stimulation)	< 10
3	Max. 1.2 times limit value exceeded	1600–2000	0–20	10–20
1	Max. 1.4 times limit value exceeded	1201–1600	21–30	
0	Max. 1.6 times limit value exceeded	801–1200	31–40	21–30
–1	Max. 1.8 times limit value exceeded	401–800	41–50	31–50
–3	Max. 2 times limit value exceeded	0–400	51–80	51–80
–5	More than 2 times limit value exceeded	–	80 <	80 <

<sup>1</sup> based on IBI Recommendations<sup>2</sup> Inhibition percentage

No positive score intervals have been set for neutral soils because pH improvement is not needed in this case. Because the high WHC of the biochar is a positive attribute, 0 score was assigned to the biochar with WHC ranging between 51–70 %, meaning that the biochar can hold water of at least 50 % of its dry weight.

Even though low WHC biochars were not favored, we refrained from allocating the extreme –5 points score, which is valid both for the nutrient- and ash content score allocation. In the case of the TOC content, a balanced score scale has been set with zero points for the 51–60 % TOC range. The biochars exceeding 85 % TOC received 5 points. For the total N content, only –1, 0, and +1 scores were assigned to reduce the parameter's weight. 0 was assigned to 0.30–0.99 % N content, and all the biochars having higher than 1 % total N content received 1 point.

Lehmann et al. [68] reported that the biochars' C/N ratio varies between 7 and 400, with a mean of 64; therefore, 0 score was given for the 50–100 C/N interval. However, the scale was balanced since the score-scale for the C/N ratio did

not include the +5, or –5 score because there are no ultimate C/N values to characterize the goodness of certain biochar.

Since the bioavailability of different organic compounds decreases when the C/N ratio is high, biochars with higher than 100 C/N ratios will be allocated a negative score. Similar intervals were applied in the case of AL-P and AL-K favoring high nutrient contents; the biochars with low P and K content (500 and 1000 mg/kg, respectively) got negative scores, as the nutrient supply from biochars is critical during degraded soil improvement.

The ash content was considered separately for the acidic and the neutral soils. Ash behaves as a liming agent in acidic soils and can control the pH; therefore, the scale for the ash content had a considerable weight favoring the high ash content. In neutral soils, there is no need to raise the soil pH; moreover, the presence of higher ash is disadvantageous. For this reason, the biochars with higher ash content received a negative score.

Since pore volume of biochars has a huge role in improving the hydraulic properties of soils, an arbitrary

scale based on experience and available data has been set favoring large pore volumes and assigning 0 point for the 0.07–0.10 pore volume range.

The scoring scale of the BET parameter was prepared according to the EBC guideline [18], stating that biochars should ideally have a surface area of over 150 m<sup>2</sup>/g, therefore, the biochars, which reached this value, were given a score of 5. The 51–80 m<sup>2</sup>/g value range was assigned 0 score, and below this, negative scores were assigned.

The concentrations of Co, Cr, Cu Ni, Zn were determined as one of the environmental efficiency factors. When the toxic element content did not exceed the lower limit value of the interval set by the International Biochar Initiative [20], the highest score (5) was assigned to the certain biochar product. The following limit values were considered: Co: 34 mg/kg, Cu: 143 mg/kg, Cr: 93 mg/kg, Ni: 47 mg/kg, Zn: 416 mg/kg.

With a uniform scale, 0 point was assigned for 1.6-fold limit value exceedance. Above this exceedance limit, negative scores were assigned. The viability index showing the sum of the number (in Colony Forming Unit – CFU/g biochar) of cultivated bacteria and fungi represents a combination of many different factors (nutrient supply, porosity, toxic element content, etc.). The viability index scale assigned "0" score for the 801–1200 range, representing the high amount of microorganisms settled on the biochar surface.

Most of the biochars tested inhibited plant growth, so the scale's highest value (5 scores) was assigned for stimulation. The scale is even; thus, the lowest score (–5) was given to biochars causing over 80 % inhibition.

Similarly, regarding the *Collembola* mortality, almost all tested biochars caused some degree of inhibition; therefore, the highest score was given to the products causing less than 10 % mortality. "0" score was assigned for the 10–30 % mortality range. Once the mortality became < 30 %, negative scores were assigned down to –5 points at > 80 % lethality rate. We assigned positive scores for > 40 % inhibition in the plant test and > 30 % lethality in the animal test because we assumed that both effects would be mitigated when mixing biochar into the soil.

