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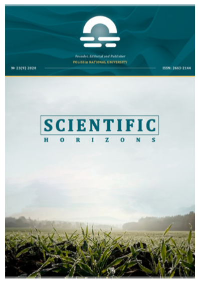

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INFLUENCE OF CARBONISED BIOMASS ON SOIL IMPROVEMENT, INCREASE IN YIELD OF AGRICULTURAL CROPS AND MITIGATION OF CLIMATE CHANGE IMPLICATIONS

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Abstract. The relevance of the study is conditioned by the need to develop and implement new technological solutions for tillage, which will improve the soil properties. The purpose of this study is to assess the impact of carbonised biomass on the properties and quality of soils, as well as the associated environmental consequences. The tasks addressed by the study were solved with the help of scientific theoretical methods: analysis, systematisation and generalisation of results. The scientific works related to the problem of the influence of carbonised biomass on soil quality were analysed in this paper. An assessment of the effectiveness of its use as an organic ameliorant and its effect on improving the agronomic properties of soils, their fertility, and on the ecological situation has been carried out. It is substantiated that the use of obsolete agricultural technologies during agricultural activities and their violation have a negative impact on soil fertility and increase in greenhouse gases in the atmosphere. It is argued that this could lead to a global food crisis. It has been emphasised that due to the use of biochar as an organic ameliorant the physical and microbiological properties of soils are improved, the availability of nutrients is optimised, and the content of toxic elements is reduced. It is shown that carbonised biomass has a positive effect on yields and also helps to reduce greenhouse gas emissions into the atmosphere. The main current problems that exist in Ukraine regarding the use of soil improvement technology with the help of carbonised biomass are identified. The ways of their solution for the further development of these technologies and their implementation in the agro-industrial sector are proposed. The practical value of the study consists in determining the effectiveness of using carbonised biomass when it is introduced into the soil to improve its quality, increase crop yields, and slow down climate change

Keywords: slow pyrolysis, biochar, hydrochar, organic ameliorant

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INTRODUCTION

Climate change on our planet is associated with an increase in the concentration of greenhouse gases (GHGs) in the atmosphere caused by human activities. Agricultural activities (tillage, application of ameliorants, mineral and organic fertilisers, plowing of crop residues) significantly increase GHG emissions from soils. The main GHG coming from soils is carbon dioxide CO_2, it is formed as a result of decomposition of organic matter, as well as during the combustion of biomass. According to the Food and Agriculture Organisation of the United Nations (FAO) [1], 0.2 billion tonnes of CO_2 are released into the atmosphere each year due to biomass combustion, which is 4% of all greenhouse gas emissions in the agricultural sector. The second greenhouse gas is nitric oxide N_2O, its global warming potential exceeds that of CO_2 by 310 times. According to various estimates, agricultural soils account for 40 to 60% of the total amount of N_2O that enters the atmosphere of the planet from all existing sources.

Climate change negatively affects soils, and this poses a threat to global food security. To strengthen the global food security agenda and combat climate change, agriculture and land use practices that increase soil organic carbon need to be improved and updated.

In the report "The State of the World's Soil Resources" (drawn up by the FAO Intergovernmental Group of Experts and timed to coincide with World Soil Day (04.12.2015, Rome) [2]) it is noted that soils are extremely important for crop production. It has also been shown that as primary carbon storage, soils help regulate carbon dioxide and other greenhouse gas emissions and are therefore a key component of climate regulation. Although, "33% of the world's soil resources are in satisfactory, poor, or very poor condition". It is reported that 28% of the world's chernozemic soils and a third of all arable land in Europe are concentrated in Ukraine. Active exploitation of agricultural land with violations of agricultural technologies, the impact of climate change, etc. leads to a rapid decline in soil quality and increase in greenhouse gas emissions. Due to various reasons, the development of national approaches to combating land degradation has been slowed down. As of 2020, Ukraine has approved the "Action Plan for the implementation of the Concept for the implementation of state policy in the field of climate change until 2030" in 2017 [4], adopted the "Low Carbon Development Strategy until 2050", began working on legislation to monitor greenhouse gas emissions [5]. Therefore, the introduction of innovative tillage technologies should ensure resilience to climate change and maintain a favourable microbiological and physical condition of soils. Therefore, it is necessary to look for new technological solutions in this direction. Development and implementation of tillage technologies by adding carbonised biomass (other names depending on the production technology: a) biochar, or biocoal are obtained by slow pyrolysis in a certain temperature range; b) hydrochar (by the method of hydrothermal carbonisation); can be one of the options of innovative tillage technologies. To do this, first of all it is necessary: to determine the effect of biochar on the properties and composition of soil; to determine its impact on greenhouse gas emissions; to identify factors that affect the composition and properties of this product and its dependence on source components and pyrolysis conditions.

