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The Effect of Biochar Applied Alone and in Combination with Mineral and Organic Fertilisers on the Yield of White Cabbage and Soil Properties

Manfred JAKOP[1*], Nataša BELŠAK[2], Erik RIHTER[1], Tjaša CENČIČ PREDIKAKA[3], Dušan KLINAR[2], Denis STAJNKO[1] , Silva GROBELNIK MLAKAR[1]
[1]University of Maribor, Faculty of Agriculture and Life Sciences, Pivola 10, 2311 Hoče, Slovenia
[2]ZRS Bistra, Scientific Research Centre Bistra Ptuj, Slovenski trg 6, 2250 Ptuj, Slovenia
[3]IKEMA d.o.o., Institute for Chemistry, Ecology, Measurements, and Analytics, Lovrenc na Dravskem polju 4, 2324 Lovrenc na Dravskem polju, Slovenia

ABSTRACT

The study aimed to investigate the effectiveness of biochar application on fertile soils in a temperate climate during the first year of application. The field trial was conducted on a nutrient-rich silt loam soil at two experimental sites in north-eastern Slovenia (Biš and Skorba). The effect of biochar applied alone or in combination with compost or mineral fertiliser on soil properties and yield of white cabbage was studied. In addition to the control (C), the soil received five treatments including biochar (B; 1.5 t/ha), compost (CO; 1.5 t/ha), biochar-mixed compost (BCO; 3.0 t/ha), standard mineral fertilisers (NPK; NPK 0.35 t/ha, potassium sulphate 0.25 t/ha and calcium ammonium nitrate 0.25 t/ha) and combined application of half the amount of NPK and BCO (NPK+BCO). The results showed that the applied treatments had no significant influence on the measured soil chemical parameters, except for the amount of total organic carbon, electrical conductivity and pH in Biš and total carbon in Skorba. All investigated parameters (cabbage head weight, head circumference, total and market yield) were higher at the experimental site Skorba. Statistically significant differences were found only at the experimental site Biš, where the treatment influenced all parameters ($p < 0.01$), except for the head circumference of the cabbage. The NPK and NPK+BCO treatments produced significantly higher total yields (66.7 t/ha and 65.8 t/ha, respectively) and marketable yields (53.2 t/ha and 51.8 t/ha, respectively) compared to the other treatments (41.3-52.6 t/ha and 30.5-42.4 t/ha, respectively). Although the differences between the other treatments were insignificant, a trend of decreasing cabbage yields towards CO > BCO > B was observed. Similar results were also obtained when analysing the average data of the two experimental sites.

Key words: biochar, soil amendments, fertilisers, soil chemical properties, cabbage yield

INTRODUCTION

According to projections (FAO, 2018), the increase in world population to 9.7 billion people in 2050 would require a 70% increase in food production. Technological advancements and the expansion of agricultural soils to meet increased global food demand will inevitably lead to continued growth in agricultural activities. Agricultural, forestry and land use activities are directly responsible for 18.4% of greenhouse gas emissions (Poore and Nemecek, 2018). One of the most important ways to reduce these emissions and improve soil carbon sequestration is to reduce the use of mineral fertilisers, combine or replace them with other types of nutrient supply, such as organic fertilisers (Holka et al., 2022; Kramberger and Podvršnik, 2021; Wang et al., 2020; Zhao et al., 2022). Although the application of mulch, compost and manure has positive effects on soil fertility, the organic matter is usually mineralised within months or years (Tiessen et al., 1994), and the carbon is released back into the atmosphere as CO2. On the other hand, agriculture is known to produce a considerable amount of different types of waste, such as by-products and co-products generated in crop and livestock production,

**Correspondence to:*
E-mail: manfred.jakop@um.si

non-food crops, urban green spaces, organic residues from food processing, and organic material in municipal solid waste (Rivelli and Libutti, 2022). These organic materials are still rich in residual substances that can be recycled and reused in agriculture under the circular economy concept (Patwa et al., 2021). One of the bio-based compounds derived from the transformation of waste is biochar. By definition, biochar is a carbonaceous, porous and alkaline product obtained by thermochemical conversion of biomass in total or partial exclusion of oxygen (pyrolysis) and used as a soil amendment (Johannes and Stephen, 2009). More recently, the definition has been expanded beyond soil use to include other materials (e.g. building and composite materials, animal feed, livestock bedding) that representing long-term C sinks (EBC, 2021).

Due to its high carbon content and condensed aromatic structure, biochar has a high degree of stability, such that the organic carbon in biochar resists biological and thermochemical degradation in the soil for hundreds to thousands of years. This property, along with the high porosity, low bulk density (less than 0.6 g/cm^3) and large surface area (100-800 m^2/g) are associated with the environmental and agronomic benefits of biochar application in soil (Downie et al., 2009). The potential of biochar to provide agricultural and environmental benefits has led to an exponential increase in the number of studies on the effects of biochar since researchers discussed the phenomenon of 'Terra Preta' — the dark and highly fertile anthropogenic soil in the Amazon — around the year 2000 (Glaser et al., 2001). In 2022 alone, for example, the authors found more than 8,700 articles on the term biochar in a search on ScienceDirect.

Studies report a wide range of effects of biochar on physical, biological and chemical soil properties and functions, as well as on plant growth. Recent meta-analyses and reviews by Agegnehu et al. (2017); Dai et al. (2020); Enaime and Lübken (2021); Joseph et al. (2021); Sanchez-Reinoso et al. (2020); Schmidt et al. (2021); Zhang et al. (2019) summarising decades of research show that biochar generally lowers soil acidity and increases buffering capacity, increases dissolved and total organic C, cation exchange capacity, available nutrients, water retention, aggregate stability, and reduces bulk density. Moreover, biochar can increase microbial activity, accelerate nutrient cycling and reduce nitrogen leaching and volatilisation. From 2020, biochar may be used throughout the EU as a fertiliser/soil conditioner in organic farming. It is listed in Annex I of the current EU Commission Implementing Regulation (Regulation 2019/2164, 2019). The maximum value for polycyclic aromatic hydrocarbons (PAHs) should not exceed 4 mg/kg DM. This value shall be reviewed every two years, taking into account the risk of accumulation due to multiple applications.

