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DOI:
10.3390/en16093945

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Perspective

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Abstract: One of the greatest challenges humankind currently faces is global warming, mainly caused by greenhouse gas emissions. Here we have attempted to show how thermal conversion products, specifically from the pyrolysis of biomass wastes such as sewage sludge, can be used effectively and equivalently to sequester CO_2 in brownfield and degraded areas. Scenarios were devised that showed the significant potential for CO_2 sequestration in the form of biochar from sewage sludge deposited on degraded and brownfield areas. With the current amount of sludge production, such sludge could even be used in its entirety as a raw material in pyrolysis processes, where, in addition to the biochar, the heat necessary for drying the sludge could be generated and high-energy gas and liquid fractions could be obtained, which could be used to produce alternative fuels. It is therefore important to consider both the potential for CO_2 sequestration on degraded and brownfield sites and the potential for sludge disposal in Europe as viable options for reducing greenhouse gas emissions and promoting sustainable waste management practices.

Keywords: sewage sludge; char; CO_2 sequestration; degraded sites; brownfield sites

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Citation: Sajdak, M.; Zajemska, M.; Ouadi, M.; Mucha, W.; Misztal, E.; Pieszko, C.; Gałko, G. Perspectives of Using Sewage Sludge Char in CO_2 Sequestration on Degraded and Brownfield Sites. *Energies* **2023**, *16*, 3945. https://doi.org/10.3390/en16093945

Academic Editor: João Fernando Pereira Gomes

Received: 14 April 2023
Revised: 3 May 2023
Accepted: 5 May 2023
Published: 8 May 2023

1. Introduction

The Industrial Revolution and subsequent development, marked by the proliferation of industrialization and urbanization, have undeniably yielded numerous advantages to the populace, contributing to the advancement of civilization. The expansion observed in recent times has been accompanied by the significant influence of human activities on natural surroundings, potentially leading to severe and enduring repercussions for the Earth. The advent of industrialization during the 18th century and its expansion in the following centuries resulted in numerous technological and scientific breakthroughs. The industrial sector facilitated the advent of mass production and emerged as a pivotal constituent of the worldwide economy; however, industry exerted a considerable influence on its natural surroundings. The emission of pollutants from heavy industry has resulted in adverse effects on the quality of the air, soil, and water [1–4]. These effects are persistent and will have long-lasting consequences. To mitigate the negative impact of industrialization, various measures have been implemented, such as the development of cleaner technologies and stricter regulations. It is crucial to continue exploring sustainable practices that balance economic growth with environmental protection to ensure a healthy planet for future generations.

As technology has progressed, further knowledge has been gained about the harmful effects of industry on the environment. There has been greater realization of the consequences of human activities on the planet and increasing attempts to reduce the negative impact of such activities on the environment. One of the biggest challenges humankind currently faces is global warming, mainly caused by greenhouse gas emissions, but an equally significant challenge is land pollution, which has a significant and negative impact on the loss of natural green areas and causes habitat degradation [5]. Unsustainable industrial development and inadequate waste management lead to land degradation, with consequent loss of biodiversity and increased threats to animal and plant populations. The loss of green areas and natural habitats also has a negative impact on people's quality of life, as it reduces access to recreational spaces and increases the risk of health effects related to lack of contact with nature. To address land pollution, we need to adopt sustainable practices in industrial development and waste management, as well as promote the restoration of degraded areas of land. Such measures will not only help preserve biodiversity and natural habitats but also improve the well-being of communities by providing them with access to green spaces and reducing the risk of health issues associated with urban living.

However, the development of civilization does not have to be associated and linked exclusively with environmental degradation. Some developmental approaches allow for sustainable urbanization and minimal negative impact on the environment. One such approach is ecological urbanism, which involves designing and planning cities in such a way as to minimize their environmental impact and, at the same time, increase energy efficiency and reduce water consumption. Ecological urbanism is based on the concept of a sustainable city that can meet the needs of its inhabitants while minimizing its impact on the environment [6,7]. One measure that could likely meet the criteria of ecological urbanism is the appropriate use of thermal conversion products from biomass and biomass-derived materials, a method that, after some stagnation, is starting to increasingly gain adherents and is expected to be used more widely in the future.