In recent years, a large number of scientific publications have been published, which cover these issues. Thus, the change in the chemical and hydrophysical properties of the soil due to the introduction of carbonised biomass was investigated by A.Ye. Ajay, R. Horn [6]. Factors that affect the composition and properties of this product are listed in the work of A.Yu. Krylova, EG Gorlov and A.V. Shumovskii [7], and the properties of carbonised biomass obtained by pyrolysis are disclosed in the work of N.P. Buchkina, E.V. Balashov, V. Szymanski, D. Igaz, J. Horak [8]. The dependence of the yield of biochar on the initial components and conditions of pyrolysis is mentioned in the work of Z. Tan, C.S.K. Lin, X. Ji & T.J. Rainey [9]. Physico-chemical properties of biochar obtained from different types of vegetable raw materials, studied by Ch. Liu, W. Nyu, H. Chu, T. Zhou, Ch. Nyu [10]. H.V. Smirnova, K.G. Giniyatullin, A.A. Valeeva, & E.S Vaganova [11], show the dependence of the elemental composition of the biochar on the content of the original biomass and the final pyrolysis temperature. The influence of dosages and fractions of biochar on the properties and physical state of soils was studied by I.O. Dubrovina, M.G. Yurkevich, V.A. Sidorova and T.V. Bogdanova [12; 13]. The effect of improving additives based on biochar and a complex of microorganisms on reducing the transition of the radioactive isotope cesium into plants, on their growth and development was studied by I. Cheshyk, O. Nikitin [14]. Assessment of the impact of biochar on the microbiological parameters of the soil was made by L.M. Sungatullina, S.A. Zabelkin, R.R. Shagidullin [15], and G. Blanco-Kanki [16] investigated the effect of biochar on soil porosity. S. Garbuz, M. Camps-Arbestein, A. McKay, B. De Vantier, M. Minor [17] conducted a study of the interaction of biochar in acidic soils with some soil fauna, namely earthworms.

The *purpose* of this study is to assess the impact of carbonised biomass on changes in the properties and quality of soils, their productivity, sustainability, and yield, as well as on the associated environmental changes.

To achieve this goal, based on the studies by scientists from different countries, the following tasks were set: to investigate changes in physical and microbiological properties of soils after the introduction of carbonised biomass; to determine the main factors influencing the composition and properties of this product;

to find out the physico-chemical properties of biochar and the dependence of their output from the initial components and the technological conditions for their production; as well as to consider the ecological and agricultural effect of their introduction into the soil.

MATERIALS AND METHODS

The theoretical and methodological basis of this paper were fundamental and applied studies on carbonised biomass efficiency (biochar, biocoal, and hydrochar as an organic ameliorant, their impact on improvement of physico-chemical and biological properties of soils, their productivity and stability, as well as reduction of greenhouse gas emissions into the atmosphere.

The solution of the tasks addressed by the study was carried out using a number of well-known scientific theoretical methods: analysis, systematisation and generalisation of results. To study this issue, the works of scientists from different countries were studied and analysed, which consider:

— technologies for obtaining carbonised biomass;

— factors that affect the composition and properties of carbonised biomass;

— the problem of global warming and the greenhouse effect due to greenhouse gas emissions, and the preconditions for their emergence as a result of human anthropogenic activities;

— the use of carbonised biomass as an organic ameliorant;

— ways to improve and restore soils by adding carbonated biomass, its impact on improving the physico-chemical and biological properties of soils, their stability and yield;

— ecological aspects of introduction of organic and inorganic fertilisers into the soil;

— issues of optimising the availability of nutrients for agricultural plants through the use of carbonised biomass, reducing the content of toxic elements in the soil;

— aspects of reducing greenhouse gas emissions into the atmosphere as a result of the introduction of carbonised biomass into the soil;

— the need to introduce innovative tillage technologies.