The available systematic reviews and global meta-analyses report that the use of biochar in soils leads to higher yields overall, although this is not the case for every soil and not for every biochar (Dai et al., 2020; Enaime and Lübken, 2021; Schmidt et al., 2021). The physicochemical properties of biochar are highly dependent on the type of feedstock and pyrolysis conditions. Enaime and Lübken (2021) concluded that pyrolysis at higher temperatures (> 350°C) improves porosity, surface area, water holding capacity and increase the pH of the resulting biochar. The content of P, Ca, Mg, K, Fe, Si, S, Zn, Cu and Mn also increases with pyrolysis temperature. However, the bioavailability of these elements decreases as they are incorporated into aromatic structures within the biochar. Dai et al. (2020) point out that biochar from lignin-rich woody biomass is more resistant to biodegradation (stores more carbon over a longer period of time), while biochar from mineral-rich material (e.g., crop residues, animal manures) is less resistant but contains more nutrients. Although biochar derived from these materials can contain and release relevant amounts of plant nutrients, their concentration is usually too low to fully replace conventional fertilisers. Therefore, biochar is generally not considered a fertiliser and should be applied in combination with organic or mineral fertilisers to improve plant nutrition (Schmidt et al., 2021).

Soils behave differently after adding biochar. As showed in meta-analysis conducted by Dai et al. (2020), improvement in soil properties and plant productivity was observed only in degraded and nutrient-poor soils, while richer soils showed less of a tendency to benefit from the adding of biochar. Therefore, plant growth would be promoted much more in acidic soils with a low C/N ratio compared to neutral or alkaline soils with a high C/N ratio and cation exchange capacity, where biochar application had no significant effects. Furthermore, the adding of biochar to sand-textured soils can elicit a significantly higher positive plant productivity response than to silt-textured soils and had little effect on clay-textured soils. No effects or negative effects on plant growth have been reported for example by Kammann et al. (2015), Prommer et al. (2014), Xu et al. (2016) and Ye et al. (2020). Ye et al. (2020) reported that there were no effects on crop yields when nutrient-poor biochar was applied without fertiliser or on nutrient-rich soils. In addition, Kammann et al. (2015) found that 2% wood-based biochar reduced plant growth, especially under N-limited conditions, likely due to reduced plant availability of nitrate and other nutrients retained by the biochar. Similarly, Xu et al. (2016) reported that biochar promoted a phosphate precipitation/sorption reaction that reduced plant P availability, which consequently led to lower plant yield in saline soils. A reduction in soil N availability was also reported by Prommer et al. (2014), especially when large amounts of biochar produced at high temperatures were used (Kammann et al., 2015).

The effect of biochar is examined on many plant species in the field, in greenhouse or in pot experiments. Most studies have been conducted on crops such as maize and oilseeds, much less on vegetables, particularly cruciferous vegetables (Agegnehu et al., 2017; Enaime and Lübken, 2021; Sanchez-Reinoso et al., 2020). In Slovenia, white cabbage is one of the most commonly grown and important vegetables in commercial production. In 2021, cabbage was cultivated on 11.4% of the area used for commercial vegetable production (SURS, n. d.).

The aim of the study was to examine the effectiveness of the application of biochar on fertile soils in a temperate climate in the first year of application. For this purpose, we carried out a field trial on fertile soils at two sites and compared the effect of biochar applied alone and in combination with compost and mineral fertilisers on the yield of white cabbage. As agriculture's mission is to reduce greenhouse gas emissions, we wanted to investigate what changes in soil properties can be expected when biochar is used for more permanent carbon sequestration and reduced use of mineral fertilisers. Using biochar alone or mixed with compost or mineral fertilisers, we tested the following hypotheses: (1) chemical properties of nutrient-rich soils with a silt-loam texture do not change significantly after the application of biochar; (2) biochar application increase marketable cabbage yield in comparison to control treatment; (3) application of biochar along with organic or mineral fertilisers improves cabbage yield in comparison to sole application of compost or mineral fertilisers.

MATERIALS AND METHODS

Experimental design and management

The trial was established in 2021 at two experimental sites in NE Slovenia: in Biš (46°53'N, 15°89'E, 226 m a.s.l.) and in Skorba (46°42'N, 15°85'E, 229 m a.s.l.), in a field of two white cabbage producers. According to the (FAO, 2006) classification system, the soil at Biš is calcaric fluvisol and at Skorba eutric gleysol, both with a silt-loam texture (25% sand, 72% silt, 3% clay and 39% sand, 59% silt, 2% clay, respectively).

As Biš and Skorba are only 10 km apart, weather data were recorded at the nearest meteorological station Letališče Edvarda Rusjana, Maribor, which is representative for both experimental sites. The mean annual precipitation in the study area for the reference period 1981-2010 is 893 mm, and the mean annual air temperature is 10.5 °C (ARSO, 2021). The area experienced a pronounced precipitation deficit in June, July, and September with only 3%, 72% and 57% of the 30-year mean, respectively (Figure 1).

The study was carried out in two parts. The first part consisted of mixing biochar with compost (both commercially available), while the second part consisted of a field trial testing the fertilisation treatments.