In this article, we have attempted to show how the products of thermal conversion, specifically pyrolysis of biomass waste such as sewage sludge, can be used effectively and in an equivalent way to sequester CO_2 in brownfield and degraded areas. The use of thermal conversion products from biomass and biomass-derived materials not only helps to reduce the carbon footprint of a city but also provides a method of waste management. The implementation of this method in urban areas can contribute to the creation of more sustainable and resilient cities. The application of biochar components for CO_2 capture is an innovative solution which incorporates the novel application of carbonized materials as a component of soil. Biochars are typically used for energy purposes; however, some materials with a huge share of balance (ash and moisture) that cannot be used for this purpose are still valuable as soil additives. Improvement of soil quality and reducing the danger of apparent climate changes are significant issues that motivate current changes.

2. Sources of Soil Contamination

To tackle the issue of soil contamination, the EU has implemented various policies and regulations to ensure proper waste management and reduce pollution. These include the Waste Framework Directive (2008/98/EC), the Landfill Directive (1999/31/EC), and the Industrial Emissions Directive (2010/75/EU). Exposure to these contaminated resources can lead to serious health problems such as cancer, neurological disorders, and developmental delays in children [8,9]. It is important to implement measures to prevent soil contamination and properly dispose of hazardous waste. Soil contamination poses a serious threat to human health. Heavy metals found in industrial waste, among other pollutants, have been linked to the contamination of food, animal feed, and water [1,10,11]. It is therefore important to take action to manage contaminated sites, determine the extent of contamination, and implement measures that meet environmental standards according to current legislation. In general, volume of emission and byproduct formation is correlated with society's enrichment and increasing purchasing power. As a result, the pollution problem in Europe (especially in the Western region) has worsened as the wealth of its population has increased. The European Union (EU) generates three billion metric tons of solid waste each year, of which experts estimate around 90 million metric tons is hazardous waste. This translates to almost six metric tons of waste per person each year (Eurostat, Environmental Data Centre on Waste [12]). Numerous industrial point sources, such as active and inactive mines, foundries, and steel mills, as well as numerous diffuse sources, such as pipelines, landfills, waste incineration, and traffic, are responsible for most heavy metal pollution [2,13,14].

Depending on their properties, different pollutants have different impacts on human health and ecosystems. The impact of a pollutant is proportional to its mobility, fat and water solubility, bioavailability, carcinogenicity, and other properties. For example, pollutants with high mobility can easily spread over large areas, while those with high fat solubility can accumulate in the fatty tissues of living organisms. Understanding the properties of pollutants is crucial for effective pollution management and prevention. Synthetic solvents and pesticides rely heavily on chlorinated hydrocarbons (CHCs). They are bioaccumulative environmental contaminants that have been detected in human tissue. The increased incidence of lymphoma, leukemia, and liver and breast cancer in humans can be attributed to exposure to these chemicals, according to epidemiological studies [15–17]. Therefore, it is essential to regulate the use and disposal of DDT to minimize its adverse effects on human health and the environment. Additionally, promoting the use of safer alternatives and implementing proper waste management practices can help reduce the levels of these pollutants in our surroundings. Partially volatile, chemically stable, and hydrophobic organic molecules called polycyclic aromatic hydrocarbons (PAHs) can be found throughout the environment and serve as useful indicators of environmental pollution from human activities in metropolitan areas [18–20].

A contaminant can be any species of metal (or metalloid) present in an undesirable location or concentration that has an adverse effect on human health or the environment. Lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), copper (Cu), selenium (Se), nickel (Ni), silver (Ag), and zinc (Zn) are metals or metalloids. Aluminum (Al), cesium (Cs), cobalt (Co), manganese (Mn), molybdenum (Mo), strontium (Sr), and uranium (U) are other less common metallic contaminants [21–23]. These contaminants can enter the environment through natural processes, such as the weathering of rocks and volcanic activity, or human activities, such as mining, industrial processes, and the improper disposal of waste. Exposure to these contaminants can lead to a range of health problems, including neurological damage, cancer, and developmental delays [14–16].

