



## OPEN Biochar from *Chlorella* sp. algae as a plant growth activator

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Modern agriculture has been looking for effective and ecological sources supporting plant growth, but there are no natural stimulants on the market. The aim of the study was to assess the impact of biochar obtained from the biomass of microalgae *Chlorella* sp. on the process of germination of radish seeds. The analysis pertained to power and output power, length and strength of seedlings and chlorophyll content. Biochar obtained as a result of the pyrolysis process (400°C) was characterised by a porous structure, the occurrence of functional groups in the bands from 2000–1500 cm<sup>-1</sup> to 1500–650 cm<sup>-1</sup>. In the available material, there is a D range in the range of 1351–1361 cm<sup>-1</sup>, which corresponds to unordered carbon structures, and a G range in the range of 1579–1588 cm<sup>-1</sup>, acting from counteracting vibrations. obtained biochar used as a stimulator of radish seed germination. The obtained biochar was tested as a stimulator of radish seed germination. Seed germination measurements consisted of determining the average germination time (1.12 for the sample fed with biochar and 1.87 for the control sample), germination energy of 93% and 88%, respectively, a germination capacity of 97% and 92%, and chlorophyll a and b content. The results indicate that biochar from *Chlorella* sp. biomass can act as a seed growth stimulant, which is not only an innovative application, but also a potential solution in the context of sustainable agriculture and environmental protection.

**Keywords** Biomass, Algae, Biochar, Plants, Germination, Sustainable agriculture

In order to protect the environment and reduce greenhouse gas emissions, the European Green Deal policy was developed, which aims to create a modern, resource-efficient bioeconomy, which will counteract biodiversity loss, reduce pollution levels and use resources more efficiently by fostering the transition to a clean, circular economy<sup>1</sup>.

One consequence of the progressive bioeconomy is a growing utilization of biomass in production. Biomass is defined as all forms of biodegradable organic matter and waste<sup>1–3</sup>. It is derived from a number of sources, including agriculture, forestry and related industries such as fishing and aquaculture<sup>3,4</sup>. Biomass can be put through biochemical, chemical and thermochemical processes resulting in new green products<sup>5</sup>. Among the thermochemical methods for the conversion of microalgae biomass *Chlorella* sp., Pyrolysis is the most advantageous due to its execution requirements and the lack of the need to apply pressure [pressure has to be applied in the case of other methods, e.g. hydrothermal liquefaction (HTL)]. Pyrolysis allows access to safe biochar with a high carbon content, divided into components and sorption components at a high separation yield. In the case of techniques such as torrefaction or HTL, biochar obtained by pyrolysis is characterized by excellent porosity and functional group content, which protects against the consumption of components in the soil. The pyrolysis process is carried out at a very high temperature of 350–900 °C, catalytic-free and anaerobic<sup>6,7</sup>. Concurrent chemical reactions occur in it, determining the molecular structure of the resulting products. The mass of the carbonized (biochar) produced through pyrolysis is uniform and contains large amounts of elemental carbon<sup>8</sup>. The most important parameters that characterize the properties of biochar are chemical composition, stability, porosity, specific surface area, bulk density, pH and ion-exchange capacity<sup>6–8</sup>. The physical and chemical properties of biochar are related to the type of biomass used to produce it, the conditions of production, and determine its suitability for a particular application<sup>6–8</sup>.

Algal biomass represents an excellent raw material for thermal conversion to biochar, with *Chlorella* sp. algae of the green algae division being particularly noteworthy<sup>9,10</sup>. Optimally selected conditions of algae culture, methods of its dehydration and pyrolysis form the basis for developing increasingly effective methods of its management in industries such as the energy, food, cosmetics, pharmaceutical and agricultural sectors<sup>11–13</sup>.

In recent years, there has been a notable advancement in the field of organic farming, which is driven by the objective of eliminating the use of chemical fertilizers and synthetic pesticides<sup>14</sup>. Biochar obtained from the biomass of microalgae *Chlorella* sp. can have a beneficial effect on soil fertility and plant growth through a number

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of interrelated physical, chemical and biological mechanisms<sup>14,15</sup> Unlike the biochar of plant origin, biochar from algae is characterized by a higher nitrogen and phosphorus content, which results from the rich protein composition of algal biomass. As a result, after introduction into the soil, it can be a source of easily accessible micro- and macronutrients (N, P, K, Mg, Fe), supporting plant growth already at the germination stage. In physical terms, biochar creates a porous structure with a large specific surface area, which allows for the storage of water and the adsorption of inorganic ions<sup>14–16</sup>. In soil conditions, this increases the ability to retain moisture and nutrients, especially in light soils and those poor in humus. From a chemical point of view, the presence of functional groups such as hydroxyl (–OH), carbonyl (C=O) and phenolic groups promotes ion complexation and buffering of pH changes. Biochar can act as a cation exchanger, reducing nutrient losses through leaching and simultaneously increasing their availability to the plant root system. Another important mechanism is the effect of biochar on soil microflora. Due to its structure, biochar creates a favorable microenvironment for the development of beneficial microorganisms (rhizosphere bacteria, mycorrhizal fungi), which in turn support the mineralization of organic compounds and the availability of phosphorus. Some studies indicate that biochar can also modulate soil enzymatic activity and affect the biosynthetic pathways of phytohormones such as auxins and cytokinins, which indirectly supports the development of the root system and the root elongation zone<sup>15–17</sup> Due to these properties, the use of algal biochar is beneficial to both farmers and the environment. Unlike biochar from lignocellulosic plants, biochar from algae does not contain lignin or cellulose, which results in different thermochemical properties and a porous structure more conducive to water and ion retention. Additionally, microalgae can be produced sustainably on small surfaces and using wastewater or waste, making their biochar a raw material with great environmental and economic potential<sup>15–17</sup>.