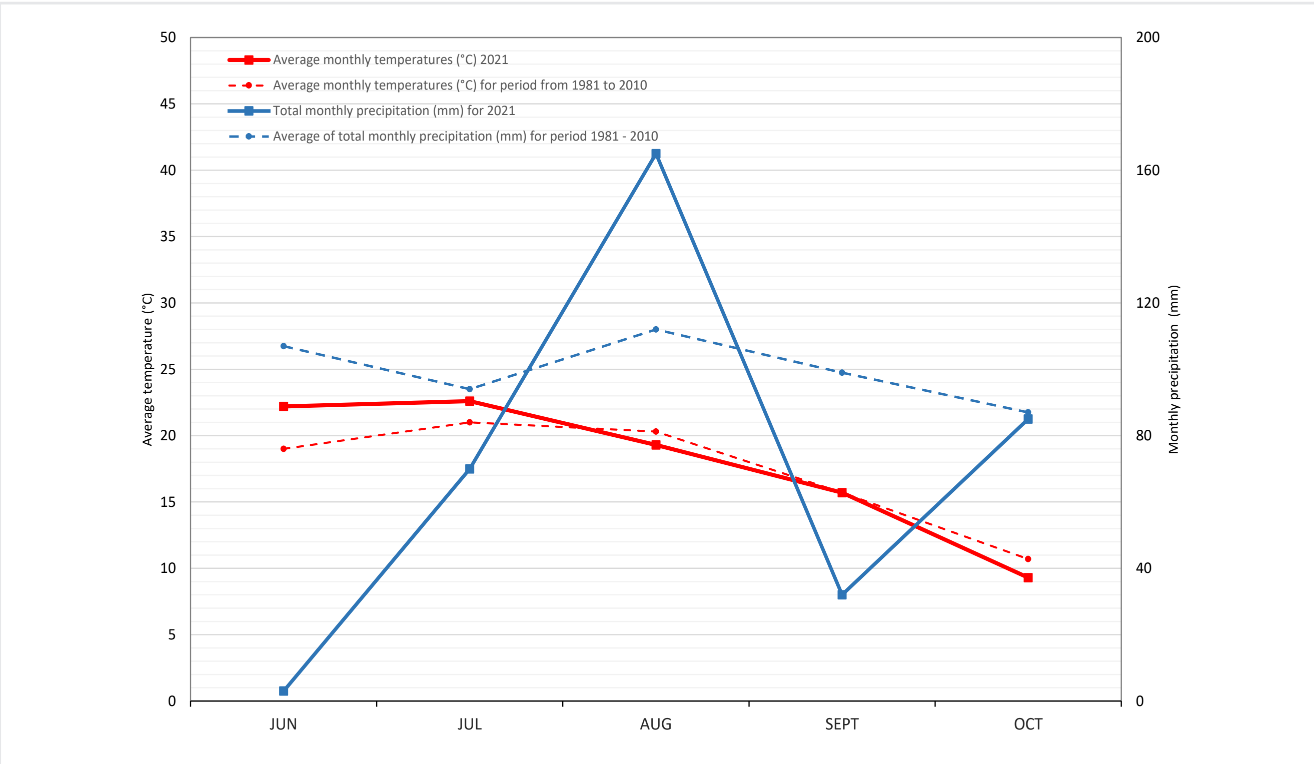


Figure 1: Average temperature and precipitation in cabbage growing cycle and the long-term average for Edvard Rusjan Airport, Maribor

The biochar used in this study was obtained from the company Sonnenerde, Austria. The biochar was made from grain husks, sunflower pods and by-products in fruit processing. As stated by the manufacturer, the biochar was produced at a pyrolysis temperature of 600 °C for 30 minutes in a Pyreg reactor. All pyrolysis vapours produced are burnt at 1,000 °C, and the waste heat is recirculated to heat the materials entering the pyrolysis unit. The biochar produced has been certified by the European Biochar Certificate as being of the highest quality (Bloomling, n. d.). As declared by the manufacturer, biochar has a bulk density of 90-150 kg/m3, contains 56 g/kg P, 50 g/kg K, 49 g/kg Ca and 31 g/kg Mg. The Corg content is 63.2%, the total N content is 0.99% (C/N ratio 63.8), pH 9.6, and the specific surface area 297 m^2/g.

Mixing of biochar with compost was carried out at the beginning of April 2021 (three months before use in the experiment) at the Vogrinec farm in Skorba. Biochar and commercial compost — a mixture of composted horse and cow manure (purchased from a company Biobrazda) — were mixed in the ratio 50:50 (w:w). Biochar and composted manure were mixed well manually with a hoe, so that both components were evenly distributed in the pile. The pile of material (2 m × 2 m × 0.5 m) was well watered and mixed again. The mixed and soaked pile was covered with a weed fleece that allows water and air to pass through until used.

The experiment consisted of six treatments: control (C), biochar applied alone (B), compost applied alone (CO), biochar mixed compost (BCO), mineral fertiliser (NPK) and mineral fertiliser + biochar mixed compost (NPK+BCO). Treatments B and CO were included in the experiment to investigate which of the components of the biochar mixed compost (a biochar or a compost) had a greater influence on soil properties and cabbage yield in the first year of application. Table 1 shows the type and amount of fertiliser used for each treatment.

The white cabbage variety used for the trial was 'Passat F1' (Bejo Zaden, Netherlands), a versatile late season variety with large, dense heads and early vigour. The variety is suitable for fresh consumption, sauerkraut production and storage.

The land, which was used in the previous season for cropping maize, was ploughed in autumn 2020 and in March 2021 the winter furrow was levelled with a harrow. Until the transplanting of the seedlings, blind cultivation was carried out with a pre-seeder in two passes, the last pass being one day before the transplanting of the seedlings. The biochar, organic and all mineral fertilisers except CAN were applied to the soil simultaneously at the time of transplanting (1 June). Materials were evenly distributed at each individual experimental plot and incorporated into the soil manually, approximately to a depth of 10 cm. Four-week-old cabbage seedlings (BBCH 14-15) were transplanted after biochar or fertiliser application at a planting density of 3,300 plants/ha. After cabbage seedlings were transplanted, for 43 days (DAT), CAN was applied as top dressing manually to the plants in the NPK and NPK+BCO treatments.

The cabbage plants were attacked by the striped flea beetle (Phyllotreta striolata Fabricius) early in the season; therefore, Karate Zeon 5 CS (lambda-cyhalothrin) was applied twice in June at a dose of 0.15 l/ha. Protection against white cabbage butterflies (Pieris brassicae L.) was carried out at the end of August with Bulldock EC 25 (beta-cyfluthrin) at a dose of 0.3 l/ha. Due to the severe drought in June, sprinkle irrigation was carried out twice in Biš and three times in

Table 1: The investigated treatments

Treatments	Description	Rate (t/ha)
Control (C)	No biochar, no fertiliser	
Biochar (B)	Commercially available biochar	1.5
Compost (CO)	Commercially available compost	1.5
Biochar mixed compost (BCO)	Biochar and compost (50:50 w:w) mixed three months before use	3.0
Mineral fertilisation (NPK) – conventional nutritional strategy	At the time of transplanting: NPK (15:15:15)	0.35
	potassium sulphate (50%)	0.25
	Top dressing at 43 DAT*: nitrogen application CAN (27%)	0.25
Combined application of mineral fertilisers and biochar mixed compost (NPK+BCO)	At the time of transplanting: NPK (15:15:15)	0.175
	potassium sulphate (50%)	0.125
	biochar mixed compost	1.5
	Top dressing at 43 DAT*: nitrogen application CAN (27%)	0.125

DAT — Days after transplanting; CAN — Calcium-ammonium nitrate

Skorba. Hoeing as a weed control measure was carried out three times in Biš and twice per growing season in Skorba. Harvesting and evaluation of the white cabbage took place on 18 October, when the variety appeared to reach horticultural maturity according to the usual visual criteria.