Currently, priority should be given to the reduction and elimination of contaminants on the basis of their toxicity, environmental persistence, mobility, and bioaccumulation, as recommended by the World Health Organization [24]. Studies in humans and animals living under high exposure conditions have shown that several heavy metals and persistent organic pollutants, including cadmium (Cd), arsenic (As), chromium (Cr), nickel (Ni), dioxins, and PAHs, are carcinogenic [24–26]. Depending on the dose and length of exposure, many of these chemicals can also be harmful to the neurological system, liver, kidneys, heart, lungs, skin, reproductive organs, and other target sites [17–19]. Therefore, it is crucial to regulate and monitor the levels of these contaminants in air, water, soil, and food to protect public health. Additionally, promoting sustainable practices and reducing the use of hazardous chemicals can prevent further contamination of the environment.

With advances in technology and environmental awareness, pollution sources have begun to be monitored, enabling the creation of databases to track the state of the environment in a given area. Such initiatives include the European Environment Information and Observation Network (EIONET) [27], the European Soil Data Centre (ESDAC) [28], the LUCAS Topsoil Survey of the European Union [29], and the pan-European SOC stock of agricultural soils [30–32]. Using the available data from these databases, it was possible to estimate the area of degraded land located in Europe and the European Union. This information is crucial for policymakers to make informed decisions about land use and environmental policies. It also highlights the need for continued monitoring and efforts to reduce pollution and protect the environment.

3. Degraded and Brownfield Sites in Europe

The large number of brownfield sites in Europe highlights the need for further investigation and remediation of these potentially contaminated sites to ensure the protection of human health and the environment. It also emphasizes the importance of implementing effective soil management practices to prevent future contamination. Based on the available data from the previously mentioned databases and the literature, it is possible to estimate that approximately 170,000 potentially contaminated sites have been identified in Europe and the European Union, i.e., sites where unacceptable soil contamination is suspected but not verified by detailed investigations. Approximately 10% of the above-defined sites, i.e., about 127,000, have been defined as contaminated sites [33], i.e., sites with a confirmed presence of soil contamination, which pose a potential risk to humans, water, ecosystems, or other receptors. According to literature reports [33], the areas that exceeded the threshold for at least one element (heavy metal) totaled 1,091,013 km^2; at least two elements totaled 95,372 km^2; at least three elements totaled 27,036 km^2; and at least four elements totaled 6205 km^2. Therefore, it is imperative to conduct further investigations and assessments to determine the extent of contamination in these areas and prioritize remediation efforts based on the level of risk posed to human health and the environment. Additionally, it is essential to establish effective monitoring systems to prevent future contamination and ensure the sustainability of natural resources.

Despite data from European institutions, estimating the total amount of degraded and brownfield land in Europe remains a difficult challenge. According to a 2019 study by the European Environment Agency [34], degraded land covers approximately 45,000 km^2 of Europe and the European Union. This difficulty is due to the lack of a common definition of and methodology for identifying and assessing degraded and brownfield land. Nevertheless, addressing this issue is crucial for promoting sustainable land use and achieving environmental goals in Europe. In the abovementioned study, land degradation was defined as the deterioration of soil, water, or ecosystem quality caused by either human activities or natural disasters. In contrast, according to the European Commission's 2020 report on sustainable transformation and recovery, it was estimated that brownfield sites cover about 25,000 km^2 across Europe [34–37]. The report also highlighted the importance of reusing brownfield sites to prevent urban sprawl and protect natural habitats. Therefore, a common approach for identifying and assessing degraded and brownfield land is necessary to ensure sustainable land use and achieve environmental objectives in Europe.

Brownfield land comprises areas that were once used for industrial purposes but are currently undeveloped due to pollution and safety concerns. Due to the omission of brownfield and decaying regions in non-EU countries and in some parts of the EU where reliable data are limited, these data may be underestimated. During the literature review, estimated quantitative data on brownfield sites were collated, which are summarized in the map below (Figure 1) [35–37]. These figures agree with the information contained in the European Commission's 2020 report, which, as previously mentioned, estimated that brownfield sites cover around 25,000 km^2 across Europe [34].