Based on the results, scores were assigned to the corresponding biochars according to the Multi-Criteria Decision Support System (MCDSS) (Table 2 and Table 3) shown in Table 4. Table 5 shows the total scores (and ranking) calculated from two different aspects:

1. aiming acidic soil improvement
2. aiming neutral soil improvement, respectively.

BC1-PFS biochar, produced from grain husks and paper fiber sludge, was ranked on the first place with the highest summarised score as suitable for acidic soil, followed by its nitrogen-enriched and stone powder and compost post-treated version (BC2-PFSA; 48 scores). The ranking order of these two biochars was reversed when scoring for neutral soil improvement.

Woodscreening biochar (BC5-W, 36 total scores) was ranked as the third for acidic soil improvement, followed by the black cherry wood biochar (BC7-BC, 33 total scores) and the miscanthus (BC14-M, with 31 scores). These biochars had the highest scores also when ranked for neutral soil improvement.

The reliability and applicability of the scoring system were verified through the results and outcomes of the subsequent research phases based on a tiered approach. The best-performing biochars from this screening phase were then tested in microcosm experiments of different duration to compare their performance in different doses and soil types.

Based on the results of the screening and microcosm experiments, the biochar from grain husks and paper fiber sludge was efficiently applied in long-term field experiments at two sites to improve the properties of an acidic sandy and a calcareous sandy soil; the field studies demonstrated that the applied biochar had positive direct and indirect influences on the acidic sandy soil [5, 69, 70].

Finally, the parameters introduced in the developed system were able to characterize both soil quality and environmental health; however not all potential parameters were considered. This work established the basis for decision support systems aiming at biochar screening and selection for soil improvement. As a future perspective, the scope of the investigations may be extended to the relation between the pyrolysis conditions, feedstock type and biological and ecotoxicological properties of biochars while testing a higher number of biochar products.

#### 4 Conclusions

A Multi-Criteria Decision Support System (MCDSS) was developed for the characterization, ranking and selection of biochar products aiming their efficient and risk-based application for soil improvement. In the framework of the MCDSS development a classification system was created for the selection and ranking of biochars suitable for the improvement of acidic and calcareous sandy soils both from technological and environmental point of view, applying a banded and weighted rating scoring system.

**Table 4** Assigned scores for the technological and environmental efficiency parameters.

Biochar	Characteristics of biochars						Technological efficiency						Characteristics of biochars					Environmental efficiency				
	pH <sup>1</sup>	pH <sup>2</sup>	Ash content <sup>1</sup> [%]	Ash content <sup>2</sup> [%]	WHC [%]	BET [m <sup>2</sup> /g]	Sum pore volume [cm <sup>3</sup> /g]	TOC [%]	Sum-N [%]	C/N ratio	AL P [mg/kg]	AL K [mg/kg]	Toxic element - Co	Toxic element - Cu	Toxic element - Cr	Toxic element - Ni	Toxic element - Zn	Viability index	Root	Plant growth I. Mustard	Plant growth 2. Wheat root	<i>F. candida</i> lethality
BC1-PFS	5	-3	3	-1	3	5	3	1	1	1	1	1	5	5	5	5	5	1	0	5	-3	3
BC2-PFSA	0	0	3	-1	3	-5	-3	-3	1	3	1	5	5	5	5	5	5	5	0	5	-1	5
BC3-BCM	5	-3	3	-1	3	0	-1	-3	0	1	1	1	-5	3	5	-1	-5	5	3	1	-5	0
BC4-BCMO	5	0	3	-1	3	-3	-3	-3	0	3	3	1	5	5	5	5	-5	5	-5	-3	-5	0
BC5-W	5	-5	0	0	3	5	-1	3	1	0	1	5	5	5	5	5	0	-5	-3	-3	0	
BC6-V	5	-5	0	0	3	5	3	0	0	-1	1	5	5	5	5	5	-3	-5	-5	-5	-1	
BC7-BC	5	-3	-3	1	3	5	0	-1	-1	-1	-3	-1	5	5	5	5	5	5	1	-1	-3	3
BC8-S	5	-5	0	0	5	-5	-3	-3	0	-1	1	5	5	5	5	5	-3	-5	-5	-5	-3	
BC9-MP	5	-3	-1	1	3	5	3	-1	-1	-3	-1	-1	5	5	3	5	5	-1	-3	3	-3	-1
BC10-NB	5	-5	-1	0	3	-1	-3	-3	-1	-1	1	3	5	5	5	5	5	1	-5	-5	-3	-1
BC11-WSD	5	-3	0	0	3	5	0	-1	0	0	-3	0	5	5	5	5	5	-1	0	-3	-3	-3
BC12-SP	5	-3	1	-1	3	-3	-3	-1	0	1	1	3	5	5	5	5	5	5	-3	1	-3	-3
BC13-CM	5	-3	1	-1	5	-5	-3	-3	-1	-1	1	5	5	-1	5	5	-5	1	-5	-5	-3	3
BC14-M	5	-5	-1	0	5	5	5	3	0	-1	0	1	5	5	5	5	5	0	-5	-5	-5	-1