The experiment was conducted in a randomised block design with three replications. Each experimental plot size was 9 m^2 (3 m × 3 m) and consisted of 5 rows (60 cm between and 50 cm within rows). At harvest, all cabbage heads were collected from three central rows of each plot to eliminate the edge effect. All heads at both experimental sites were considered marketable, i.e., there were no signs of damage due to physiological disorders, diseases, or insect infestation. The cabbage heads were weighed with and without leaves (total yield and marketable yield, respectively) and the head equatorial circumference was measured.

Soil, biochar and biochar mixed compost sampling and analyses

Before the trial started, two replicated samples of soil, biochar and biochar mixed compost were analysed for a set of physicochemical properties. Soil properties (0-20 cm depth) were analysed before applying the experimental treatments in early May and after harvesting the cabbage in October. Soil samples were collected in accordance with standard ISO 18400-100:2017. In May, parameters were determined from composite samples taken from the entire experimental area at each site, and in October, from individual experimental plots. The analyses of the biochar and biochar mixed compost were carried out one week before its use in the trial. Sampling was carried out according to SIST EN 12579:2013. The sampling points were randomly selected, and their number was calculated according to point 6.4.1 of the above standard.

All analyses were carried in IKEMA d.o.o laboratory (Institute for chemistry, ecology, measurements, and analytics) with EN ISO/IEC 17025 accreditation (accreditation certificate LP-048). Air dried (40 °C) and sieved (2 mm aperture size) soil samples were used for the measurement of electrical conductivity (EC), P_2O_5 and K_2O contents, and pH. For determination of additional chemical properties, soil samples were grinded in accordance with SIST EN 16179:2013 and used for the determination of total organic carbon (TOC), total carbon (TC), total nitrogen (TN), and polycyclic aromatic hydrocarbons (PAHs). Biochar and samples of biochar mixed compost were prepared according to SIST EN 15002:2015. Analysis of biochar and biochar mixed compost samples included: TOC, EC, TN, TC, certain macro- and micronutrients and trace metals, pH, and PAHs contents.

For determination of chemical properties of individual samples, the following methods were used. Electrical conductivity (EC) was measured according to SIST-TS CEN/TS 15477:2007. For pH value determination, a 60 ml of air-dried sample was placed in an extraction vessel and extracted with five times the volume of sample (300 ml) in a 0.01 mol/l calcium chloride solution. Solution was shaken for 1h and pH was directly measured with a pH meter (Mettler Toledo). TC and TOC were determined according to EN 15936:2012, method A and method B, respectively. TN was determined according to the Dumas method (SIST EN 16168:2013). Plant nutrients and trace metals were determined after microwave-assisted digestion (with hydrofluoric, nitric, and hydrochloric acid mixture) in accordance with SIST-TS CEN/TS 15411:2007. After digestion, metal determination was performed with inductively coupled plasma — optical emission spectrometry (ICP-OES, Spectro) in accordance with SIST EN ISO 11885:2009. The P_2O_5 and K_2O contents in soil samples were determined with ICP-OES after extraction with ammonium lactate solution. Analysis on PAHs content was performed in accordance with SIST EN 15527:2009 using gas chromatography mass spectrometry (GC/MS). Extraction was performed in Soxhlet extraction system with petroleum ether in boiling range at 40-60 °C. After extraction, samples were concentrated to a known volume and measured on Agilent 6890 gas chromatograph equipped with an Agilent 5973 mass selective (MS) detector. Phenanthrene d-10 was used as an extraction standard and 1-metil naphthalene was used as an internal standard.

Properties and chemical composition of soil samples are presented in Table 2, composition of biochar and biochar mixed compost are shown in Table 3. The content of the sum of the set of 16 PAHs, proposed by the Environmental Protection Agency for the prevention of health threats, in biochar and in biochar mixed compost (Table 3) did not exceed the thresholds of 12 mg/kg. The sum of 16 PAHs in soil was below 2 mg/kg DM (data not presented).

Table 2: Properties of soil at Biš and Skorba experimental site

	Biš experimental site	Skorba experimental site
TOC (%)	1.70 ± 0.01	2.44 ± 0.01
EC (µS/cm)	103.75 ± 1.35	123.65 ± 3.65
C/N	9/1	8/1
TN (mg/kg DM)	0.19 ± 0.00	0.30 ± 0.00
TC (mg/kg DM)	1.91 ± 0.17	4.27 ± 0.19
P_2O_5 (mg/100 g)	33.6 ± 0.71	27.1 ± 1.32
K_2O (mg/100 g)	25.9 ± 3.78	7.7 ± 1.40
pH (in CaCl2)	6.96 ± 0.02	7.98 ± 0.02

TOC — total organic carbon; EC — electrical conductivity; TN — total nitrogen; TC — total carbon

Table 3: Properties of biochar and biochar mixed compost

Properties	Biochar	Biochar mixed compost
Dry matter (%)	97.56	31.62
EC (μS/cm)	382	318
TN (%)	0.998	1.195
TC (%)	59.08	45.05
pH (CaCl2)	10.87	9.99
Arsenic (mg/kg DM)	< 8	< 8
Copper (mg/kg DM)	< 15	24
Barium (mg/kg DM)	33.53	107
Zinc (mg/kg DM)	35.27	100
Phosphorus (mg/kg DM)	4,375	5,111
Cadmium (mg/kg DM)	< 3	< 3
Potassium (mg/kg DM)	1,1470	3,463
Cobalt (mg/kg DM)	< 7	< 7
Chromium (mg/kg DM)	< 7	14
Magnesium (mg/kg DM)	2,238	7,153
Molybdenum (mg/kg DM)	< 8	< 8
Nickel (mg/kg DM)	< 5	12
Selenium (mg/kg DM)	<15	< 15
Lead (mg/kg DM)	< 5	< 5
Vanadium (mg/kg DM)	< 15	< 15
Iron (mg/kg DM)	1,314	5,203
Mercury (mg/kg DM)	< 3	< 3
PAH ∑ 16 (mg/kg DM)	< 2	2.76

