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Development of Biochar to Improve Soil Health and Increase Potato Yields

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ABSTRACT

Potato growing is one of the main branches of agriculture, the main task of which is to obtain maximum yields of high-quality potato tubers. Therefore, the food security and stability of the country may significantly depend on the state of the potato industry as a whole. The urgency of the problem is related to the state of soil fertility, which is deteriorating almost everywhere. The purpose of the study: to develop an ameliorant as biochar for assessing potato yield and physicochemical properties of sod-podzolic sandy loam soil. The carbonised biochar obtained by pyrolysis of rice husks at a temperature of 400°C was used as an ameliorant. Rice husks are used as a more affordable and cheaper material. It has been established that the use of biochar in agriculture leads to high crop yields at lower water costs. The introduction of biochar into the soil accelerates biological processes and promotes long-term soil fertility. Not only agricultural parameters are improving, but also the efficiency of biochar for storing carbon dioxide is increasing.

1. INTRODUCTION

The state of soil fertility is deteriorating almost everywhere [1]. Due to the maintenance of livestock in rural farmsteads, a high level of fertility of settled lands was maintained [2]. At the output of manure per year, 8 tonnes per cow and 4 tonnes per unit of young animals, not counting sheep and birds, at least 25 tonnes of organic fertilisers were applied to 40 acres of the garden in terms of 1 ha. Due to a sharp reduction in the number of cattle and the almost complete absence of manure in the personal subsidiary farm, its use in the world has decreased to an insignificant 1.0 t/ha of arable land. At the same time, for a deficit-free balance of humus [3, 4], it is necessary to contribute at least 7 t/ha, and if 50% of row crops are present in the structure of the sown areas, respectively, at least 10-15 t/ha of crop rotation area [5]. Due to increased imports of foreign crops, the share of potato varieties is decreasing. Therefore, it is necessary to introduce methods for a successful harvest on the territory to refuse the services of foreign producers.

Potatoes are included in the daily diet of the majority of the population, which uses it for a long time, the demand for it is only growing. The yield of 250 kg of tubers can yield a profit of 1.5-2.0 times more compared to another crop. Despite its importance in human nutrition, potatoes remain a high-cost crop, which in general over the past 20 years has led to a decrease in the area of its planting and the purchase of these products abroad [6]. According to the latest data from the World Potato Congresses [7], it follows that this crop has a high demand on the world market compared to other crops, therefore, the productivity of seed potatoes is growing. Notably, potato processing production is at the initial level of development. The increased chemicalisation of the industry leads to a significant accumulation of harmful substances in potato tubers, deterioration of the ecological condition of tubers, and the negative impact of such products on the human body [8].

Biological coal is a material obtained by burning biomass by pyrolysis at high temperatures in an oxygen-free environment [9]. Any type of biomass is used in the production of biological coal, but the most preferred are agricultural and logging industry waste. After the pyrolysis process, the new product has high carbon content in the form of stable aromatic compounds [10] and is used as an ameliorant, with the main purpose, namely, to sequester carbon in the soil for a long time, up to hundreds of years, reduce greenhouse gas emissions and improve soil characteristics [11]. Biochar will be characterised by a different composition of elements, ash content, odour and pH. These indicators in the complex favourably affect the density of the soil itself, changing its water-physical and physicochemical properties, mineral composition, biological activity and, as a result, increases the growth and development of plants [12], which determine the effectiveness of the use of biochar for soil improvement [13]. It has been established that biochar, as a soil ameliorant, can contribute to improving the quality and cultivation of soils [14], reducing acidity, reducing greenhouse gas emissions (CO_2, N_2O, CH_4), and also affecting crop yields [15].

In connection with the above, to ensure high tuber collections, it is necessary to solve the problem of maintaining soil cultivation by such parameters as humus content and water-physical properties, in the absence or lack of organic fertilisers. Therefore, the presented research is an attempt to fill this gap, and the purpose of the research is to develop an ameliorant as biochar for assessing potato yield and physicochemical properties of sod-podzolic sandy loam soil.

