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Prospects for the use of paper waste in the production of biochar

Brikmans Anastasia[1], Nesterova Olga[1*], Bovsun Mariia[1], Semal Viktoriia[1]
[1]Far Eastern Climate Smart Lab, Institute (School) of the World Ocean, Far Eastern Federal University, Russian Federation;
brikmans.av@dvfu.ru (B.A.) nesterova.ov@dvfu.ru (N.O.) bovsun.mal@dvfu.ru (B.M.) semal.va@dvfu.ru (S.V.).

Abstract: The transition of the economy to the processing of finished products is an important strategy of environmental management. Paper waste is one of the most common types of waste and is recyclable. There are studies on the possibility of recycling paper waste into biochar, but the impact of this biochar remains a poorly understood topic. This article presents the first results of the evaluation of biochar from office paper waste as a soil improver. Biochar was obtained by pyrolysis at a temperature of 800 °C for 1 hour. The analysis of the properties of biochar was carried out according to the methods of the international standard IBI. The yield of biochar compared to the weight of the original paper was about 31.5%. Biochar, characterized by a low content of carbon and nutrients. Biochar did not contain heavy metals, which means it is environmentally friendly. Biochar had a pH of 12.47, which can have a beneficial effect when applied to acidic soils. Additional tests are needed to obtain complete results, but it can be concluded that recycling office paper into biochar is an environmentally friendly way to recycle paper and create climate projects based on it.
Keywords: *Biochar standards, Biochar, Heavy metals, Paper waste, Plant nutritional elements, Pyrolysis, Recycling.*

1. Introduction

In the process of restoring disturbed soils, owners and users of land plots often face the task of recreating original characteristics such as soil structure, nutrient content, and acid-base properties. At the initial stages, mineral or organic fertilizers may be used to improve chemical properties, but more innovative approaches are required to solve physical problems.

The water-air regime of the soil plays a crucially important role in providing plant nutrition and significantly affects their productivity. This makes the production of soil structures based on natural substances increasingly relevant. Among effective soil improvers, biochar, a product of pyrolysis processing of biomass, is of particular interest [1, 2]. The interest in biochar arises from several factors. On the one hand, it provides rational management of biological waste by allowing carbon retention in its structure over time. On the other hand, due to its high carbon content and porous structure with a reactive surface area [3], biochar positively affects a wide range of chemical, microbiological, and physical properties of soil [1]. As for the effect of biochar on the physical properties of soil, it has already been proven that it contributes to an increase in field moisture capacity, a decrease in soil density (bulk mass), improvement in soil structure and aggregate stability, and porosity [4, 5]. At the same time, the decrease in soil density is most noticeable in heavy soils, while the increase in porosity is due to the formation of new pores associated with biochar characteristics, changes in pore structure, and increased soil aggregation and mesofauna activity [6]. An increase in field moisture capacity results from an increase in both soil porosity and surface area [6].

It has been proven that the introduction of biochar increases the diameter of soil aggregates [7], and there is evidence of the effect of biochar on reducing soil erosion [8]. There are also studies on the correlation between different fractions of biochars and their effect on water retention capacity in soil.

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* Correspondence: nesterova.ov@dvfu.ru

The effects of biochars on soil structure are actively being studied both in Russia, including the Primorsky Territory [8-10], and abroad [11-14].

Due to its physical and chemical properties, biochar is able to influence the water-air properties of the soil, the pH values of soil solutions, soil aggregation, the availability of nutrients, and the availability of organic carbon. Lehmann et al. [15] promote plant growth, increase crop yields, and reduce the amount of pollutants [16]. The main process of biochar production is pyrolysis, in which biomass is processed at high temperatures and necessarily in an inert atmosphere at various temperatures and durations of the process. The process can be carried out in various types of carbon-burning furnaces Rizhiya et al. [10], at temperatures ranging from 50 to 950°C for several seconds, hours, or even days [17]. Due to the high sorption properties of biochar and the relatively low cost of industrial production, it is being actively used to purify soils from heavy metal pollution, and many publications have already appeared on such studies in Chinese soils [18], which means it is suitable for the reclamation of disturbed urban soils. According to the official international website of the International Biochar Initiative (IBI), biochar is defined as a solid material obtained as a result of thermochemical transformation of biomass in an oxygen-limited environment [19]. In 2012, the IBI and EBC (European Biochar Certification) issued official standards for assessing the quality and properties of biochars.