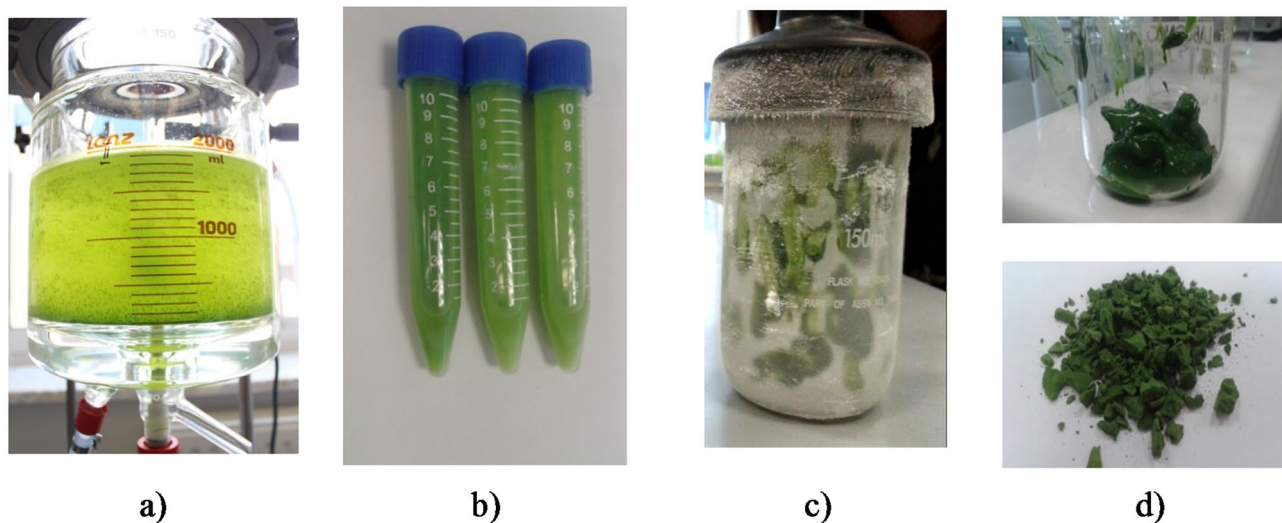
In the future, reducing the cost of biochar production and increasing the interest in sustainable agriculture could boost the importance of algal biochar worldwide. In addition, biochar is sustainable and environmentally friendly, making it an attractive tool for the agriculture of the future, particularly in the context of combating climate change and improving soil quality<sup>17–20</sup>.

The aim of the study was to investigate the effect of biochar, obtained from the biomass of microalgae *Chlorella sp.*, on the germination process of radish (*Raphanus sativus* L.) seeds by assessing the germination energy, seedling mass and length, and chlorophyll content. The novelty of the study is the use of biochar from microalgae as a direct activator of plant growth in laboratory conditions, which is an alternative to traditional organic fertilizers and has not been widely studied so far. The novelty of the work is that most studies focus on the use of biochar in soil or its sorption properties in the environmental context, while few studies describe its use as a direct factor stimulating seed germination in soil-independent systems. Additionally, the use of *Chlorella sp.*, as a source of biomass with high nitrogen and phosphorus content, allows obtaining biochar with favorable agrochemical properties.

## Methods

### Algae cultivation

*Chlorella sp.* genus algae were used for culture preparation. The algal strains were derived from an in-house culture, initiated on the basis of BA 103 cultures, from the CCBA of the Institute of Oceanography at the University of Gdańsk. The culture stages and research methodologies used were described in the authors' earlier publications (Fig. 1)<sup>21–23</sup>:



**Fig. 1.** The Stages of biomass production of *Chlorella sp.* microalgae (a) cultivation in reactors, (b) biomass separated in the substrate, (c) biomass prepared for the freeze-drying process, (d) dehydrated and freeze-dried biomass.

### Obtaining biochar from algae biomass

The *Chlorella sp.* algal biomass was subjected to pyrolysis at the next stage of the study. The process was conducted in an FCF-V12RM furnace with a PID MRT-4 controller manufactured by Czylok. The process parameters are: 3-stage cascade heating, temperature — 400 °C (Fig. 2), total process time — 105 min, sample residence time at maximum temperature — 15 min, seasoning time — 24 h, gas flow rate — 5.0 dm<sup>3</sup>/min, sample mass — 100 g ± 1 g.

The biochar produced was grounded in a Testchem's laboratory vibrating mill. The grain size of the biochar was checked by sieve analysis using sieves with a mesh size of 0.040 mm.

### Method for testing the properties of biomass and Biochar from *Chlorella sp.* algae

#### Scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS)

The microstructure of biomass and biochar from the *Chlorella sp.* algae was examined using a Hitachi SU-70 high-resolution scanning electron microscope (SEM) equipped with an NSS 312 energy-dispersive X-ray spectroscopic (EDS) microanalyzer manufactured by Thermo Scientific. The tested materials were analysed under the following conditions: magnification — 500x and 1.00x, acceleration voltage — 15 kV, emission current — 50 A, analysis time — 100 s, radiation angle — approx. 30°. EDS analysis was carried out by means of a model-free method, using up to 100% concentration of the identified elements. The final result of the measurements was reported with an accuracy of 0.1%.