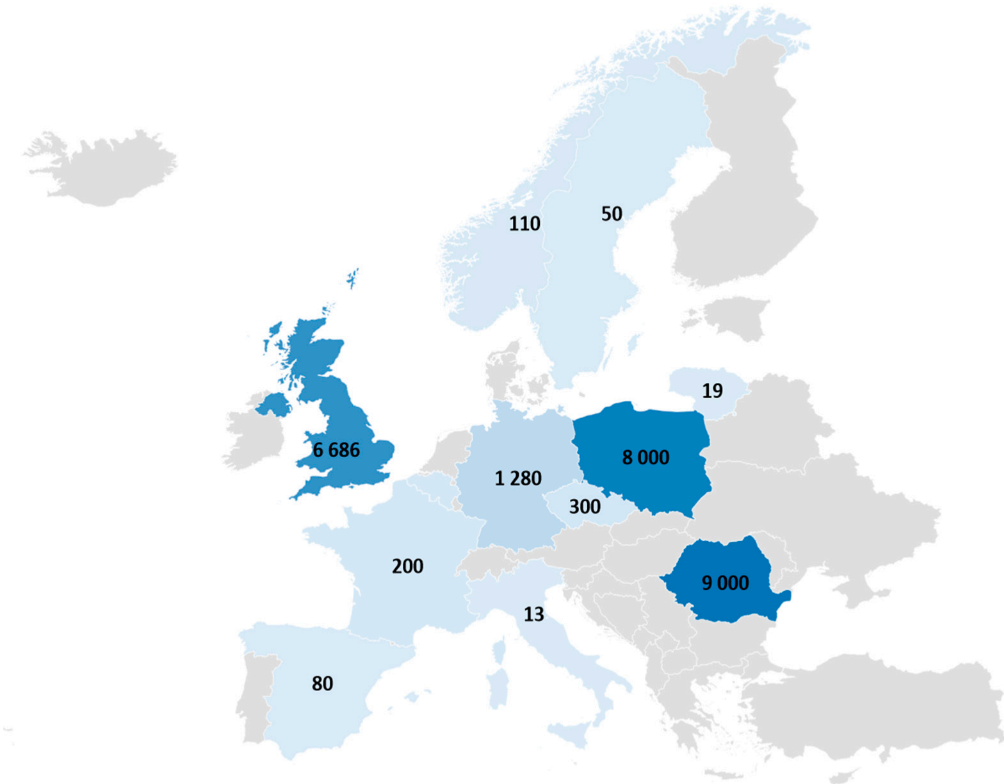

Figure 1. Map of Europe with the area of brownfield sites in km^2 according to the available literature [35–37] (gray—no data available).

4. The Prospect of Using Biomass Waste in CO_2 Sequestration on Degraded and Brownfield Sites

The possibility of using biochar derived from biomass and biomass-derived materials as an excellent additive to soils, especially those that are barren, eroded, or have a low organic carbon content, has been recognized for many years. Biochars can be obtained from different kinds of biomass materials, and its quality and milling degree determines its further transformation during the pyrolysis process. Some biochars, such as hazardous sludge, are specific and require the application of additional protection tools. Unfortunately, not all biochars can be widely used, mainly due to their physicochemical characteristics and the legal regulations regarding the volume of heavy metals that can be introduced into soil through fertilizers, which have been discussed in previous studies [34]. Therefore, there is a need to further explore and develop suitable biochars that can be used as soil additives without negatively impacting the environment or human health. This can be achieved by identifying and optimizing the most promising candidates for widespread use in agriculture through extensive research and development.

In addition, the possibility for subsequent use of biomass biochar is influenced by the technology by which it is obtained. For example, rapid pyrolysis of biomass, which is optimized to maximize the number of hydrocarbon products in the form of bio-oil, produces biochar with a low pH [38], which may limit its direct use as a soil additive, particularly in the case of acidic soils. At the same time, however, it should be noted that the low pH of biochar can be an important factor for the immobilization of metals such as copper (Cu) [39]. Therefore, it is important to consider the specific soil conditions and the intended use of biomass biochar when selecting the most suitable technology for its production. Additionally, further research is needed to determine the long-term effects of using biochar as a soil amendment on crop yields and soil health.