EC — electrical conductivity; TN — total nitrogen; TC — total carbon; PAH ∑ 16 — the sum of the set of 16 polycyclic aromatic hydrocarbons proposed by the Environmental Protection Agency

Statistical methods

Analysis of variance (ANOVA) for the completely randomised block design performed on the data related to soil properties at the end of the cabbage growing cycle and fertiliser treatment by cabbage yield was determined separately for each experimental site. A two-way ANOVA was performed for the effects of experimental site and fertiliser treatment and their interactions on white cabbage yield. All data were analysed with the programme Statgraphics Centurion (Manugistics Inc., Rockville, MD, USA). Differences between treatments were estimated using Duncan's Multiple Range Test ($\alpha = 0.05$). Results are presented as means of replicates with a standard error of the mean (± SEM).

RESULTS AND DISCUSSION

Changes in the chemical characteristics of soil

The results of the soil chemical analysis after harvest, in October 2021, show that there was a statistical difference for TOC, EC and pH at Biš and only for TC at the experimental site Skorba (Table 4). The TOC value at Biš and the value of TC at Skorba were lower in the treatments where biochar and compost were added. The phenomena can be explained by the biochar mineralisation dynamics. Based on observations of biochar-derived CO_2 with stable (^{13}C) and radioactive (^{14}C) carbon isotopes, Wang et al. (2016) meta-analysed degradation of biochar in soil. They found that the amount of biochar decomposition increased logarithmically with the duration of the experiment and the rate of decomposition decreased with time. They calculated the mean value of biochar decomposition rate for studies lasting < 0.5 year being 0.023% per day, i.e., more than four times faster than that from studies lasting longer than 1 year (0.005% per day). Despite the major content of aromatic C, the results of short-term studies mainly represent the degradation of uncondensed or less condensed fraction of biochar. Results from several studies indicate that this initially intense decomposition disappeared after 2 years and was maintained at very low levels for longer periods. In addition, crop-derived biochar degrades faster (0.025% per day) than other feedstocks examined in studies included in the mentioned meta-analysis. For example, wood-derived biochar had the slowest decomposition rate (0.004% per day) due to its high C content (66.4% vs. 59.8% for crops). The relatively low clay content in the soil at both experimental sites (3% in Biš and 2% in Skorba) may also have contributed to a faster biochar decomposition rate. As reported in the meta-analysis (Wang et al., 2016), slower biochar decomposition was common in soils with the highest clay content (0.003% per day, clay content 40-70%), while no significant difference was found in soils with a lower clay content.

Although purchased compost was not analysed, the lower TOC and TC values in soil from treatment where compost was added may reflect mineralisation of organic matter by microbial activity. As reported by García-Gómez et al. (2003), samples of the composting mixture, when poorly transformed through the biostabilisation process, showed high CO_2-C releases in soil due to a microbial attack on easily degradable organic fractions still present in the mixture. The highest electrical conductivity measured in the NPK+BCO treatment is likely due to the highly soluble nutrients in the mineral fertilisers and the continuous mineralisation of biochar mixed compost. Hence the release of cationic and anionic nutrients that contribute to the electrical conductivity in the soil. Although a non-significant difference in pH value at the end of the trial was expected in calcerous soil at both experimental sites (Dai et al., 2020; Jeffery et al., 2017), the parameter was influenced by fertilisation treatment at Biš. Compared to the control, the soil pH value was unexpectedly lower in all treatments, except in the NPK treatment.

Effects of different treatments on yield

Because there was no significant difference in the interaction between studied factors (Table 5) for all measured variables, analysis of the results is focused on the differences within the main effects variables, which included experimental site (ES) and fertilisation treatment (F).

All investigated parameters were higher at the experimental site Skorba. Statistically significant differences ($p < 0.001$) were found regarding total yield and marketable yield, average weight, and head circumference of the cabbage (Table 5). Compared to the experimental site Biš, the total yield and marketable yield of cabbage in Skorba were about 30% and 20% higher, respectively. As the trial was conducted under the same conditions at both experimental sites, we can assume that the more suitable physicochemical properties of the soil in Skorba (higher values of TOC, EC, TN, phosphorus, and pH) led to better yield formation of white cabbage. However, regardless of the differences, the good fertility status of the soils at both locations (Leskošek and Mihelič, 1998) is also reflected in the marketable yields achieved (30.5-53.2 t/ha). These are comparable to the average yields of Slovenian commercial cabbage producers, which averaged 40.6 t/ha in 2019-2021 (SURS, n. d.).

Statistically significant differences between fertiliser treatments were only found at the experimental site Biš, where treatments influenced all parameters ($p < 0.01$), except the cabbage head circumference (Table 5). The NPK and NPK+BCO treatments provided significantly higher total yield (66.7 t/ha and 65.8 t/ha, respectively) and marketable yield (53.2 t/ha and 51.8 t/ha, respectively) compared to the other treatments. Although the differences between the other treatments were not significant, a decreasing trend in cabbage yields was observed in the direction of CO > BCO > B.

Table 4: Soil analysis at the experimental site Biš and Skorba as affected by fertilisation treatment