#### FTIR spectroscopy

The chemical composition of biochar from the *Chlorella sp.* algae was evaluated using Jasco's FTIR 6200 spectrometer with a diamond crystal ATR attachment, applying the diffuse reflection method. The analysis was conducted under the following conditions: spectral range — 4000–650 cm<sup>-1</sup>, resolution — 4 cm<sup>-1</sup>, TGS detector, mean spectrum from 30 scans.

#### RAMAN spectroscopy

The structure of the *Chlorella sp.* algae biochar and its degree of ordering was analysed on the basis of the intensity ratio of the D/G bands determined using a Jasco NRS 5100 Raman spectrometer equipped with a 532.12 nm excitation laser and a CCD detector. The measurement parameters are: diffraction grating — 600 lines/mm, laser power — 4.8 mW, numerical aperture — d4000 μm, resolution — 1.37 cm<sup>-1</sup> (slit — 10 × 1000 μm), lens magnification — 50×, an exposure time — 60 s with an accumulation of 20. The test samples were placed on glass plates and at least three spectra were recorded for each of the 100–3700 cm<sup>-1</sup> samples. The spectra were processed using Spectra Manager Analysis software (cutting out interfering signals and smoothing the baseline by means of the Means-Movement method).

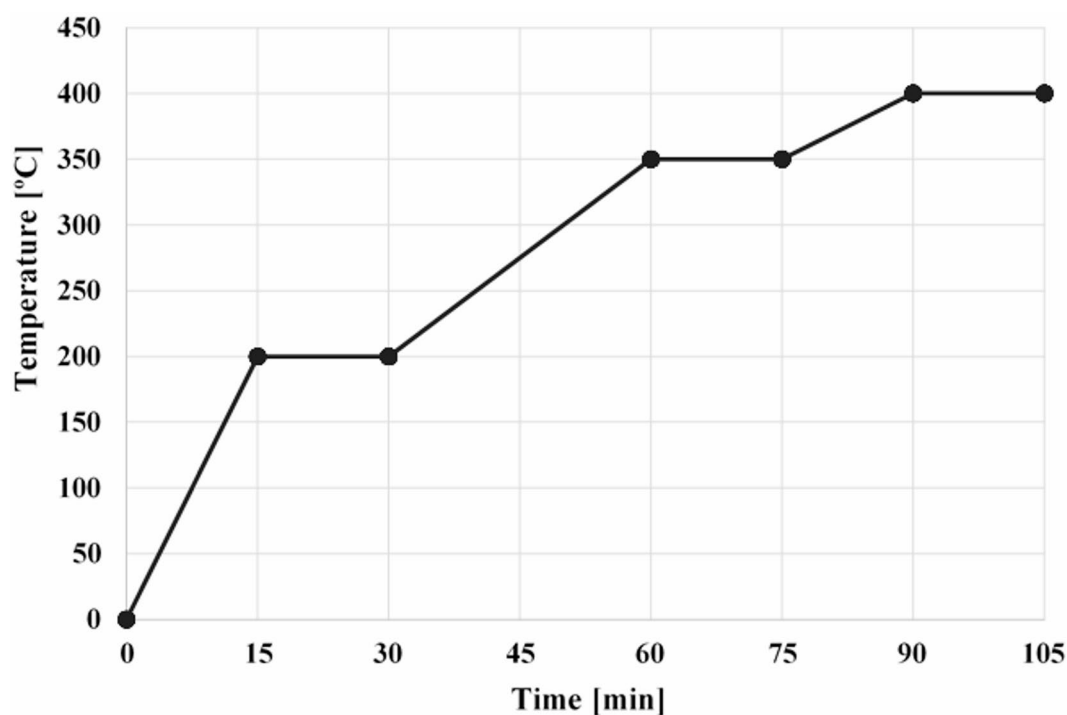


Fig. 2. Changes in the heating temperatures of the algal biomass sample during the pyrolysis process (400°C).

## The use of Biochar from *Chlorella sp.* algal biomass as an activator of radish seed germination

The experiment (6 test trials, 1 control trial) was conducted on petri dishes, and.  $10 \pm 0.1$  g of lignin moistened with  $30 \text{ cm}^3$  of distilled water was laid on each. On the test sample dishes,  $0.1 \text{ g} \pm 0.001$  g of the produced biochar from the *Chlorella sp.* algal biomass was put?. The control sample dish was left with no biochar added. In the next step, 25 radish seeds were spread evenly on each dish and watered with  $5 \text{ cm}^3$  of distilled water. The duration of the experiment was 14 days. The cultures were watered with distilled water,  $5 \text{ cm}^3$  for 4 days and  $10 \text{ cm}^3$  for subsequent 10 days. Radish seeds come from the Polan seed breeding and production plant in Krakow.