<sup>1</sup> aiming acidic soil improvement,

<sup>2</sup> aiming neutral soil improvement,

**Table 5** Summary of the assigned scores for the technological and environmental efficiency parameters. (Ranking is given in brackets.)

	SUM scores (and ranking) – acidic soil	SUM scores (and ranking) – calcareous soil
BC1-PFS	55 (1)	43 (1)
BC2-PFSA	44 (2)	40 (2)
BC3-BCM	11 (12)	-1 (12)
BC4-BCMO	16 (10)	7 (10)
BC5-W	36 (3)	26 (4)
BC6-V	27 (7)	17 (8)
BC7-BC	33 (4)	29 (3)
BC8-S	8 (13)	-2 (13)
BC9-MP	26 (8)	20 (6)
BC10-NB	14 (11)	5 (11)
BC11-WSD	24 (9)	16 (9)
BC12-SP	29 (6)	19 (7)
BC13-CM	4 (14)	-6 (14)
BC14-M	31 (5)	22 (5)

The benefits in the acidic sandy soil of the grain husk and paper fiber sludge biochar ranked first were confirmed both in laboratory microcosm and field studies of the subsequent research phases.

This system is unique in the literature especially because it could be flexibly adapted for the selection of biochars to different soil problems and it takes into account environmental aspects in addition to technology efficiency.

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## Appendix

**Table 6** Results of the biochar screening – evolution of technological efficiency parameters.

Biochar	pH	Characteristics of biochars - Technological efficiency								
		Ash content [%]	WHC [%]	BET [m <sup>2</sup> /g]	Sum pore volume [cm <sup>3</sup> /g]	TOC [%]	Sum N [%]	C/N ratio	AL-P [mg/kg]	AL-K [mg/kg]
BC1-PFS	8.8±0.0	40.2±3.1	169.1±6.1	175.0±26.3	0.145±0.022	63.2±9.5	1.49±0.22	42.5±6.4	5713±857	8889±1333
BC2-PFSA	6.8±0.0	68.5±1.6	105.3±0.7	4.6±0.7	0.021±0.003	20.9±3.1	1.37±0.206	15.2±2.3	5010±752	20894±3134
BC3-BCM	8.3±0.0	63.3±1.0	115.8±0.8	57.0±8.6	0.044±0.007	21.4±3.2	0.69±0.10	31.0±4.7	5913±887	9260±1389
BC4-BCMO	8.0±0.0	60.1±3.2	113.7±0.5	19.0±2.9	0.029±0.004	22.6±3.4	0.83±0.12	27.2±4.1	9343±1401	9768±1465
BC5-W	9.3±0.0	19.6±1.4	150.9±2.2	284.0±42.6	0.053±0.008	74.1±11.1	1.15±0.17	64.4±9.7	1610±242	16871±2531
BC6-V	9.8±0.1	16.0±11.7	178.8±2.1	257.0±38.6	0.148±0.022	52.3±7.9	0.35±0.05	147.6±22.1	4757±714	16262±2439
BC7-BC	8.5±0.0	4.6±1.5	168.5±3.4	183.6±27.5	0.099±0.015	38.6±5.8	0.21±0.03	187.9±28.2	403±60	2887±433
BC8-S	10.0±0.0	18.4±0.8	312.1±1.4	9.9±1.5	0.011±0.002	30.3±4.6	0.27±0.04	111.0±16.7	1837±276	35570±5335
BC9-MP	9.0±0.0	6.8±0.4	196.9±1.2	260.0±39.0	0.145±0.022	41.1±6.1	0.14±0.02	297.3±44.6	703±105	1622±243
BC10-NB	9.9±0.0	14.3±0.1	135.2±2.3	35.8±5.4	0.038±0.006	27.0±4.0	0.24±0.04	110.2±16.5	4300±645	14518±2178
BC11-WSD	8.4±0.0	17.82±0.83	153.4±4.1	185.0±27.8	0.090±0.014	32.5±4.9	0.39±0.06	82.6±12.4	373±56	3084±463
BC12-SP	9.0±0.0	30.6±0.3	107.3±11.0	22.0±3.3	0.036±0.005	38.0±5.7	0.84±0.13	45.2±6.8	3664±550	10403±1561
BC13-CM	8.5±0.1	25.6±0.4	265.1±0.6	8.7±1.3	0.015±0.002	26.2±3.9	0.24±0.04	109.3±16.4	4527±679	16667±2500
BC14-M	9.2±0.1	12.3±1.8	267.6±9.2	440.0±66.0	0.234±0.035	80.0±12.0	0.60±0.09	133.3±20.0	1100±165	7500±1125