Parameters/Treatments	C	B	CO	BCO	NPK	NPK+BCO
	Biš experimental site					
TOC (%)*	1.40 ± 0.05ab	1.29 ± 0.02bc	1.25 ± 0.03c	1.29 ± 0.04bc	1.33 ± 0.00ab	1.46 ± 0.03a
EC (µS/cm)*	39.65 ± 2.25bc	34.35 ± 0.55c	37.40 ± 3.00cd	39.55 ± 0.35bcd	43.95 ± 0.35ab	45.75 ± 3.35a
C/N^{ns}	11/1	10/1	10/1	10/1	11/1	11/1
TN (mg/kg DM)^{ns}	0.14 ± 0.01	0.13 ± 0.01	0.12 ± 0.00	0.13 ± 0.01	0.12 ± 0.01	0.14 ± 0.00
TC (mg/kg DM)^{ns}	1.55 ± 0.42	1.51 ± 0.00	1.45 ± 0.02	1.55 ± 0.00	1.50 ± 0.06	1.66 ± 0.31
P_2O_5 (mg/100 g)^{ns}	38.7 ± 4.63	26.4 ± 6.74	30.1 ± 3.60	40.9 ± 3.84	32.1 ± 6.72	42.4 ± 1.95
K_2O (mg/100 g)^{ns}	35.9 ± 0.85	26.6 ± 4.55	34.2 ± 4.40	36.5 ± 6.13	29.5 ± 1.20	37.7 ± 1.16
pH (in $CaCl_2$)***	7.44 ± 0.02a	6.93 ± 0.04d	7.07 ± 0.04c	7.27 ± 0.05b	7.57 ± 0.04a	7.12 ± 0.03c
	Skorba experimental site					
TOC (%)*	2.14 ± 0.03	2.22 ± 0.02	2.17 ± 0.04	2.25 ± 0.03	2.21 ± 0.01	2.20 ± 0.07
EC (µS/cm)*	56.75 ± 3.45	56.65 ± 3.75	63.8 ± 4.50	56.75 ± 3.65	63.95 ± 0.75	71.45 ± 4.75
C/N^{ns}	9/1	10/1	10/1	10/1	9/1	9/1
TN (mg/kg DM)^{ns}	0.23 ± 0.00	0.23 ± 0.00	0.22 ± 0.00	0.23 ± 0.01	0.24 ± 0.01	0.24 ± 0.00
TC (mg/kg DM)^{ns}	4.10 ± 0.03ab	4.06 ± 0.01b	4.07 ± 0.00b	4.13 ± 0.01a	4.14 ± 0.00a	4.09 ± 0.01ab
P_2O_5 (mg/100 g)^{ns}	37.6 ± 4.99	36.00 ± 1.70	38.2 ± 1.03	36.3 ± 0.13	35.5 ± 0.85	35.7 ± 0.60
K_2O (mg/100 g)^{ns}	19.30 ± 3.48	13.5 ± 0.30	12.8 ± 0.89	15.00 ± 1.11	16.1 ± 2.79	13.0 ± 0.64
pH (in $CaCl_2$)	7.51 ± 0.02	7.43 ± 1.11	7.49 ± 0.06	7.56 ± 0.01	7.52 ± 0.01	7.55 ± 0.01

TOC — total organic carbon; EC — electrical conductivity; TN — total nitrogen; TC — total carbon; TOC — total organic carbon; EC — electrical conductivity; TN — total nitrogen; TC — total carbon; C — control; B — biochar; CO — compost; BCO — biochar-mixed compost; NPK — standard mineral fertilisers; NPK+BCO — combined application of half the amount of NPK and BCO; *, *** significant at the 0.05 and 0.001 probability levels, respectively; ns — nonsignificant; a–c mean values (± SEM) followed by different letters are significantly different (Duncan, α = 0.05)

Table 5: The effect of treatments on the total and marketable yield of white cabbage, and on head weight and circumference

Treatments	Total yield (t/ha)	Marketable yield (t/ha)	Head weight (kg)	Head circumference (cm)
	Biš experimental site			
C	41.3 ± 3.86b	30.5 ± 4.82d	1.79 ± 0.15b	55.1 ± 3.18
CO	52.8 ± 1.99ab	42.4 ± 1.36bc	1.74 ± 0.27b	62.9 ± 1.40
B	40.2 ± 1.06b	30.8 ± 2.37d	1.46 ± 0.07b	55.8 ± 3.00
BCO	48.0 ± 4.70b	37.5 ± 5.03cd	1.83 ± 0.22b	57.3 ± 3.87
NPK+BCO	65.8 ± 5.84a	51.8 ± 6.71ab	2.64 ± 0.08a	64.7 ± 5.77
NPK	66.7 ± 7.58a	53.2 ± 5.80a	2.52 ± 0.23a	64.9 ± 3.96
$T_{average}$	52.5 ± 3.03^{B}	41.0 ± 2.52^{B}	2.00 ± 0.12^{B}	60.1 ± 1.62^{B}
	Skorba experimental site			
C	62.0 ± 8.25	44.1 ± 7.28	2.55 ± 0.46	63.7 ± 6.59
CO	70.8 ± 4.02	50.1 ± 4.24	2.65 ± 0.17	66.9 ± 1.38
B	65.9 ± 5.90	49.2 ± 5.24	2.37 ± 0.18	65.9 ± 2.63
BCO	62.8 ± 7.94	45.8 ± 5.25	2.51 ± 0.20	69.9 ± 1.79
NPK+BCO	65.9 ± 4.49	44.4 ± 6.61	2.79 ± 0.38	74.5 ± 1.16
NPK	73.9 ± 4.48	51.8 ± 1.91	2.82 ± 0.51	67.9 ± 1.18
$T_{average}$	66.9 ± 2.33^{A}	47.6 ± 1.98^{A}	2.62 ± 0.13^{A}	68.1 ± 1.35^{A}
F_{ES}	21.61***	6.53*	16.39***	21.62***
F_{T}	3.90*	3.26*	2.89*	3.07*
$F_{ES×T}$	1.51^{ns}	2.30^{ns}	0.74^{ns}	0.79^{ns}