The results were the arithmetic mean of the samples. The radish seeds were selected for the experiment due to their quick germination, uniform size and seed weight. Selected seeds respond to changes in humidity, pH and nutrients, which allows to precisely determine which conditions favor germination, and they are also clearly visible, making it easier to measure the length of roots and shoots. The results made it possible to determine the indicators for assessing seed viability. Equations to determine seed viability rates (1) germination energy ( $E_k$ ), (2) germination capacity ( $Z_k$ ), (3) average germination time ( $C_k$ )<sup>24–26</sup>.

$$E_k = \frac{I_1 + I_2 + \dots + I_n}{L} \times 100 \quad (1)$$

$$Z_k = \frac{I_1 + I_2 + \dots + I_m}{L} \times 100 \quad (2)$$

$$C_k = \frac{I_1 d_1 + I_2 d_2 + \dots + I_m d_m}{L} \quad (3)$$

where  $I_1 \dots I_n$  — The number of seeds capable of germinating on consecutive trial days during the initial period (4 days);  $I_1 \dots I_m$  — The number of seeds capable of germinating on consecutive trial days over a 14-day period;  $L$  — The total number of seeds planted;  $d_1 \dots d_m$  — The consecutive days of the trial from its inception until its completion.

Equations to determine seed viability rates (1) germination energy ( $E_k$ ), (2) germination capacity ( $Z_k$ ), (3) average germination time ( $C_k$ ).

In the next step, chlorophyll was extracted from cultured radish plants. 0.5 g of the plants was weighed from each test sample. Each sample was homogenized using 25 ml of cooled acetone. The resulting suspensions were filtered through a MN 619 filter paper and poured into flasks, wrapped in a blackout film. The precipitates on the filter paper were washed with water until the chlorophyll was completely extracted. Using a Dr. 6000 spectrophotometer manufactured by Hach Lange, the absorbance of the resulting extracts was measured at 645 nm and 663 nm against an 80% aqueous acetone solution<sup>24–26</sup>.

$$c_a = 12,7 A_{663} - 2,7 A_{645} \left[ \text{mg} (\text{dm}^3)^{-1} \right] \quad (4)$$

$$c_b = 22,9 A_{645} - 4,7 A_{663} \left[ \text{mg} (\text{dm}^3)^{-1} \right] \quad (5)$$

where  $A$  — Absorbance at the corresponding wavelength (663 nm, 645 nm); Formulas for determining the chlorophyll content of cultured radish plants: (1) the determination of chlorophyll a, (2) the determination of chlorophyll b.

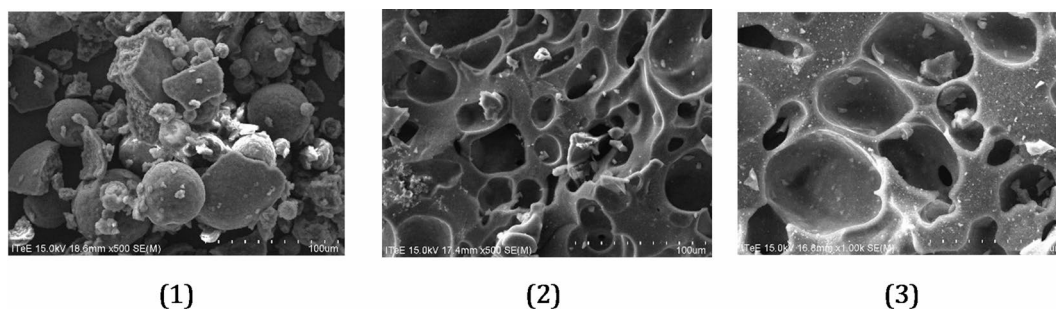
## Results

The cultured *Chlorella sp.* algal biomass was separated from the substrate. For this purpose, sedimentation, centrifugation, freezing and freeze-drying were carried out. The use of the freeze-drying process provided conditions for microbiological and biochemical stability, and protected the biomass from contaminants and microorganisms. The algal biomass thus prepared was subjected to thermal decomposition at  $400 \text{ }^\circ\text{C}$ .

In order to determine the exact structure of the biochar obtained from the *Chlorella sp.* algal biomass, topography images were generated using a scanning electron microscope (SEM). For comparison, photographs showing the structure of the biomass before the pyrolysis process were also taken (Fig. 3).

In the images showing the surface of the tested materials (biomass and biochar), a significant change in morphology can be observed. The SEM images of the biomass sample show surface features specific to dead organic matter. The surface *Chlorella sp.* algal biomass has a poorly developed structure, on which some residues of the applied culture medium are visible. The treatment of biomass with high temperature yields biochar, which differs in the morphological features observed in SEM images and has a more porous surface compared to the biomass. The observations of the structure of the obtained biochar confirm the presence of pores of varying sizes and shapes, in particular, macropores and mesopores. Micropores and mesopores in biochar have key functions in improving soil quality in agriculture. Micropores are responsible for adsorbing fine particles, including water and nutrients, while mesopores facilitate the transport of these substances and create space for microorganisms. These properties allow biochar to improve water retention, promote microbial growth and increase the sorption capacity of the soil.

EDS microanalysis made it possible to determine the chemical composition of the biochar obtained from the *Chlorella sp.* algal biomass. EDS analysis revealed that the analyzed biochar features building elements, i.e., carbon and nitrogen, as well as micro- and macronutrients, i.e. phosphorus, potassium, calcium, magnesium, and



**Fig. 3.** SEM images of the sample of: (1) algal biomass (2) biochar from algal biomass at magnification  $\times 500$  (3) biochar from algal biomass at magnification  $\times 1.00$ .