The results of the study showed that the introduction of biochar into the soil, both individually and together with nitrogen fertiliser, led to an insignificant decrease in its bulk density compared to the initial state. Also, it was showed the

absence of a significant effect of biochar on the change in the content of mobile P in the soil under potatoes, compared with others, both with individual application and combined with azophoska. So, it was indicated that the introduction of biochar, both for barley and potatoes, changed the biochemical composition of these crops.

The presented article was developed in four sections: the Introduction section substantiates the relevance and purpose of the research; the Materials and Methods section describes the research methods and their application; the Results and Discussion section contains the main data; the Conclusions section summarizes the main findings.

2. MATERIALS AND METHODS

The small-scale field experiment was first performed in April 2015 at the Menkovsky branch of the Agrophysical Research Institute. The studied soil is sod podzolic sandy loam on Devonian sands. A biocar obtained by rapid pyrolysis of soft-leaved wood (aspen, alder, and birch) in an oxygen-free environment was used in this experiment. Pyrolysis was carried out at a temperature of 550°C, with a short time of hot steam treatment of coal equal to one second [16]. The area of the experimental site was 500 m^2, on which plots were divided for growing potatoes (Solanum tuberosum L.) of the Lomonosovsky variety (2X4 m^2) and barley (Hordeum vulgare L.) of the Leningradsky 96 variety (1X2 m^2). The experimental design included 4 options: (1) control soil (C), (2) soil + biochar, introduced at the rate of 5 tonnes ha-1 (B), (3) soil with azophoska ($N_{16}P_{16}K_{16}$) at the rate of 90 kg per ha-1 (N), (4) soil with biochar and azophoska (B + N).

The characteristics of the soil and the studied biochar are presented in Table 1. According to Table 1, it was established that the acidity of biochar was higher than the acidity of the soil. In addition, the ratio of total organic carbon and nitrogen content was significantly higher in biochar. In turn, no ash was detected in the soil, while it was 0.23 in biochar.

Table 1. Characteristics of sod-podzolic sandy loam soil and woody biochar (initial data before the experiment)

Object	pH KCl	C total (g kg^{-1})	N total (g kg^{-1})	C/N	N min (mg kg^{-1})	Ash, %	P (mg kg^{-1})	K (mg kg^{-1})
Soil	5.2	18.5 ± 0.6	1.4 ± 0.1	13	13.6 ± 0.8	-	118	75
Biochar	7.0	874.0	3.8	230	0.9	0.23	25	117

Note: C total – total organic carbon content; N total – total nitrogen content; N min – of mineral nitrogen ($NH_4 + NO_3$) content; P – exchangeable phosphorus content; K – exchangeable potassium content.

Humidity, bulk density, and soil temperature were measured weekly according to standard methods. Soil samples were selected to analyse the content of mineral nitrogen, mobile forms of phosphorus and potassium in them [17]. Notably, the selection of soil samples in potato variants was carried out only from furrows, but not ridges. Soil air sampling was carried out weekly by the method of closed chambers. The concentration of N_2O in air samples was measured on a gas chromatograph (Carlo Erba Strumentasione, Italy) equipped with an electronic capture detector. The analysis of biomass and crop yield was carried out according to the Dospekhov method. For barley, the selection was carried out by the method of continuous threshing, taking into account the harvest from the entire accounting area of each plot and adjusted for offsets, sparsity and headland, and for potatoes, samples were taken from a certain number of potato bushes and adjusted for offsets and headland furrows. Statistical processing of the findings included calculations of the values of averages, standard deviations and linear correlation coefficients at $p \leq 0.05$. The reliability of the differences in the mean values was evaluated using the system for analysis (ANOVA – analysis of variance) at $p \leq 0.05$.