Another important aspect of biomass biochars is their adsorption properties for pollutants such as PAHs [40,41]. In their study, they showed a high biochar-soil sorption efficiency for phenanthrene of more than 99.0% for biochar obtained at 300 and 400 °C, with a biochar-soil content of 5.0%. However, it should be remembered that PAHs are also produced during pyrolysis and thus are present in the produced biochar. Studies [42] have found that biochars produced at temperatures above 700 °C have higher PAH content, making them dangerous due to their carcinogenic and mutagenic properties. Biochars obtained at lower temperatures of 350–600 °C are characterized by significantly lower PAH content [43]. In addition, it is important to note that the presence of PAHs in biochar can also affect its effectiveness as a soil amendment, as PAHs can negatively impact soil microbial activity and nutrient cycling. Therefore, it is crucial to carefully consider the production methods and quality of biochar before using it for agricultural purposes. In the future, care must be taken to ensure that biochar that is produced as a soil and crop improvement material and will come into contact with food is specifically produced at low temperatures [43].

Such relatively low-temperature conditions may not always be achievable. Such an example is the thermal treatment of sewage sludge that already contains a high PAH content in its composition, which disqualifies its wider use. However, by processing such sludge using pyrolysis methods at temperatures as high as 700–800 °C, it is possible to remove PAHs very effectively with an efficiency of up to almost 100% [44]. The processing of sewage sludge by thermal conversion methods with the subsequent possibility of using the resulting biochar for CO_2 sequestration becomes particularly important in the context of annual sludge production in Europe. Therefore, pyrolysis methods can be viable processes for the treatment of sewage sludge and can lead to the production of a useful product. Additionally, this method can contribute to reducing the carbon footprint of wastewater treatment plants by sequestering CO_2 in the resulting biochar.

According to EUROSTAT (sewage sludge production and disposal) data [44], sludge production in Europe varies quite considerably from country to country. In 2018, Germany produced the highest amount of sludge, approximately 1.7 million metric tons, and France produced approximately 1.2 million metric tons. The total amount of sludge produced in Europe in 2018 was approximately 6.4 million metric tons. Below (Figure 2) are the current uses of sewage sludge according to EUROSTAT data [44]. Most sewage sludge is processed by incineration or used in agriculture, but unfortunately, around 520,000 metric tons are still landfilled. This may be due to its high PAH or heavy metal content, which prevents its use, for example, in agriculture. Processing the sludge using pyrolysis methods to produce biochar, which could provide material for CO_2 sequestration in degraded and brownfield areas, is another possibility for solving the problem of its storage.