The most relevant studies from the standpoint of the efficient use of carbonised biomass as one of methods of increasing productivity and sustainability of soils and influence of its use on ecology were selected from the received material. These works formed the information base of this study. The analysis was used to process the obtained information on the impact of carbonised biomass on individual properties of soils, which considered the scientific and practical achievements of specialists in this field and summarised these results.

For this purpose, by comparing the results with a sample of studies in which this problem occurred, an assessment was made of the effectiveness of using carbonised biomass as an organic ameliorant, and its effect on improving the agronomic properties of soils, their fertility, as well as the impact on the ecological situation. The criteria were various qualitative and quantitative characteristics, such as: alkalinity, density, water-physical and physico-chemical properties, mineral content, biological activity, plant growth and development, as well as emissions of carbon dioxide and other greenhouse gases. Based on the findings, conclusions were made on the impact of carbonised biomass on the improvement of physical and microbiological properties of soils and crop yields and reduction of greenhouse gas emissions into the atmosphere.

RESULTS AND DISCUSSION

Technologies for production of carbonised biomass and analysis of factors influencing its composition and properties

The study considers the impact of carbonised biomass on improvement of soil and ecology. Notably, only raw materials of plant origin are considered for its production: utilised agricultural waste; organic crop waste; waste from the forest and woodworking industry.

Biomass processing can be performed with dry or wet biomass, the moisture content of which is crucial to determine the best process for this raw material. Depending on this factor, a distinction is made between:

- biochar and biocoal – obtained by slow pyrolysis at different temperatures (biochar is a by-product of synthesis gas production);
- hydrochar – obtained in the process of hydrothermal carbonisation.

According to [8], biochar can also be obtained by rapid pyrolysis, but in this case it is only a by-product in the production of electricity and heat. Slow pyrolysis is the most effective technology for the conversion of raw materials into carbonised biomass [7]. The carbonised biomass obtained by this technology at temperatures from 450 to 600 ^{0}C has a higher reclamation effect than its analogues, which are formed as a result of high-temperature slow pyrolysis (at temperatures above 600 ^{0}C – biocoal) and rapid pyrolysis [8]. It is a product with a high content of stable polyaromatic hydrocarbons, low density of composition and high adsorption capacity, which can be used for application into the soil to improve its chemical, physico-chemical, biological and hydrophysical properties. Any carbonised biomass is suitable for reducing greenhouse gas emissions, regardless of the technology of its production. Depending on the initial components and pyrolysis conditions, the yield of the biochar usually varies within 20-70% of the initial weight [9]. Slow pyrolysis is characterised by a low heating rate of 0.1-1 K/s [7], relatively low temperature and long residence time (from hours to days) in an environment with limited oxygen content. Pyrolysis of biomass at higher temperatures is aimed at obtaining bio-oil [18] and synthetic gas.

The study [19] shows that the biochar obtained during pyrolysis has different characteristics. Its composition and properties are influenced by many factors, such as: the nature of the raw material; the chemical composition of the raw material (the higher the lignin content in the raw material, the higher the yield of biochar); particle size of raw materials and its initial humidity; technological conditions: process temperature and heating rate, duration of stay of raw materials at a certain temperature; final heating temperature; speed of gas flow circulation through a layer of raw materials, etc. [7; 10; 11]. The dependence of biochar composition on pyrolysis conditions is mentioned in [20], where the authors show that the product produced under various technological conditions, obtained in the pyrolysis process, will differ in physical and mechanical composition, namely: in porosity, bulk density, strength, hygroscopicity and moisture absorption; elemental composition; ash content; aromaticity, acidity pH, etc. Together, these indicators have a different effect on the bulk density of the soil, its water-physical and physicochemical properties, the content of mineral substances, biological activity and on the growth and development of plants [8]. The ash content depends on the composition of the raw material; in the biochar from straw and husk, the ash content is higher than in the biochar obtained from wood. In addition, the size of pores (macro-, meso- and micropores) and their distribution in the biochar depend on the initial biomass.