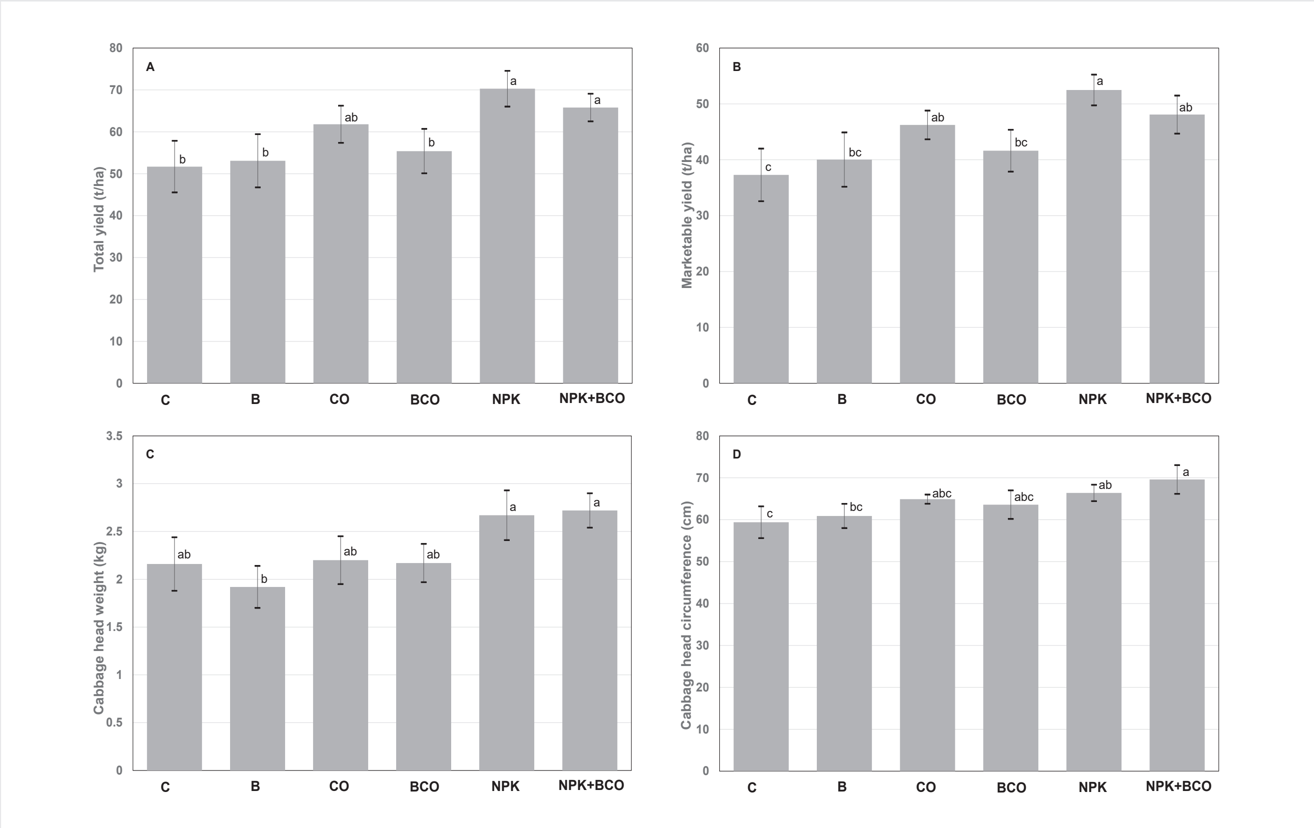
C — control; B — biochar; CO — compost; BCO — biochar-mixed compost; NPK — standard mineral fertilisers; NPK+BCO — combined application of half the amount of NPK and BCO; *, *** significant at the 0.05 and 0.001 probability levels, respectively; ns – nonsignificant; a—c and A—B mean values (± SEM) followed by different letters are significantly different (Duncan, α = 0.05) between treatments within experimental site and between experimental sites, respectively

On average, fertilisation had a significant effect on total ($p < 0.001$) and marketable yield of cabbage ($p < 0.05$) (Figure 2A and Figure 2B). The highest yields were achieved with mineral fertiliser (NPK), but comparable values were obtained in treatments where mineral fertiliser and biochar mixed compost were applied together, both in a quantity reduced by half (NPK+BCO), and in treatments where cabbage was fertilised with compost (CO). In the 2022 situation, when the average price of nutrients in mineral fertilisers has increased by more than 270% compared to the previous year in Slovenia (SURS, 2022), fertilisation with BCO also becomes economically comparable, especially if we also take into account the environmental aspect of reducing greenhouse gas emissions by using less mineral fertiliser.

On average, fertilisation had a significant effect on the weight and circumference of the individual cabbage head ($p < 0.05$). In the treatments where biochar was applied alone (B), smaller (circumference 60.9 cm) and lighter heads (1.92 kg) were harvested than in the treatments where biochar-mixed compost was combined with mineral fertiliser (NPK+BCO), and the heads had an average circumference of 66.4 cm and weighted 2.67 kg (Figure 2C and Figure 2D).

The results obtained did not show a positive response to the application of biochar on the yield of white cabbage. Considering the high price (2,300 €/t) and the limited financial resources within the project, biochar was applied in a quantity of 1.5 t/ha. This quantity is rather small compared to the quantities reported in global analyses (5–100 t/ha) (Agegnehu et al., 2017; Enaime and Lübken, 2021; Jeffery et al., 2017; Sanchez-Reinoso et al., 2020). This means that biochar itself, although it contained certain amounts of nutrients (Table 3) and was added to soil with a good fertility status (Table 2), did not cover all the nutrients needed for yield formation of the rather highly demanding white cabbage (MKGP, 2021).

On the other hand, Jeffery et al. (2017) in their meta-analysis compile 1,125 observations from 109 independent studies for which location data were available. This global-level analysis shows that biochar has on average no or even a negative impact on crop yields (–3%) in temperate



C — control; B — biochar; CO — compost; BCO — biochar-mixed compost; NPK — standard mineral fertilisers; NPK+BCO — combined application of half the amount of NPK and BCO; a-c mean values (± SEM) followed by different letters are significantly different (Duncan, α = 0.05)

Figure 2: Influence of fertilisation treatments on total (A) and marketable yield (B), cabbage head weight (C) and circumference (D)

regions at a median biochar application rate of 30 t/ha, but an average yield increase of 25% in the tropics at a median biochar application rate of 15 t/ha. These results clearly show that the impact of biochar on yield cannot be extrapolated from tropical to temperate regions. According to the authors, the reason for the differences in biochar application rates is unclear, but it is probably because the potential feedstock materials are more limited in the tropics. Studies we found in available literature that investigated the application of biochar on cabbage (Chinese cabbage and white cabbage) performance were mainly conducted in the tropics (Akolgo et al., 2020; Baiga and Rajashekhar Rao, 2017; Carter et al., 2013; Cox et al., 2021; Kang et al., 2021; Ofori et al., 2021; Schmidt et al., 2017; Sun et al., 2022), and only some in temperate climates (Chun et al., 2022; Grafmüller et al., 2022; McDonald et al., 2019).