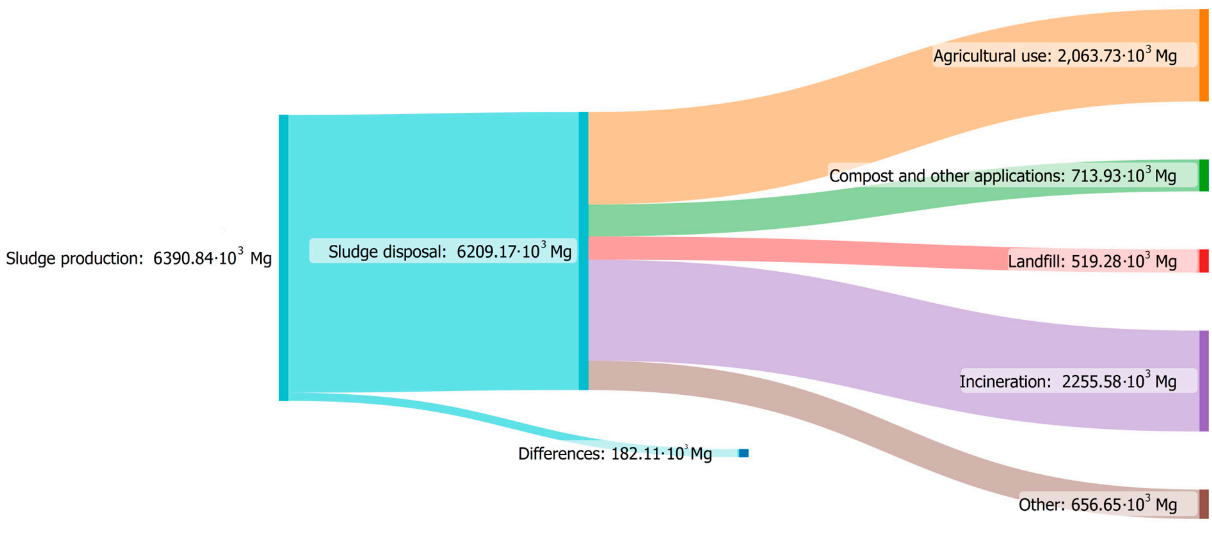

Figure 2. A Sankey diagram of sewage sludge production and management in Europe in 2018 (data from [44]).

To determine in a broader context the amount of biochar that could be used to sequester CO_2 in degraded soils, the overall carbon sequestration potential of soils in Europe, referred to as soil organic carbon (SOC), was checked. According to the available data, the soil carbon sequestration potential in Europe varies between 0.4 and 0.8 t C ha^{-1} yr^{-1} [30].

Considering existing technologies for the thermal conversion of sewage sludge, 125 kg/h of char, 80 kg/h of process water, 30 kg/h of raw bio-oil, and 65 kg/h of gas can be obtained from 300 kg/h of sewage sludge (with a moisture content of approximately 10%) [45]. The biochar obtained, which represents almost 42% of the total sludge mass, has a carbon content of 34.4%, which is equivalent to 1261.3 kg CO_2 per Mg of biochar. Considering the area of degraded (45,000 km^2) and brownfield land (25,000 km^2) and the potential for soil carbon sequestration across Europe ranging from 0.4 to 0.8 t C ha^{-1} yr^{-1}, it is possible to determine the prospective amount of sequestered CO_2 on these sites.

Four scenarios were assumed:

1. Sequestration will only be carried out on brownfield sites (25,000 km^2), with the lowest assumed soil carbon sequestration potential of 0.4 t C ha^{-1} yr^{-1}.
2. Sequestration will be pursued on both brownfield and degraded land (45,000 km^2), with the lowest assumed soil carbon sequestration potential of 0.4 t C ha^{-1} yr^{-1}.
3. Sequestration will only occur on brownfield sites (25,000 km^2), with the highest assumed soil carbon sequestration potential of 0.8 t C ha^{-1} yr^{-1}.
4. Sequestration will take place on both brownfield and degraded land (45,000 km^2), with the highest assumed soil carbon sequestration potential of 0.8 t C ha^{-1} yr^{-1}.

In addition, due to other possible remediation pathways for both degraded and brownfield sites, an increase in the area available for sequestration from 5% of the assumed area in the scenarios to 40% of the assumed area in the scenarios in 2055 was assumed for each of the above scenarios.

The results showing the potential for CO_2 sequestration on degraded and brownfield land under the assumed scenarios were compared with the potential to produce biochar from the sewage sludge generated annually in Europe (Figure 3). As can be seen (red dotted line), Europe has a large potential for the utilization of sewage sludge, which could even be used in its entirety as a feedstock in pyrolysis processes, where, in addition to the biochar, the heat necessary for drying the sludge could be generated, and high-energy gas and liquid fractions could be produced, which could in turn be used to produce alternative fuels. Therefore, it is important to consider both the potential for CO_2 sequestration on degraded and brownfield land and the potential for utilization of sewage sludge in Europe as viable options for reducing greenhouse gas emissions and promoting sustainable waste management practices. These findings highlight the importance of exploring multiple pathways toward achieving climate change mitigation and sustainability goals.