**Table 7** Results of the biochar screening – evolution of environmental efficiency parameters.

Biochar	Toxic element– Co. Cu. Cr. Ni. Zn [mg/kg]	Characteristics of biochars - Environmental efficiency				<i>F. candida</i> lethality [%]
		Viability index [CFU/g] Bacteria + Fungi	Plant growth 1. Mustard [%]		Plant growth 2. Wheat root [%]	
			Root	Shoot		
BC1-PFS	<LOD; 52.0±5.0; 20.8±1.4; <LOD; 116.2±11.2	1.41E+06	39.9±0.1	-27.29±2.6	58.39±2.0	10.0±0.9
BC2-PFSA	<LOD; 20.7±2.2; <LOD; <LOD; 55.5±6.1	7.09E+06	38.7±2.7	-29.78±1.5	42.97±0.8	0.0±0.0
BC3-BCM	199.2±39.2; 140.4±0.5; 43.9±13.1; 77.8±18.0; 855.3±52.3	1.99E+07	9.8±0.3	22.19±1.2	83.55±9.6	25.0±0.0
BC4-BCMO	<LOD; 132.7±9.1; 23.6±4.3; <LOD; 863.4±77.1	1.21E+07	87.3±6.4	60.10±7.5	91.94±18.1	30.0±0.0
BC5-W	<LOD; 41.1±3.5; <LOD; <LOD; 334.0±9.5	1.05E+06	84.2±6.6	61.92±4.2	67.74±11.3	22.5±0.0
BC6-V	<LOD; 111.8±3.0; 29.1±1.4; <LOD; 219.7±27.6	1.22E+04	94.3±24.2	97.70±41.2	88.22±19.3	35.0±5.8
BC7-BC	<LOD; 16.4±2.3; <LOD; <LOD. 46.2±0.8	4.94E+06	20.7±1.6	49.65±7.1	78.75±10.1	17.5±2.6
BC8-S	<LOD; 23.2±1.7; 33.3±13.6; <LOD; 274.3±37.2	2.10E+04	93.1±15.4	95.71±10.4	100.00±0.0	52.5±7.9
BC9-MP	<LOD; 42.7±3.8; 70.2±18.9; <LOD; 48.6±9.1	6.25E+05	57.0±8.8	19.14±2.6	75.85±5.2	37.5±4.8
BC10-NB	<LOD; <LOD; <LOD; <LOD; 30.3±4.6	1.37E+06	100.0±0.0	100.00±0.0	77.54±12.7	50.0±7.5
BC11-WSD	<LOD; 23.1±3.5; <LOD; <LOD; 343.8±12.6	4.93E+05	39.8±0.9	50.94±9.7	60.32±5.3	55.0±8.6
BC12-SP	<LOD; 72.1±1.7; <LOD; <LOD; 224.5±7.5	3.04E+06	61.7±5.4	23.75±1.1	72.90±11.8	67.5±10.6
BC13-CM	<LOD; 250.8±14.8; <LOD; <LOD; 893.6±55.3	1.44E+06	97.5±21.2	97.86±41.0	66.42±2.3	15.0±1.2
BC14-M	<LOD; 48.6±0.2; 46.7±7.3; <LOD; 160.6±17.8	8.33E+05	100.0±0.0	100.00±0.0	91.94±16.4	40.0±7.3