Component	Biomass [%]	Biochar [%]
C	38.59	51.64
N	10.65	14.37
O	46.58	21.31
P	1.13	4.08
K	0.70	2.27
Ca	0.49	0.56
Mg	0.30	1.43
At	0.93	3.53
S	0.57	0.74
Cl	0.06	0.07

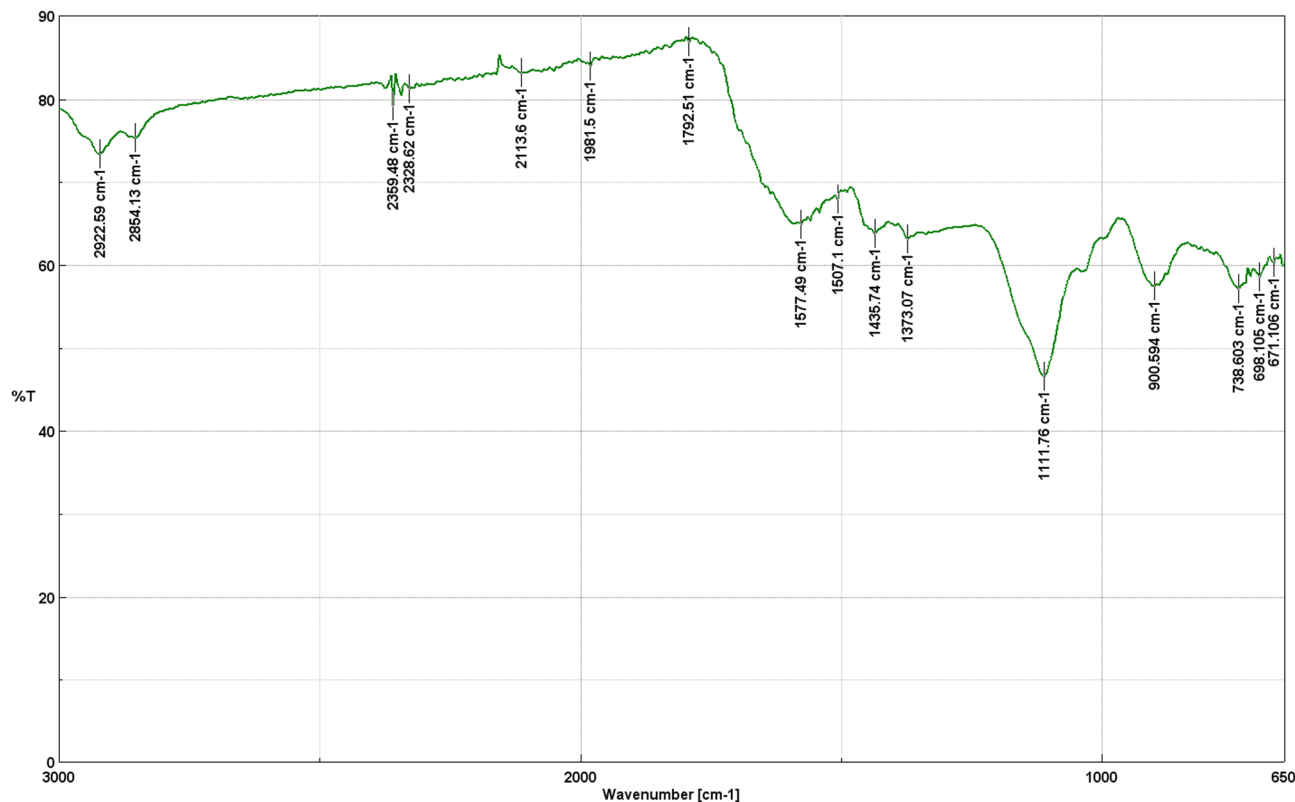
**Table 1.** The elemental EDS analysis of biomass and Biochar from the *Chlorella sp.* Algae.

sodium. Their percentages are presented in Table 1 and compared with the values obtained after the analysis of freeze-dried algal biomass.

In the samples analyzed, the content of most elements in biochar can be observed to rise compared to the biomass. During the pyrolysis processes of the controller of loss of volatile nitrogen, e.g.  $\text{NH}_3$ ,  $\text{HCN}$ , in the case of the application studies within the article, additional importance of these elements. This is a phenomenon that can be explained as executive mechanisms. During pyrolysis, the loss of mass of the material formed in the form of steam, formed from carbon and many greenhouse gases. In increasing quantities, the relative concentration of less volatile components, such as phosphorus, and originally from nitrogen. This phenomenon is defined as an effect of densification and formation, by, among others, Chen et al.<sup>11</sup> and Abdalla et al.<sup>27</sup>. Biochar can be stored as a part of nitrogen in the form dependent on heterocyclic compounds (e.g. pyridine, pyrazine). These compounds are resistant to thermal degradation and, as such, they are present in the final product. The phosphorus increases due to its volatility. Phosphorus occurs in the biomass of microalgae mainly in the form of inorganic compounds (calcium, potassium or magnesium phosphates), which are not volatilised under moderate pyrolysis conditions. As a result, although the total mass of the material decreases, the percentage of P increases, which is also confirmed by the studies of Gascó et al.<sup>17</sup> and Vieira Costa et al.<sup>18</sup>. Additionally, it should be emphasised that the biomass of *Chlorella sp.* microalgae naturally contains a high amount of protein (up to 50% of dry mass), which is associated with a high level of organic nitrogen already in the starting material. Thanks to this, even with a partial loss of volatile forms of nitrogen, it is possible to obtain biochar with a relatively high content of this element<sup>28</sup>. The presence of carbon and nitrogen in biochar is crucial for its agricultural benefits. Biochar with a high carbon content, especially in the form of persistent aromatic structures, is highly stable in soil, which translates into improved soil structure, increased water retention and a greater activity of soil microorganisms. The nitrogen content of biochar affects its fertilizing value. The biochar can act as a nitrogen storage and carrier, limiting its leaching from the soil and improving fertilization efficiency. Biochar contains significant amounts of stable carbon, which can remain in the soil for hundreds or even thousands of years, making it an effective tool for reducing carbon dioxide emissions and mitigating climate change. Additionally, its presence in soil can reduce emissions of other greenhouse gases, such as nitrous oxide ( $\text{N}_2\text{O}$ ). The oxygen content, although reduced in the biochar compared to the initial biomass as a result of the pyrolysis process, remained at 21.31%, indicating the ability of the biochar to adsorb water and nutrients.