Despite numerous studies confirming the positive effect of biochar on soil properties, the results can vary significantly depending on initial soil characteristics, pyrolysis temperature, origin of biomass, and climatic conditions [4, 20].

In many countries, especially in Europe, the use of biochar in agriculture is strictly regulated. Its introduction into the soil is allowed only after mandatory certification. When considering biochar as a tool for restoring and reclaiming disturbed soils, the key issue is choosing economically advantageous raw materials for its production. One promising solution is recycling paper waste into biochar. Although there are few studies in this area, foreign scientists are gradually collecting data on the potential of this approach.

For example, an analysis of publications conducted by Justo et al. in 2025 showed that there were still no convincing studies on the economic feasibility of alternative uses for pulp and paper waste [21]. This highlights the need for further comprehensive research. Herath et al. evaluated the potential of pyrolysis to convert waste into biochar, a product with a wide range of applications in ecology, agriculture, and industry [22]. The authors recommend improving the waste sorting and collection infrastructure, implementing sustainable waste management practices, raising public awareness, and investing in research and development.

Two main approaches are used for the disposal of cellulosic waste (for example, cardboard). Biochemical methods, including anaerobic digestion, make it possible to obtain biogas and compost; however, they require a long processing time and high-purity raw materials (cardboard separated from solid household waste). Thermochemical methods, primarily pyrolysis, are more flexible and efficiently convert various organic materials into oil, syngas, and coke.

A number of key studies have shed light on the possibilities of pyrolysis. In laboratory experiments in Gondar [23], the effect of slow pyrolysis parameters, temperature, air flow, heating rate, and residence time in the reactor, on the release of biochar from waste paper was studied. Waste paper was processed at a low temperature (167 °C), and the results showed that key factors determining product yield are controlled by temperature and air flow rate.

In a study by Farid et al., corrugated cardboard was pyrolyzed at temperatures of 350, 400, and 450 °C [24]. The resulting products, biochar and bio-oil, were carefully analyzed. Biochar was characterized by a low content of ash and nitrogen, and levoglucosone was found in the bio-oil, which confirms its potential for further processing into fuel [24].

A study by Zuhara et al. focused on the pyrolysis of bio-waste (obtained during wastewater treatment), cardboard, and their mixtures [25]. The experiment was conducted in a muffle furnace at temperatures ranging from 350 to 850 °C, with a heating rate of 3-10 °C/min and a residence time in the furnace between 30 and 180 minutes. The results showed that the highest biochar yield was achieved using bio-waste, followed by mixed samples and cardboard. The main factors influencing the yield included temperature and the proportion of components. At 650 °C, the surface area of the biochar was 10.34 m^2/g for bio-waste, 170.4 m^2/g for cardboard, and 124.8 m^2/g for mixtures. Particle size had minimal impact on product yield. Based on the data obtained, the authors concluded that temperatures below 550 °C are preferable for economical pyrolysis because they provide optimal biochar yields, ash content, and metal levels. Additionally, mixing waste improves biochar quality and yields while enhancing the environmental friendliness of the process [25].

If we consider raw materials in a global context, lignocellulose waste (containing cellulose, hemicellulose, and lignin) is well-suited for thermal processing. Although many studies focus on regional waste such as rice husks, bamboo waste, or corn straw, cardboard is a versatile raw material available everywhere.

New research directions open up additional perspectives. In the work of Shen and Chen [26], the synthesis of catalysts based on biochar obtained from cardboard waste from express packaging is described. Ščasná et al. [27] propose using biochar from cardboard as an adsorbent to remove pesticides from aquatic environments. Zhang et al. [28] explore the use of biochar from paper waste for wastewater treatment.