The field trial conducted by McDonald et al. (2019) in Ontario (Canada) over three years did not involve the application of pure biochar, but investigated the effect of a biochar-compost mixture (0.6 kg/m^2 and 2.4 kg/m^2) with and without mineral NPK fertiliser, and compared it with compost. Similar to our results, the authors found that white cabbage grown in plots treated with a higher amount of biochar compost mixture + NPK or NPK fertiliser alone had heavier heads, marketable and total yields compared to other treatments, including compost alone.

The economically justified use of biochar in fertile temperate soils was demonstrated by Grafmüller et al. (2022). They pointed out that among all previous studies investigating different biochar and biochar-based formulations no study compared different ways of incorporating biochar into the soil either in the pot or in the field. In all published studies, biochar or biochar-based fertilisers were evenly distributed in the pot or incorporated into the topsoil. The authors argued that this results in low biochar concentration in close proximity to the plant root system, especially when economically justifiable amounts of biochar (less than 2 t/ha) are added to the soil. They assumed that the application of biochar-based fertilisers in the root zone would be beneficial, as this would allow targeted and effective fertilisation. The authors conducted a pot experiment with white cabbage grown in a nutrient-rich, silt loam soil with neutral pH (7.1) from the temperate zone. They tested two nitrogen fertilisers (ammonium nitrate and urea), two types of biochar application in the root zone (soil-mix root-zone amendment and hotspot application under transplanted seedlings) and two nitrogen fertilisation methods (N fertilisation at the soil-surface and application of biochar enriched with mineral fertiliser). Biochar was applied at a low rate of 1.3 t/ha. In the treatments where N-enriched biochar was applied, they obtained on average 12% higher yield of dry cabbage heads than in the fertilised control without biochar. Compared to the control, they observed the highest yield increase in treatments where pure biochar was amended as a hotspot and additional soil surface nitrogen was applied in the form of ammonium nitrate (24% higher dry cabbage yield). A 14% increase in yield was observed with urea-enriched biochar applied as a hotspot. In addition, the type of amendments in the root-zone amendments and the method of nitrogen fertilisation altered the root architecture. Although the application of biochar or N-enriched biochar in the root zone is promising and economically viable in Germany, where the authors assumed a commercial biochar price of up to 1,000 €/t, the technologies to implement such hotspot or soil-mix amendments still need to be developed. However, further studies, including other species and varieties, as well as trials under field conditions are needed to validate this new method.

CONCLUSIONS

This study investigated the influence of biochar after the first year of application on white cabbage yield and soil chemical properties. The application of biochar in a soil with a silt-loam texture, which is well supplied with nutrients, has a C/N ratio of less than 15:1 and an almost neutral pH, did not change the chemical properties of the soil, except for TOC, EC and pH at the experimental site Biš. Our second hypothesis was that the application of biochar alone would increase cabbage yield compared to the unfertilised treatment (control). This hypothesis is not supported by the data we obtained. At the experimental site in Skorba there were no differences in yield between all treatments, but in Biš cabbage grown on soil amended with biochar had the lowest marketable yield, which was statistically equal to that of the unfertilised control. We also cannot confirm the third hypothesis that applying biochar together with organic or mineral fertilisers improves cabbage yields compared to applying sole compost or mineral fertilisers. Although the difference in yield between the application of sole compost and the application of compost mixed with biochar cannot be confirmed statistically, an increasing tendency in favour of compost can be seen. Similarly, the difference in cabbage yield was insignificant when comparing the sole mineral fertilisers application (NPK) with the combined application of mineral fertilisers with biochar mixed compost (NPK+BCO), although the amounts of the components in NPK+BCO are halved. The results of a one-year study on biochar, which still needs to be researched under cultivation conditions in Slovenia, indicate that the use of biochar on fertile soils is only justified in combination with organic and mineral fertilisers. Further studies need to be conducted to draw more solid conclusions. These include multi-year studies that examine not only the changes in chemical soil properties and yield, but also the microbiological activity of the soil and the economic aspect of the use of biochar.

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Učinek samostojne aplikacije biooglja in v kombinaciji z mineralnimi in organskimi gnojili na pridelek belega zelja ter lastnosti tal

POVZETEK

Namen študije je bil raziskati učinkovitost uporabe biooglja na rodovitnih tleh v zmernem podnebju v prvem letu uporabe. Poljski poskus smo izvedli na s hranili bogati meljasto ilovnati zemlji na dveh poskusnih mestih (Biš in Skorba), kjer smo preučevali vpliv biooglja, uporabljenega samostojno ali v kombinaciji s kompostom ali mineralnimi gnojili, na lastnosti tal in pridelek belega zelja. Poleg kontrole (C) smo v raziskavo vključili obravnavanja z biiogljem (B; 1,5 t/ha), kompostom (CO; 1,5 t/ha), mešanico komposta in biooglja (BCO; 3,0 t/ha), lahko topnimi mineralnimi gnojili (NPK; NPK 0,35 t/ha, kalijev sulfat 0,25 t/ha in kalcijev amonijev nitrat 0,25 t/ha) in kombinirano uporabo polovične količine NPK in BCO (NPK+BCO). Rezultati so pokazali, da vključena obravnavanja niso imela bistvenega vpliva na izmerjene kemijske lastnosti tal, razen na količino skupnega organskega ogljika, električno prevodnost in pH v Bišu ter skupni ogljik v Skorbi. Vsi raziskani parametri (masa zeljne glave, obseg glave, skupni in tržni pridelek) so bili višji na poskusni lokaciji v Skorbi. Statistično značilne razlike so bile ugotovljene le na lokaciji v Bišu, kjer je tretiranje vplivalo na vse parametre ($p < 0{,}01$), razen na obseg glave zelja. Gnojenje z NPK in NPK+BCO je vplivalo značilno na višji skupni pridelek (66,7 t/ha oziroma 65,8 t/ha) in tržni pridelek (53,2 t/ha oziroma 51,8 t/ha) v primerjavi z ostalimi obravnavanji (41,3–52,6 t/ha oziroma 30,5–42,4 t/ha). Čeprav razlike med ostalimi obravnavanji niso bile značilne, je bil opažen trend padanja pridelka zelja v smeri CO > BCO > B. Podobne rezultate smo dobili tudi pri analizi povprečnih podatkov obeh poskusnih lokacij.

Ključne besede: biooglje, izboljšanje tal, kemijske lastnost tal, pridelek zelja