At the next stage, the functional groups in the biochar obtained from the *Chlorella sp.* algal biomass were identified. As a result of the study, a spectrum was arrived at, which shows the characteristic bands for biochars within the ranges of  $2000\text{--}1500\text{ cm}^{-1}$  and  $1500\text{--}650\text{ cm}^{-1}$  (Fig. 4).

On the spectrum of values, biochar in the  $2000\text{--}1500\text{ cm}^{-1}$  range is responsible for valence vibrations of C=C, C=O, C=N, N=N double bonds, deformation vibrations of N-H and O-H bonds from water. The stretching vibrations that occur in this area indicate the possibility of various organic compounds of alkenes,



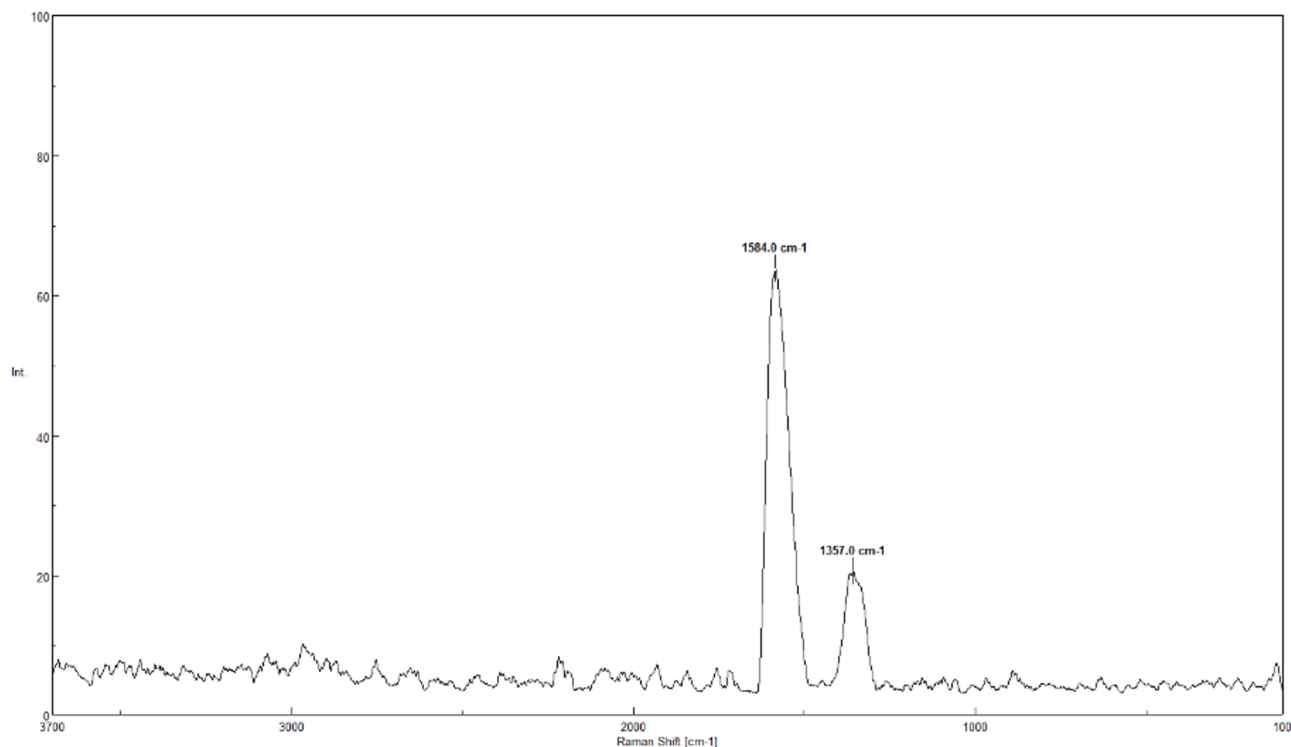
**Fig. 4.** FTIR spectrum of biochar obtained from *Chlorella sp.* algal biomass.

aldehydes, ketones, acids and esters. In the 1500–650  $\text{cm}^{-1}$  range, there are areas primarily responsible for valence vibrations of C-C, C-N, C-O bonds and C-H deformation vibrations. The presence of hydroxyl (O-H) and carbonyl (C=O) groups affect the hydration of biochar. As a result, biochar can act as a storage for water and nutrients, helping to improve growing conditions in soils with low retention. The presence of aromatic groups (C=C) in biochar has a beneficial effect on its interactions with soil microorganisms, primarily by increasing the soil stability, providing an appropriate microstructure for colonization, and participating in chemical and redox interactions in the soil environment. Although aromatic groups themselves are not a source of easily assimilable carbon, their presence creates favorable living conditions for microorganisms and may affect the composition and functions of the soil microbiome<sup>29</sup>.