Thus, the recycling of paper waste into bio-coal can become the basis for rational environmental management through the recycling of raw materials. This approach makes it possible to reduce the environmental burden, increase business sustainability, and obtain value-added products for bioenergy and other industries. However, the problem of using paper biochar for soil improvement remains unresolved; therefore, the purpose of this study is a preliminary assessment of biochar obtained from paper waste.

2. Materials and Methods

The object of the study is biochar obtained from used office paper. Office-used paper was pyrolyzed in a SAFTherm STZ 1214 furnace (Henan Sante Furnace Technology Co., Ltd, China) in a nitrogen stream at 800°C for 60 minutes. The heating rate was 8.3 degrees/min, and nitrogen consumption was 3 liters/min. The appearance of the paper after pyrolysis is shown in Figure 1.

Figure 1.
A photo of biochar made from used office paper by pyrolysis at 800°C for 1 hour.

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The study was conducted using a method presented by the International Initiative for the Production of Biochar (IBI) [19].

The yield of biochar from the pyrolysis of air-dried material was calculated using equation 1 [29]:

$$Biochar\ yield\% = \frac{W_{biochar}}{W_{seaweed}} \times 100\% \quad (1)$$

where Wbiochar is the weight of the biochar (g), Wseaweed is the weight of the initial seaweed (g).

The pH value of the aqueous extract was determined according to the standard methods of Rajkovich et al. [30]. To determine the pH of the aqueous extract, biochar was crushed, and a fraction with a particle size less than 1 mm was selected. This was then filled with 25 mL of distilled water and stirred for 60 minutes. After mixing, the pH was measured using a combined electrode and electrical conductivity sensor from Mettler Toledo (USA).

The total nitrogen content in biochar was determined using the Kjeldahl method [31]. Available forms of phosphorus and potassium in biochar were determined using the spectrophotometric method [19]. The content of heavy metals was determined according to Methods for the Examination of Composting and Compost [32].

The carbon content in biochar was determined according to the methodology presented in the recommendations of the International Biochar Initiative (IBI) [19].

3. Results and Discussion

For any feedstock used to produce biochar, it is necessary to determine the pyrolysis temperature in advance in order to maximize the yield of biochar. The yield of biochars is the amount of biochar produced from the feedstock as a result of thermochemical processes such as pyrolysis and hydrothermal carbonization. It is typically expressed as a percentage of the weight of the starting material. Factors that influence the biochar yield include the type and composition of feedstock, process temperature, heating rate, processing time, pressure, and pretreatment of raw materials.

Paper is a recyclable product (with ink impurities present, etc.), so a pyrolysis temperature of 800°C was selected. At this temperature, the yield of biochar was 31.5% (Table 1). This indicates a low biomass yield compared to other materials, where the temperature does not exceed 500°C.

Table 1.
Characteristics of biochar obtained from used office paper at a temperature of 800 °C for 1 hour.

Parameter	Parameter Value
Biochar yield, W	31.5±0.5
pH	12.47±0.2
EC, mS/(m^{-1})	9.16±0.1
N %	0.3±0.1
P_2O_5 %	-
K_2O, %	0.01±0.001
Corg, %	36.6±0.2

The pH value of biochar is usually alkaline and falls within the range of 7 to 12, depending on the feedstock. The alkaline pH level is due to the formation of alkaline substances such as calcium (Ca), sodium (Na), and potassium (K) during pyrolysis (the production of biochar from organic biomass without oxygen). It is believed that, due to its high alkaline pH, biochar can neutralize acidic soils and improve their condition, promoting plant growth. Biochar can also affect nutrient availability for plants, for example, increasing the availability of phosphates in acidic soils. Therefore, the pH level is a key characteristic that determines the effectiveness of biochar for agriculture and soil improvement.

Studies of the acid-base properties of biochar have shown that the reaction of the biochar medium obtained from paper is 12.47 (Table 1). This indicates a highly alkaline pH, making it a suitable material for application to acidic soils to modify the pH of the medium. The electrical conductivity of biochar is in the range of 9.16 dS/m.

