Chapter

The Role of Biochar Systems in the Circular Economy: Biomass Waste Valorization and Soil Remediation

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Abstract

The circular economy is considered as an alternative model to the unsustainable linear “take–make–waste” approach that characterizes contemporary economic systems. It aims to achieve sustainable development by promoting the responsible and cyclical use of resources to maintain their value in the economy and minimize pressures on the environment. Biochar systems offer opportunities for operationalizing the CE model. They are multifunctional systems that can be used for bioenergy and biochar production using an extensive range of biomass feedstocks, including biowaste. They can contribute to climate change mitigation, as producing biochar and mixing it with soil is a means for sequestering atmospheric CO_2. Moreover, the produced biochar has a wide range of applications, including its use for agricultural soil amendment, wastewater treatment, manufacturing of cement, and remediation of contaminated soils. This versatility of biochar systems creates great opportunities for developing circular models of waste management that can valorize different waste streams. This chapter provides an overview of the CE concept and describes biochar systems, focusing on systems for the synergistic valorization of wood waste and contaminated soils. It also discusses the role of these systems in the CE indicating that they can contribute to the transition toward the CE.

Keywords: circular economy, sustainable development, biochar systems, wood waste, contaminated soil

1. Introduction

The CE has emerged as an alternative model to the prevailing “take–make–waste” approach to production and consumption in contemporary economic systems, which is an unsustainable path leading to resource depletion and severe environmental problems, such as climate change, air and water pollution, and biodiversity loss [1, 2]. In the linear economy, resources are extracted from nature, transformed into products that are then consumed within the human economic system until they are finally disposed of as waste back to nature [2]. By contrast, the CE model fosters the responsible and cyclical use of resources to maintain their value within the economy, while minimizing pressures on the environment [3, 4]. It operates at three system levels; the micro level (products, consumers, companies), the meso level (eco-industrial parks), and the macro level (cities, regions, countries), with the ultimate aim to achieve sustainable development [5].

The transition toward the CE requires, among others, the development of new technologies [6, 7]. An emerging technology that could promote the operationalization of the CE model is biochar systems. These are multifunctional systems that can produce bioenergy and biochar through the thermochemical conversion of different types of biomass feedstocks (e.g., wood, agricultural residues, and wastewater sludge) in an oxygen-limited environment [8, 9]. Biochar is a porous solid carbonaceous material with versatile physicochemical properties that has a multitude of applications, including its use for amendment of agricultural soils, water purification and wastewater treatment, concrete and steel production, and remediation of contaminated soils [10]. The application of biochar to soils is probably its most prominent application, as, apart from improving soil quality, it sequesters atmospheric CO_2, thereby contributing to climate change mitigation [11]. The multi-functionality of the biochar systems offers opportunities for developing integrated systems for valorizing different waste streams [12, 13], which is vital for the implementation of the CE model.

In this chapter, biochar systems, for valorizing wood waste and contaminated soils, are presented, and the potential role of these systems in the CE is explored. The rest of the chapter is structured as follows: Section 2 provides an overview of the CE concept and its principles to set the context of the study; Section 3 provides a brief description of different biochar systems; Section 4 focuses on biochar systems for valorizing wood waste and contaminated soils, and describes a case study, where the environmental performance of such systems is assessed; Section 5. discusses the role of biochar systems in the CE; and Section 6 summarizes the conclusion of the study.

2. The circular economy

The concept of CE originates in different schools of thought, including industrial ecology, general systems theory, and ecological and environmental economics [14]. Its conceptual roots can be traced back to notions put forth decades ago, such as the "Spaceship economy," [15] the irreversible degradation of natural resources when used by economic activities [16], the economy of loops [17], and the analogy between ecosystems and industrial systems [18]. The contemporary conceptualizations of CE include features from relevant concepts, including, but not limited to, the regenerative design [19], industrial symbiosis [20], "cradle to cradle" design [21]' and performance economy [22].

Over the past 10–15 years, the CE has been attracting increasing attention from academia, companies, citizens, and policymakers [23]. It is regarded as a potential solution to the challenges of resource depletion and environmental degradation caused by the unsustainable linear "take–make–waste" paradigm that has dominated the contemporary economic systems [1, 2]. To address these challenges, the CE promotes system innovations that aim to maximize resource value, promote the cascading use of renewable resources and minimize waste generation to reduce negative environmental impacts and build natural, social, and economic capital [1, 24].

Overall, there is a general understanding that the CE is connected to sustainability and sustainable development. Geissdoerfer et al. [23] identified three different general types of relationships between the CE and sustainability; 1) conditional, where the CE is seen as one of the main conditions to attain sustainability, 2) beneficial, where the CE is regarded as beneficial in regard to sustainability, and 3) trade–off, where the CE is seen as a concept that can generate both benefits and costs in terms of sustainability. Having this study as a point of departure, Suárez-Eiroa et al. [25] suggested that there is a close relationship between the CE and sustainability and that the CE is at least beneficial for achieving sustainable development, as it can address some of the causes of current sustainability-related problems. The relevance of CE for achieving sustainable development was also confirmed by Schroeder et al. [26], who demonstrated that CE practices can contribute to achieve a significant number of Sustainable Development Goal targets. Despite these perspectives, the exact relationship between the CE and sustainability and sustainable development remains still unclear and debatable [27, 28].