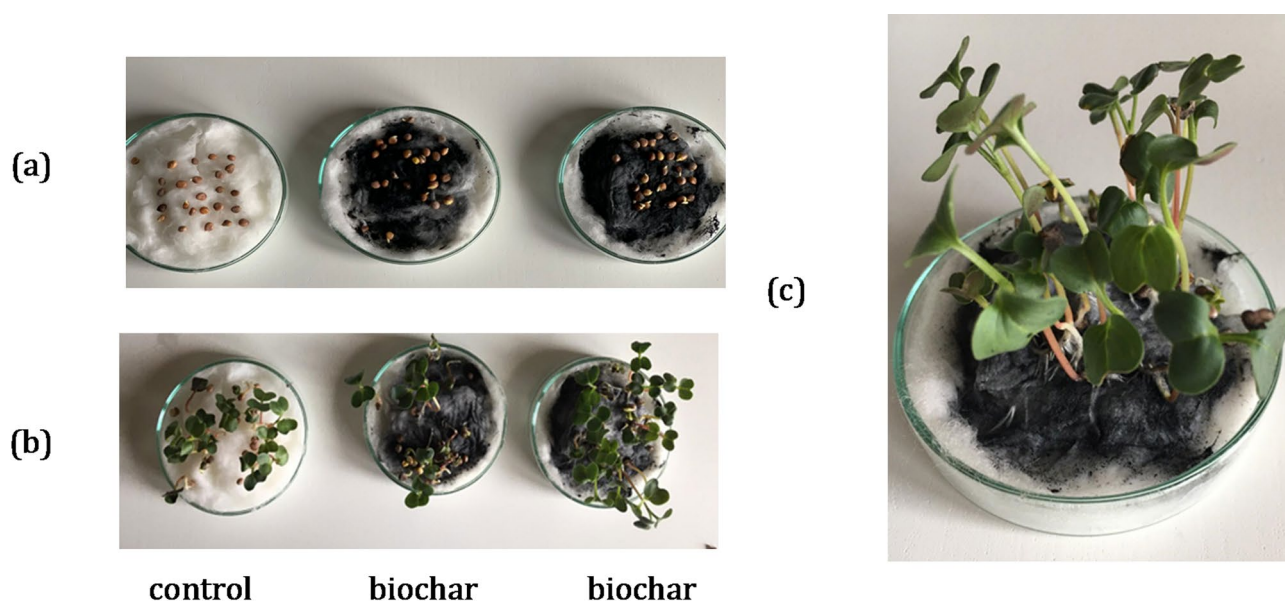
The degree of the ordering of the obtained biochar's structure was evaluated based on Raman spectra (Fig. 5).

The presence of a D band in the 1351–1361  $\text{cm}^{-1}$  range corresponding to disordered carbon structures and a G band in the 1579–1588  $\text{cm}^{-1}$  range, derived from stretching vibrations, were found. The intensity ratio of the D/G bands, measured by the magnitudes of the areas under the peaks 1357  $\text{cm}^{-1}$  and 1584  $\text{cm}^{-1}$ , which is one of the key parameters that characterize the structure of carbon materials, was determined. In the case of the obtained algal biochar, it was 0.25.

At the next stage of the study, the biochar produced from the *Chlorella sp.* algal biomass was tested as a growth stimulator for radish seeds. The cultures were grown for 14 days. Lignin was used as a neutral, sterile and biodegradable material ensuring the stability of the substrate and maintaining humidity around the seeds, which promotes better rooting of plants. The function of the biochar was to store nutrients and increase the substrate's water retention capacity. The prepared crops were watered (5  $\text{cm}^3$  in the first 4 days, then 10  $\text{cm}^3$  for the next 10 days). This dosage was intended to reflect the different water requirements at the subsequent stages of seed development. In the first phase (imbibition), too much water could lead to an inhibition of germination due to limited access to oxygen. Therefore, a small dose of water (5  $\text{cm}^3$ ) was used to prevent the substrate from overflowing, and to ensure a proper hydration of lignin and activation of the sorption properties of biochar. After the emergence of sprouts, when plants enter the phase of intensive growth, their water requirement increases, therefore the watering volume was increased to 10  $\text{cm}^3$  in the later part of the experiment. An even distribution of biochar on the surface of the lignin substrate, and not, for example, seed coating, allowed for an even contact with water and seed material, without a direct chemical effect on the structure of the seeds. The method of application reproduced the actual conditions in which biochar is mixed or deposited in the upper layer of soil, affecting the microenvironment around the seeds. Placing biochar on lignin allowed for observing its effect on the distribution of water in the substrate, which was important from the point of view of the role of biochar as a carrier of water and nutrients. The surface application ensured greater repeatability of the experiment and eliminated the variability resulting from the seed coating technique, which is difficult to standardize in laboratory conditions.



**Fig. 5.** The Raman spectrum of biochar from Chlorella algae.



**Fig. 6.** The photographs of radish seed growth on the (a) 1st day of culturing, (b) 14th day of culturing, and (c) 14th day of culturing with biochar—side view.

Overview photographs of radish seed growth is shown in Fig. 6.

After growing the culture, the germinated plants were weighed and measured, and the resulting data allowed the determination of seed viability and chlorophyll indices. The study results are presented in Table 2.