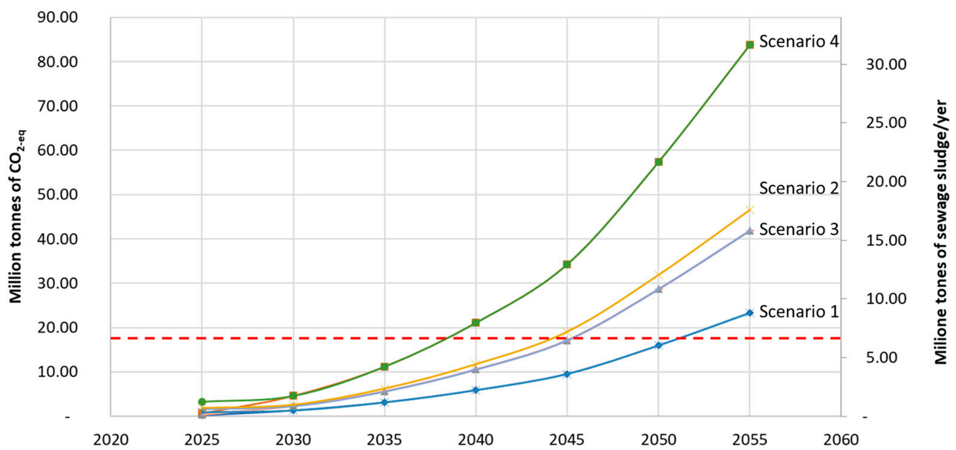

Figure 3. Possible levels of CO_2 sequestration in the form of sludge char on degraded and brownfield sites, depending on the scenario.

5. Conclusions

Biochars derived from biomass and biomass materials have long been acknowledged as excellent soil additives, particularly in barren and eroded soils with low organic carbon content. Biochar has a number of characteristics that make it an effective soil amendment. First, it has a large surface area and a porous structure, which allows it to absorb and retain water, nutrients, and other beneficial soil substances. This improves soil fertility and reduces nutrient loss due to leaching. Second, biochar is a stable form of carbon that can aid in carbon sequestration in soil. This can help to mitigate climate change by lowering carbon dioxide levels in the atmosphere. Third, by increasing soil porosity and decreasing compaction, biochar can improve soil structure. This can help with water infiltration, drainage, root growth, and nutrient uptake.

The current climate changes, soil deterioration, and still-significant CO_2 emissions indicate challenges for possible CO_2 capture through sequestration. Soils enriched by biochar additives are therefore a valuable tool in environmental protection.

However, owing to the conditions under which it was produced or the material from which it was made, not all biochar may be suitable for such use. This is due to the specifications that biochar must satisfy to be used as a valuable and biodegradable additive, for example, in applications such as agriculture (low levels of heavy metals and PAHs). To examine the potential uses of biomass-derived wastes such as sewage sludge in CO_2 sequestration, the introduction of biochar produced from their pyrolysis into degraded and post-industrial areas was investigated. To this end, the overall carbon sequestration potential of soils in Europe was investigated, and four scenarios were proposed, demonstrating that even with 40% utilization of the available degraded and post-industrial land (10,000 km^2), it would be possible to sequester (capture) between 23 and 84 million metric tons of CO_2 in the form of biochar from sewage sludge by 2055; sewage sludge generated in Europe could be used as the sole feedstock for pyrolysis and carbon production for CO_2 sequestration on such sites by this date.

As a result, both the potential for CO_2 sequestration on degraded and post-industrial sites, as well as the potential for sludge disposal in Europe, must be considered as feasible options for reducing GHG emissions and promoting sustainable waste management practices. This research emphasizes the potential of using sewage sludge biochar to sequester carbon in degraded and post-industrial sites. It also emphasizes the significance of reducing greenhouse gas emissions by considering both the possibility for CO_2 sequestration and sustainable waste management practices.

Author Contributions: Conceptualization, M.S. and G.G.; methodology, M.S.; formal analysis, M.S.; resources, M.S. and G.G.; writing—original draft preparation, M.S. and G.G.; writing—review and editing, M.S., M.Z., W.M., M.O., E.M., C.P. and G.G.; visualization, M.S. and G.G.; supervision, M.S.; funding acquisition, M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was performed under the project sponsored by the Polish National Agency for Academic Exchange under the Bekker Program, Project no. NAWA BPN/BEK/2021/1/00103.

Data Availability Statement: Publicly available datasets were analyzed in this study.

Acknowledgments: This research was supported by the Faculty of Energy and Environmental Engineering, Silesian University of Technology (statutory research).

Conflicts of Interest: The authors declare no conflict of interest.

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