3. RESULTS AND DISCUSSION

The soil moisture content plays an important role in the management of soil processes. This indicator is one of the limiting factors for high crop yields. The moisture content of the soil depended significantly ($p<0.05$) on rainfall, air temperature, and crop cultivation agro-technology. The dynamics of humidity showed that the introduction of biochar into plots with barley significantly increased this indicator ($p<0.05$), on average, by 1.3 times during the growing season. The introduction of azophoska resulted in an insignificant increase in soil moisture, while the application of biochar and nitrogen fertiliser together significantly increased ($p<0.05$) soil moisture during the growing season, but the differences with the soil variants where biochar and azophoska were applied separately were not significant, they are shown in Figure 1. The introduction of the studied biochar, azophoska and their combinations under potatoes and under barley increased soil moisture, on average during the growing season by 1.2, 1.1 and 1.2 times, respectively. The demand of this crop for water is greater than that of cereals, and biochar contributed to maintaining moisture in the soil during the growing season in comparison with soil without biochar. Earlier studies on the influence of biochar on the change in the basic hydrophysical characteristics have shown that biochar contributes to an increase in water retention capacity due to its high porosity and aromatic structure [18].

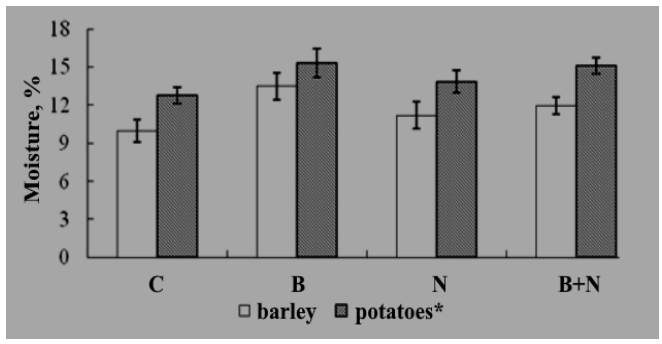

Figure 1. Average soil moisture under potatoes and barley during the growing season

Note: C – control soil variant; B – soil with biochar; N – soil with nitrogen fertiliser; B+N – soil with biochar and nitrogen fertiliser; * – moisture content in the furrows.

The density of soil composition in the variants of cultivated crops increased during the growing season from 1.1 ± 0.2 to 1.4 ± 0.1 g cm^{-3} and also depended on climatic data and agrotechnology of crop cultivation. During the growing season, potato hilling was carried out, which led to a decrease in the

density of soil consistency in the row spacing of this crop, while under barley there was a gradual increase in the density from the beginning of the growing season to the end. Significant differences in the content of mineral nitrogen (N min) in the soils under the studied crops were noted in the variant with azophoska, as shown in Figure 2. The maximum content of mineral nitrogen was noted in the variants with azophoska, an average of 33 and 59 mg kg^{-1} were noted during the growing season, respectively, for soils under barley and potatoes.

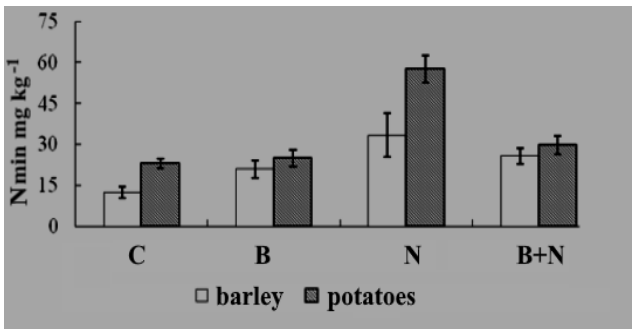

Figure 2. Average content of mineral nitrogen in the experimental variants during the growing season of 2015
Note: N min – the sum of N-NH_4^{++}N–NO_3-.

The introduction of biochar into the soil for barley individually and together with azophoska increased the content of mineral nitrogen by 17% and 21%, respectively. The joint application of biochar with azophoska significantly reduced ($p<0.05$) the content of this indicator by 1.3 times compared to the variant with azophoska. The introduction of biochar into the soil for potatoes did not have a significant effect on the change in this indicator, but significantly reduced ($p<0.05$) the concentration of ammonium and nitrates, on average by 2 times, compared to the variants of soils with azophoska. A significant predominance ($p<0.05$) of mobile phosphorus (P) content was observed in soil variants under barley over soil variants under potatoes (Figure 3). There was a significant increase in phosphorus in the soil under barley ($p<0.05$) by 1.5-1.7 times when biochar, azophoska, and biochar together with azophoska were applied, but without significant differences between the above variants.