The impact of the use of carbonised biomass on soil improvement

Biochar changes the physical, chemical and hydrophysical properties of soils due to direct and indirect effect on them [6; 11]. The study [21] on the effect of biochar on soil hydrology concluded that the direct effect changes the filtration capacity of the soil and the moisture supply available to plants. A study [12] showed that the indirect effect of biochar is associated with changes in the microaggregate and structural composition of soil. The efficiency of biochar enrichment is regulated by the size of the applied biochar and the particle size distribution of the soil [13]. All this affects the availability of nutrients and leaching of solutes; the activity of soil fauna; the course of microbiological processes, in particular those that promote the generation of greenhouse gases such as CO_2, N_2O and CH_4.

The paper [22] shows that biochar promotes plant growth, increases crop yields and reduces the amount of pollutants. Due to the neutral or alkaline acidity, biochar is able to increase the pH of acidic soils [12], which helps to optimise the availability of nutrients and their use by plants. It also reduces the content of toxic elements for plant growth such as AL_{3+} and Mn_2. The positive effect of biochar on soils and plant growth is associated with the effect of liming, which is substantiated in [23; 24]. Soils with pH = 5.5 or less reduce plant yields and limit the choice of crops. The study [25] claims that cereals react negatively to acidic soils and the application of biochar to increase soil pH promotes good crop yields. At the same time, the authors note that on soils with a pH of 7.1-8.0, the biochar does not significantly affect yields.

In [14] it is reported that soil-improving additives based on biochar reduce the bioavailability of Cs-137 and its transition to the aboveground mass of plants, while also having a positive effect on plant growth and development. In addition, the introduction of biocoal contributes to an increase in gross nitrogen in the soil [15].

The most important property of the biochar is the porous structure, as it provides a great potential for colonisation by soil microorganisms appropriate in pore size. Biochar has a porosity of 70 to 90% [16]. In [26], it is shown that due to its fine-porous structure, the biochar helps to improve soil quality: it increases the availability of nutrients and moisture, as well as binds carbon. The [27] shows that the presence of micro- and mesopores in the biochar causes its high inner surface, which plays an important role in chemical reactions, and macropores promote access of adsorbents to the inner surface of the biochar. The porous space of the biochar obtained by slow pyrolysis is covered with resins that do not burn during slow pyrolysis, but harden, covering a thin layer of pores that serve as a refuge for some microorganisms. Their activity is expressed in the increase of CO_2 emissions due to increased decomposition of organic matter and is associated with the release of nutrients, which is an important factor that affects soil fertility and yield. In addition, resins have a high ability to ion exchange, i.e., ions of the useful substance can easily join them and be assimilated by plant roots or hyphae of mycorrhizal fungi, which increases crop yields. In addition, the use of biochar can increase the porosity of the soil from 2 to 41% [16].

The interaction of the biochar with the soil fauna has not been studied enough. However, it is well known that its interaction with worms improves the spatial distribution of the soil and the availability of nutrients and creates good productivity potential for acidic soils [17]. This can lead to an increase in plant consumption of inorganic nitrogen, which in turn will improve their yield.

The biochar obtained in the process of hydrothermal carbonisation (hydrochar) is inferior in its properties to the biochar obtained by slow pyrolysis. Comparison of hydrochar with biochar obtained from the same raw material showed that hydrochar is more acidic [28]. High concentrations of hydrochloride can adversely affect plants because it may contain toxic phenolic and aromatic substances. Due to the fact that hydrochars have a much higher calorific value than biochar, more homogeneous and dense structure, lower ash content and CO_2 emissions during combustion, they are more suitable for heat generation and electricity generation.

A number of experiments have shown that biochar in some cases can have not only a positive but also a negative impact on the water properties of the soil and their ability to cause erosion [29]. Furthermore, in some cases there was a negative impact of biochar on the physical, physico-chemical and biological state of soils [8]. These results are explained by insufficient amount of nutrients (nitrogen, phosphorus), suboptimal dose of biochar, and irreversible adsorption of non-aromatic compounds. Aldehydes, phenols adsorbed on the surface of biochar, and polyaromatic carbohydrates generated during the thermal decomposition of ligno-cellulosic raw materials can have toxic effects on plants and microorganisms. Biochar can serve as a sorbent for pesticides and therefore promote weed growth.