The content of chlorophyll a and b in seedlings was higher in the biochar sample, 17.28 and 6.05, respectively, compared to 15.76 and 5.89 in the control sample. Chlorophyll, as the main photosynthetic pigment, is responsible for absorbing light and converting solar energy into chemical energy used by plants in the photosynthesis process. Its higher concentration in leaf tissues indicates a better physiological condition of plants and their greater potential for effective photosynthesis. Biochar contributes to the increasing chlorophyll content in plants

Parameter	Control trial	Research sample 1
Length of sprouts [cm]	1.9	3.9
Mass of sprouts [g]	1.964	3.874
Chlorophyll a	15.76	17.28
Chlorophyll b	5.89	6.05
Germination energy [%]	88	93
Germination ability [%]	92	97
Average germination time [day]	1.87	1.12

**Table 2.** Radish seed germination culture results.

indirectly by improving the physicochemical properties of the soil. It improves soil structure, increases water retention and the availability of nutrients, especially nitrogen, phosphorus, potassium, iron and magnesium, elements essential for chlorophyll synthesis. A better supply of these components to plants promotes chlorophyll biosynthesis, and thus increases photosynthetic efficiency, which translates into better biomass growth and yield. In addition, biochar can affect the activity of soil microorganisms that indirectly support the absorption of nutrients, which can also result in a higher chlorophyll content. At the same time, the ratio of chlorophyll a to b remained at a similar level 2.8:1 in the research sample and 2.6:1 in the control sample suggesting that biochar does not disturb the balance between these two forms of chlorophyll. Maintaining a typical ratio of pigments is a positive indicator of plant health and their proper metabolic functioning<sup>30,31</sup>.

## Discussion

The discussion on the impact of algae biochar on the germination of plants such as radish begins with several key connections: the extension of coverage conditions, the associated benefits associated with the additional effect, and the impact of biochar on various physical parameters of plants. Provenance studies around the world that algae-derived biochar with its ingredients can be launched and obtained from plants under natural conditions. Biochar produced from algae biomass is a rich endowment such as nitrogen, phosphorus and microelements that can trigger the growth and development of young plants. Research results worldwide show that biochar obtained from algae biomass can be effectively used in field crops, improving plant growth conditions even in unfavorable soil conditions<sup>32</sup>.

The discussion on the use of algae biochar in radish cultivation indicates its positive effect, especially in moderate doses. Benefits such as increased water retention, greater availability of nutrients and bioactive substances may be important for improving the emergence and development of young plants. In the context of organic farming, biochar can be a valuable tool to support sustainable food production by reducing the use of chemical fertilizers and improving soil quality. However, too high doses may cause toxic effects, highlighting the need for further research into dosage optimization. As shown in the work of Abdalla et al.<sup>27</sup>, algal biochar is characterized by a high content of organic compounds and a low level of toxic pollutants compared to biochar from terrestrial biomass, making it a more environmentally friendly solution in agriculture<sup>32,33</sup>.

Recommended future research should focus on analyzing the long-term effects of algal biochar on different soil types and its interactions with soil microbiota. Moreover, it is worth conducting research on the possibility of using biochar in combination with other methods of improving soil fertility, such as composting or organic fertilizers. Optimizing the composition of biochar by adjusting the pyrolysis temperature and analyzing interactions with other organic substances may contribute to even more effective use of this material in agriculture.

An increasingly important part of sustainable methods contributing to global initiatives for environmental equity and agricultural sustainability is algae-based biochar. In the study by Silva et al.<sup>32</sup>, which analyzed different types of biochar, showed that soil enriched with algal biochar increases water retention by approximately 20%. In radishes, better growth was observed in the initial stages as better water availability facilitated seed germination. The publication<sup>27</sup> reviews the processes used to produce biochar from algae, highlighting its specific properties and comparing it with other forms of biochar, in particular for agricultural applications.

The publication<sup>28</sup> presents the use of microalgae-based fertilizers in sustainable agriculture and examines practical methods for their implementation in agricultural practices. The properties and composition of microalgae are presented, including a comparison with traditional synthetic fertilizers, highlighting their potential to improve soil quality and crop production. It also examined the benefits, uses, challenges and impacts of microalgae use in agriculture, including their impact on soil microbiota and associated production costs, examining associated challenges and providing recommendations for future research and development<sup>32–35</sup>.

## Conclusion

The paper presents the results of a study on producing biochar from the *Chlorella sp.* algal biomass and testing its performance as a radish seed growth activator. The biochar produced through pyrolysis was characterized by a porous structure, the presence of functional groups, an ordered carbon structure and a high (above 50%) carbon content. Cultures grown with radish seeds have shown that biochar can act as an effective growth activator, increasing germination energy rates, germination capacity, accelerating average germination time and increasing chlorophyll content in plants. The use of biochar from *Chlorella sp.* can therefore support more efficient and sustainable crops, positively influencing germination rates and healthy plant growth. The next

step in the research will be to evaluate the effect of biochar on microbial biodiversity under real greenhouse conditions, which will allow a better understanding of its potential in agriculture. If biochar proves beneficial to the soil microbiome, it could promote plant growth by improving the health and function of the soil ecosystem, which would promote long-term organic agricultural production.

## Data availability

Data is provided within the manuscript.

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### Declarations

#### Competing interests

The authors declare no competing interests.

#### Additional information

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