The results of the experiment showed no significant differences in the content of exchangeable potassium between the control variants of barley and potatoes. At the same time, in the variants with biochar (introduced both individually and together with azophoska), a significant ($p<0.05$) decrease of this element concentration under potatoes in comparison with barley was observed. The maximum content of mobile potassium was observed in the variant with the introduction of azophoska, both in the variants with barley and potatoes, which reached an average value of 137 and 107 mg kg^{-1} during the growing season, respectively, for crops. The introduction of biochar into the soils under barley led to a high increase in the content of this element compared to the control by 1.6 times, in the soils under potatoes there were no strong changes between the corresponding variants [19]. In the variants of joint application of biochar and azophoska, a decrease in the concentration of exchangeable potassium was noted compared to the variant with azophoska, the results are shown in Figure 4.

The introduction of biochar on plots with potatoes led to a slight increase ($p>0.05$) in potato yield by 10% compared to the control variant, and led to an unreliable ($p>0.05$) decrease in yield by 10% in the variant with the complex use of biochar and fertiliser compared to the soil variant with fertiliser. The properties of barley and potato grains formed during the growing season have a decisive influence on many processes of its post-harvest storage and processing [20]. As can be seen from the presented data (Table 2), the introduction of biochar individually and together with azophoska allowed using nutrients with maximum efficiency, while maintaining soil fertility and good crop quality.

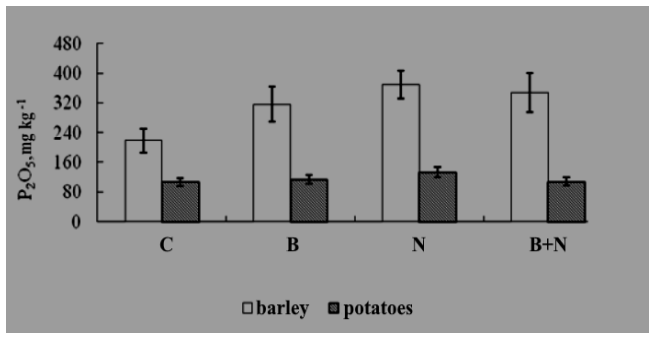

Figure 3. Average content of mobile phosphorus in the experimental variants during the growing season of 2015

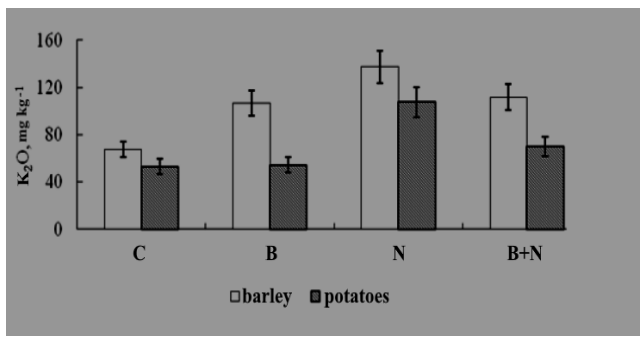

Figure 4. Average content of exchangeable potassium in the experimental variants during the growing season of 2015

Table 2. Average biochemical composition of barley and potatoes in different variants of the experiment

Variant	Barley, grain (Leningradsky 96)				Potatoes, tubers (Lomonosovsky)			
	C	B	N	B+N	C	B	N	B+N
Moisture, %	14.2	13.7	14.3	13.9	75.0	70.2	74.3	72.2
Starch, % of bulk density	52.0	54.0	56.0	58.0	18.0	18.6	17.5	18.4
Protein, %	9.5	10.3	10.5	10.6	1.8	2.1	2.2	2.3
Fibre, %	4.8	5.5	5.2	5.6	0.6	0.8	0.8	0.9
Dry matter, %	67.5	69.3	70.2	74.5	26.3	27.5	26.5	24.9
Crude ash, % of dry matter	2.1	2.0	2.3	2.2	3.0	2.5	3.3	2.1