There are difficulties in the study of biochars and their effects on different soils due to their different properties depending on the raw materials used, heat treatment, climatic conditions, soil type and many other factors. Therefore, sometimes the results of the introduction of biochar into the soil have an adverse or unpredictable result. The same is shown in [30], which concludes that although biochar can be recommended to improve the structural condition of unstructured soils, the long-term effects of its introduction on soil properties still need to be studied. Therefore, long-term experimental studies are needed to recommend the use of carbonised biomass. But the acquired knowledge about the structure and composition of various biochars, as well as about their interaction with soils allows producing a specific biochar for solving many specific problems.

Influence of the use of carbonised biomass on climate change mitigation

Greenhouse gas emissions from agriculture account for 13% and are mainly caused by three gases: carbon dioxide (CO_2), nitrous dioxide (N_2O), methane (CH_4) [31].

One of the many methods to mitigate the effects of greenhouse gas emissions is waste management technology (conversion to carbonised biomass), fertiliser management and restoration of degraded land, in particular through the use of carbonised biomass.

The study [32] suggests that the introduction of carbonised biomass into the soil helps to reduce greenhouse gas emissions. Confirmation of this can be found in [33], where the authors note that when introduced into the soil, it mineralises much more slowly than the original biomass. It provides long-term sequestration of the main greenhouse gas CO_2 (released from agricultural soils by microbiological decomposition of plant precipitation and organic matter soil), and can reduce its increasing concentration in the atmosphere, increase CO_2 sequestration by creating stable carbon effluents, as well as mitigate the effects of other greenhouse gas emissions [31]. The introduction of carbonised biomass into the soil can mitigate the effects of carbon emissions by 12% [34].

Another greenhouse gas that enters the atmosphere from soils is nitrous oxide N_2O, which is released mainly by organic and inorganic fertilisers introduced into the soil. Agricultural soils are the main source of N_2O emissions, accounting for 62% of all nitrous oxide emissions of human origin [31].

The lifespan of the N_2O molecule in the atmosphere is 150 years. Most agricultural soils emit N_2O in the amount of 1.5% of the applied nitrogen, reducing its use reduces N_2O emissions. Only half of the nitrogen input is captured by crop biomass, the rest is lost to the system by leaching and gaseous losses. Therefore, any method that strengthens the links between soil nitrogen release and growing crops improves fertilisation efficiency and reduces the need for exogenous nitrogen while reducing N_2O emissions. Numerous field and laboratory studies of carbonised biomass have shown that it has a positive effect on reducing N_2O emissions from soils [35]. Its introduction into the soil improves the water and air regimes of the soil and reduces its high density. This results in a large number of pores with low oxygen content, which helps to reduce the denitrification process. Changing soil pH increases the overall diversity of soil biota and its efficiency. The reduction of N_2O emission from the soil by 50-80% was experimentally confirmed [36] after the introduction of biochar. Furthermore, the reason for the decrease in nitrogen emissions from the soil may be due to the increased intensity of plant growth. The carbon contained in biochar and fertilisers promotes increased nitrogen uptake by plants, which reduces the available mineral nitrogen for the generation of N_2O

The third greenhouse gas coming from the agricultural sector is methane CH_4. In terms of heat retention in the atmosphere, its effect is 21 times stronger than CO_2. Sources of methane emissions are: cattle (intestinal fermentation, manure management); rice cultivation (methane release occurs as a result of anaerobic decomposition of rice in flooded rice fields); recommended burning of shrouds; burning of agricultural residues [31]. Thus, agricultural soils are both a source and a runoff for CO_2 in the atmosphere. It has been experimentally proven that biocoal increases the level of carbon in the soil [37]. Of paramount importance is the influence of carbonised biomass on the stabilisation or conversion of stable carbon in the soil [38].

Improving the cultivation of arable land can lead to the accumulation of carbon in the soil. Improving the physical and chemical condition of the soil will change the balance between N_2O and non-greenhouse N. CH_4 emissions in the agricultural sector can be reduced by converting agricultural residues into carbonised biomass instead of direct combustion.

Today, in Ukraine and in the world, there is no comprehensive soil improvement programme with biochar. Its use in the fight against greenhouse gases is mainly experimental, not widely used and is at various stages of development. Given that this is a relatively new approach, it is necessary to inform farmers and energy producers about the sequestration of biochar and its positive impact on soil characteristics. Inexpensive pyrolysers available to farmers need to be developed and their production expanded. Studies have shown that pyrolysis can be cost-effective by combining sequestration and energy production when the cost of a tonne of CO_2 reaches USD 37 [39]. Binding of carbon and mitigation of greenhouse gas emissions allows taking advantage of quotas on carbon emissions in the quota market. Carbon credits sold by carbon sequestration in the biochar are economically competitive when prices reach USD 58/ t CO_2-eq [40].