Any resulting biochar must meet the quality standard. Currently, the only quality standard accepted in the international community is the International Standard of the International Biochar Initiative (IBI) [19], which provides recommendations for biochar production. The resulting biochars, according to IBI standards, can be categorized into ABC, depending on their purpose. First, we were interested in category A (fertilizers), where there is a grading system based on the "carbon content," with class 1 having more than 60% carbon, class 2 having not less than 30% but not more than 50%, and class 3 having between 10% and 30%. Studies have shown that biochar made from paper has a carbon content of 36.6%, which makes it suitable for classification as class 2.

An element such as nitrogen is closely related to carbon, which also affects soil fertility. The total nitrogen content in biochar is 0.3% (Table 1), which is a low indicator compared to biochars obtained from wood, for example.

Biochar can be a significant source of phosphorus for soils, but its concentration and availability depend on the raw materials and production technology. As expected, no available phosphorus was found because office paper does not contain phosphorus in its initial composition, and therefore, there is nothing to inherit from vegetable raw materials.

Biochar is able to influence the potassium regime of soils, enriching them with forms of potassium available to plants (water-soluble and exchangeable). Water-soluble potassium is the most accessible form for plants, and exchangeable potassium is the closest source of plant potassium nutrition after water-soluble forms. It is represented by potassium ions adsorbed to soil colloids, where some of the adsorbed potassium enters the soil solution when it is exchanged for other cations, making it easily accessible to plants.

Studies have shown that the content of exchangeable potassium does not exceed 0.01%. These values are very low for assigning a class according to the IBI standard.

One of the most important parameters in biochar that must be considered before applying it to soil is the presence of pollutants that may initially be present in the feedstock. Office paper is a recycled product that undergoes a certain stage of preparation during the manufacturing process, which includes a complex technological process. The main raw materials used for paper production are wood (pine, birch, poplar, maple), and more valuable species such as oak, chestnut, and cedar are used less frequently. The main step in paper preparation is bleaching, and to give a white color, it is treated with special chemicals such as chlorine dioxide (ClO_2), hydrogen peroxide (H_2O_2), and sodium hypochlorite (NaClO). Additionally, to fix fibers and reduce absorption, paper is treated with adhesive solutions. Ink also contains various solvents, coloring agents, pigments, surfactants, and preservatives. In this regard, the resulting biochar was analyzed for the presence of heavy metals. The research results are presented in Table 2.

Table 2.
The content of acid-soluble forms of heavy metals in biochar from used office paper, mg/kg.

Parameters	**Zn**	**Ni**	**Cd**	**Pb**	**Cu**	**Co**	**Mo**	**Mg**	**Fe**	**Mn**
Paper biochar	-	0.86	0.30	0.12	10.4	1.91	0.005	88	226	200
IBI scale	416-7400	47-420	1.4-39	-	143-6000	34-100	5-75	-	-	-
MPC for soils	-	-	-	32.0	-	-	-	-	-	1500

According to Table 2, the content of the elements Ni, Cd, Pb, Cu, Co, Mo, Mg, Fe, and Mn in biochar made from used office paper does not exceed the established norms according to the IBI standard and relevant soil standards. This indicates that the use of biochar in soils will be environmentally safe.

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4. Conclusion

Thus, the analysis showed that biochar obtained from paper had low levels of carbon, phosphorus, and potassium, which did not allow it to be classified as efficient according to the IBI standard. Additionally, according to IBI standards, heavy metal content in biochar was undetectable. Therefore, biochar made from office paper will not harm the environment when applied to soil.

Due to its high pH, biochar made from used office paper should be used on acidic soils and with caution on neutral and alkaline soils, as it can lead to problems such as reduced nutrient availability, inhibition of specific soil organisms, and damage to soil structure.

In order to predict all the advantages and disadvantages of biochar produced from used office paper, it is necessary to conduct additional tests, such as measuring the total content of C, O, and N, as well as calculating the O/C and C/N ratios, which allow us to determine the rate of decomposition and stability of the biochar. It is also necessary to measure the surface area and pore space of biochar, as well as its water retention capacity, in order to assess its potential impact on the water properties of the soil, element exchange, and microbiological indicators.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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