The introduction of biochar into sod-podzolic sandy loam soil has led to a change in the moisture content in the soil, which increased by 7-29% on average during the growing season compared to the control variant [21]. The density of the soil composition did not depend on the presence of biochar in the soil. The content of mineral nitrogen in the soil with biochar increased by 1.7 and 2.3 times compared to the control, respectively, for barley and potatoes. The joint application of biochar with nitrogen strip led to a decrease in the content of mineral nitrogen compared to the soil variant with nitrogen fertiliser. Biochar did not affect the yield of the studied crops, but improved their biochemical parameters [22]. Thus, biochar has had a positive impact on soil indicators, growth and development of the studied cereals and row crops, however, additional long-term studies are required to recommend the comprehensive use of this product in agriculture. The efficiency of potato production is largely determined by the yield of this crop and the quality of tubers, depending on their intended purpose. At the same time, an increase in the yield and quality of potatoes, environmental safety and economic efficiency of its production is possible only based on preserving and increasing soil fertility, using sound potato cultivation technologies.

However, without the use of mineral and organic fertilisers, a high yield and its good quality are hardly possible. Organic fertilisers, including manure, are now in short supply due to a sharp reduction in the number of livestock. All this necessitates the search of additional ways to enrich the soil with nutrients. The use of biological ameliorants is directly related to organic farming, since it allows obtaining environmentally friendly agricultural products without the use of industrial fertilisers [23]. Biological ameliorants play an important role in alternative agriculture, as they positively affect the agrophysical properties of the soil and its biological activity, increasing the amount of organic matter and reducing the clogging of plantings. First of all, to avoid undesirable consequences, it is necessary to take measures to improve the soil before planting potatoes, then it will be possible to obtain a good harvest [24]. Over the past years (from 2000 to 2017), significant efforts of researchers have been directed to the study of new types of organomineral fertilisers based on local agricultural ores; environmental assessment and development of optimal doses of lime-containing industrial waste; combination of chemical and biological reclamation in vegetable and potato specialised crop rotations; adaptation of product quality, mineral nutrition and soil fertility to changing soil and climatic conditions [25]. In the experience of the Research Institute of Potato Farming (2000-2005), a high agroecological efficiency of average doses of new types of organomineral fertilisers ("Fermersky", based on brown coal and vermicompost, biohumus based on bird droppings) was established in comparison with conventional mineral fertilisers. The beneficial effect of these organomineral fertilisers on soil fertility indicators and the increase in crop yield of vegetable and potato crop rotation was more noticeable and prolonged.

Most researchers call the presence of residual amounts of chemical pesticides and nitrates in tubers the main factor that worsens the ecological quality of food potatoes. Many serious diseases occur in the population due to an excess of toxic, harmful substances in crop production, including potatoes [18]. Prolonged, cumulative intake of increased amounts of pesticides and nitrates into the human body with food gradually destroys people's health, causing serious diseases, including carcinogenic ones. Once in the bloodstream, harmful substances affect the human body in many ways, non-specifically, with various consequences up to its generative properties. At the same time, various diseases that appear are recognised with difficulty. Among the categories of the population, children and adults exposed to chronic diseases have the greatest vulnerability to increased concentrations of harmful substances in crop production. It is necessary to take urgent measures to supply environmentally friendly food for children, as the steadily deteriorating health of the younger generation may affect the national security of the country. Potatoes for baby food should be environmentally friendly, should be completely free of chemical pesticides, and the nitrate content should not exceed 3 mg%. Nitrates pose a significant danger to human and animal health. In the gastrointestinal tract of warm-blooded animals and humans, nitrites are produced from nitrates by some intestinal bacteria. Nitrites (NO_2) and secondary amines and nitrosamines are very toxic [25]. They block the haemoglobin of the blood, disrupting its main function, namely, the transfer of oxygen to the cells of the body. With the participation of nitrates in the blood, methaemoglobin is formed instead of haemoglobin, which is especially dangerous for children.