Efforts must be made to make the use of biochar a sustainable carbon sequestration procedure that will ensure higher unrealised carbon emissions. Further dissemination of this technology depends to a large extent on the progress of global negotiations on climate change in terms of financing climate-safe technologies.

CONCLUSIONS

1. Based on the study of the impact of carbonised biomass as an organic ameliorant on soil improvement, increase in its productivity, stability, yield, as well as the associated reduction of greenhouse gas emissions into the atmosphere, it was found:

- carbonised biomass obtained by slow pyrolysis has a higher reclamation effect than its analogues obtained by high-temperature slow pyrolysis and rapid pyrolysis;
- introduction of carbonised biomass into the soil has a positive effect on the physical, physico-chemical and biological condition of soils, which provides high crop yields, as well as water properties of the soil. However, under certain conditions, the result can be zero or even negative;
- any carbonised biomass is suitable for reducing greenhouse gas emissions, regardless of the technology of its production;
- due to the use of carbonised biomass, the content of toxic elements in the soil can be reduced.

2. The findings suggest that the technology of increasing productivity and stability of soils through the use of carbonised biomass is promising for development, both in Ukraine and globally. However, due to the fact that this trend is relatively new today, it has not gained wide popularity. Therefore, it is necessary to conduct further research, which will allow developing mechanisms to address the problem of using biochar as an organic ameliorant. For this purpose, it is necessary to inform farmers and energy producers about the sequestration of biochar and its positive impact on soil characteristics, to develop pyrolysers and promote the expansion of their production.

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ВПЛИВ КАРБОНІЗОВАНОЇ БІОМАСИ НА ПОКРАЩЕННЯ ҐРУНТІВ, ПІДВИЩЕННЯ ВРОЖАЙНОСТІ СІЛЬГОСПКУЛЬТУР І ПОМ'ЯКШЕННЯ НАСЛІДКІВ ЗМІНИ КЛІМАТУ

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Анотація. Актуальність дослідження обумовлена необхідністю розробки та впровадження нових технологічних рішень щодо обробки ґрунтів, які сприятимуть поліпшенню їх властивостей. Мета даної роботи – розглянути вплив карбонізованої біомаси на властивості та якості ґрунтів, а також на пов'язані з цим екологічні наслідки. Рішення поставлених у статті завдань здійснювалося за допомогою наукових теоретичних методів: аналіз, систематизація та узагальнення результатів. У роботі проаналізовано наукові праці, що стосуються проблеми впливу карбонізованої біомаси на якості ґрунтів. Проведена оцінка ефективності її використання в якості органічного меліоранту, та її впливу на поліпшення агрономічних властивостей ґрунтів, їх родючість, і на екологічну ситуацію. Обґрунтовано, що використання застарілих аграрних технологій під час проведення сільськогосподарських заходів та їх порушення в процесі експлуатації має негативний вплив на родючість ґрунтів і збільшення парникових газів в атмосфері. Аргументовано, що це може привести до глобальної продовольчої кризи. Підкреслено, що завдяки застосуванню біочару як органічного меліоранту поліпшуються фізичні та мікробіологічні властивості ґрунтів, відбувається оптимізація доступності поживних речовин і знижується вміст токсичних елементів. Показано, що карбонізована біомаса позитивно впливає на врожайність, а також сприяє зменшенню викидів парникових газів в атмосферу. Визначено основні сучасні проблеми, які існують в Україні щодо використання технології покращення ґрунту за допомогою карбонізованої біомаси. Запропоновано шляхи їх вирішення для подальшого розвитку цих технологій і впровадження їх в агропромисловому секторі. Практична цінність наукової роботи полягає в визначенні ефективності використання карбонізованої біомаси при внесенні її у ґрунті для покращені їх якості, збільшення врожайності сільськогосподарських культур, та уповільненні змін клімату

Ключові слова: повільний піроліз, біочар, гідрочар, органічний меліорант