Due to nitrate poisoning, carcinogenic, mutagenic and embryotropic diseases occur in humans and animals. Mineral fertilisers (their nitrogen part) applied under potatoes are the most active factor that increases the accumulation of nitrates in potato tubers. High and unbalanced doses of mineral fertilisers are especially dangerous. Alternative sources of nutrients are needed in agriculture in order to reduce the doses of mineral fertilisers applied to potatoes [21]. The problem with yields has become more complicated due to the conditions of the market economy. To obtain a good quality harvest, it is necessary to improve the properties of the soil to increase its fertility, which depends on the amount of humus and its qualitative characteristics. Nowadays, the main task in agriculture is to find a way to replenish the reserves of organic matter of the soil without any costs. In this regard, biological ameliorants and organic fertilisers are used, and their effect on the soil is investigated, how the indicators of soil fertility change, what kind of potato crop can be obtained with their use. Common disadvantages of existing fertilisers are a high density of the substrate with an insignificant degree of porosity, an increased content of leached formaldehyde, low moisture capacity and sorption capacity to toxicants, low biostimulation; lack of information about the effect of urea-formaldehyde foam on the intake of heavy metals into plants and, in general, on product quality. The issues of biologisation of the processes of soil fertility increase with the use of high-molecular polymers through the directed use of the positive properties of the plant itself have not been studied.

Tuberous potatoes (Solanum tuberosum L.) are the world's most important food, fodder, and technical crop. It accounts for more than 10% of the global potato volume, but the average yield of this crop in the Russian Federation remains one of the lowest [6]. The main reasons include the poor quality of planting material, significant losses during the growing season as a result of damage by numerous pests and diseases, and due to infestation of plantings. A significant contribution to the reduction of potential yield is made by the consequences of abiotic stresses: droughts, unfavourable physical and agrochemical properties of soils, unbalanced mineral nutrition. The most important features of this crop include increased requirements for nutrition elements, especially potassium, and

a long period of nutrition, with a maximum of nitrogen and phosphorus entering the plants before flowering, and the intake of potassium continues until the full physiological maturity of the tubers. Potassium stimulates the synthesis of sugars and high-molecular carbohydrates such as starch, cellulose, pectin substances, xylans, both in potato leaves and tubers. Potatoes are responsive to the application of fertilisers, primarily potash. The main type of potash fertiliser used in agriculture is potassium chloride. However, it is undesirable for potatoes to use fertilisers containing chlorine, since carbohydrate metabolism is disrupted during crop development [23]. Therefore, it is necessary to expand the range of potash fertilisers of other forms.

4. CONCLUSIONS

The main task in agriculture is to find a way to replenish the reserves of organic matter of the soil without any costs. In this regard, biological ameliorants and organic fertilisers are used, and their effect on the soil is investigated, how the indicators of soil fertility change, what kind of potato crop can be obtained with their use. The introduction of the studied biochar, azophoska and their combinations under potatoes, and under barley, increased soil moisture during the growing season on average by 1.2 times. The demand of this crop for water is greater than that of cereals, and biochar contributed to maintaining moisture in the soil during the growing season in comparison with soil without biochar. Thus, biochar has had a positive impact on soil indicators, growth and development of the studied cereals and row crops, however, additional long-term studies are required to recommend the comprehensive use of this product in agriculture.

Organic fertilisers, including manure, are now in short supply due to a sharp reduction in the number of livestock. All this necessitates the search of additional ways to enrich the soil with nutrients. The use of biological ameliorants is directly related to organic farming, since it allows obtaining environmentally-friendly agricultural products without the use of industrial fertilisers. It has been established that biochar, as a soil ameliorant, can contribute to improving the quality and cultivation of soils, reducing acidity, reducing greenhouse gas emissions (CO2, N2O, CH4), and also affecting crop yields. In modern natural conditions of the main potato cultivation zones, the successful development of the potato growing industry requires an accurate analysis of soil and climatic conditions and the duration of the growing season, the selection of the most yielding varieties, the selection of well-cultivated fields for specialised potato crop rotations, including seeded fallows, the introduction of balanced doses of mineral fertilisers, foliar spraying during the growing season with trace elements, growth regulators, and anti-stress drugs.

The limitation of this study is that the use of biological ameliorants was investigated only to improve the condition of the soil and increase the yield of potatoes. Therefore, the direction of future research is the study of biological meliorants to increase the yield of other agricultural crops.

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