Moreover, there is a lack of consensus in defining the CE. Kirchherr et al. [5] provided evidence of the heterogeneity in the definitions of the CE, by identifying 114 different definitions within academic articles, policy documents, and reports. The scholars also found that only a few of the identified definitions show explicit linkages between the CE concept and sustainable development. They also highlighted that the social dimension of sustainable development is highly overlooked, compared to the environmental and economic dimensions.

There is also a lack of consensus in conceptualizing the CE principles. A principle is defined "as a basic idea or rule that explains or controls how something happens or works." [29] Reike et al. [30] analyzed 69 academic articles and identified that divergent approaches in conceptualizing the CE principles dominate the literature. More specifically, the scholars focused on the R-principles of the CE and found varying numbers of these R-imperatives, ranging from 3Rs (Reduce–Reuse–Recycle) through 5Rs (Reduce–Reuse–Remanufacture–Recycle–Recover) to the more nuanced 10Rs (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover). In addition, they revealed that different authors ascribe different meanings in their conceptualizations of the R-principles and that some authors apply a clear hierarchy when defining them, while others are more vague and suggestive.

Apart from the R-principles, alternative CE principles have also been proposed in the literature. Suárez-Eiroa et al. [25] used the term operational principles to define theoretical strategies that explain how CE operates. They proposed seven operational principles: (1) Adjusting inputs to the system to regeneration rates, (2) Adjusting outputs from the system to absorption rates, (3) Closing the system, 4) Maintaining the value of resources within the system, (5) Reducing the system's size, (6) Designing for CE, and (7) Educating for CE. Moreover, Bocken et al. [31] introduced the three principles: (1) Narrowing loops, (2) Slowing loops, and (3) Closing loops, to guide business strategists and designers in the transition from a linear to a CE. In a recent study, Velenturf and Purnell [28] proposed 10 principles for the design, implementation, and evaluation of sustainable CE. These are: 1) Beneficial reciprocal flows of resources between nature and society, 2) Reduce and decouple resource use, 3) Design for circularity, 4) Circular business models to integrate multi-dimensional value, 5) Transform consumption, 6) Citizen participation in sustainable transitions, 7) Coordinated participatory and multi-level change, 8) Mobilize diversity to develop a plurality of circular economy solutions, 9) Political economy for multi-dimensional prosperity, and 10) Whole system assessment.

According to Kalmykova et al. [32], the divergent approaches in defining and conceptualizing the CE can hamper the advancement of the CE. However, the CE is an evolving and dynamic field that involves different stakeholders with different interests and priorities and thus the adoption of a single unifying definition is perhaps impossible and undesirable, as it would disregard some interests and fail to capture recent developments [33]. This, of course, is not a reason to stop striving for greater conceptual clarity on the CE. In this context, it is important to define explicitly the concept and its principles early in a study.

In this chapter, we embrace the definition proposed by Kirchherr et al.[6(p229)]:

> *"A circular economy describes an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers."*

We adopt this definition as a basis for exploring the role of biochar systems in the CE, as we consider it as one of the most comprehensive and insightful definitions of the CE in the literature. It highlights that the transition toward the CE requires the implementation of the model at three system levels (micro, meso and macro level). Moreover, it clearly relates the CE with the three dimensions of sustainable development (social, economic, environmental) and indicates that the CE has a key role as a means to achieve sustainable development. It is also important that it has an explicit reference to the 4Rs (Reduce–Reuse–Recycle–Recover) principle of the CE.

3. Biochar systems

Biochar is the porous solid carbonaceous material derived from the thermochemical conversion of biomass in an oxygen-limited environment [9]. It can be produced from various biomass feedstocks, including wood, wood waste, agricultural wastes (e.g., straw, rice husk), wastewater sludge, and food waste [8]. The most commonly used thermochemical conversion process for biochar production is pyrolysis, though other processes, such as gasification, torrefaction, and hydrothermal conversion, can also be used [34]. Pyrolysis is the thermochemical decomposition of biomass into condensable liquids, non-condensable gases, and biochar in the absence of oxygen [35]. The distribution of these end products and their properties depends on the process conditions (i.e., temperature, heating rate, and residence time) and the type of biomass feedstock [36]. Based on the process conditions, pyrolysis is classified as slow, fast, rapid, or flash, with slow pyrolysis being more appropriate for a biochar targeted product [37].

Biochar systems using pyrolysis can be deployed at different scales (small-, medium- and large–scale) and can perform multiple functions, as they can be used for biowaste treatment and bioenergy generation, along with biochar production and use [38]. Bioenergy can be produced through the combustion of the pyrolytic gas and oil products, known as syngas and bio-oil (or bio-tar), respectively. Moreover, bioenergy can be produced by using the produced biochar as solid fuel [9]. In addition to bioenergy production, biochar can be used for a variety of applications, mainly because of its versatile physicochemical properties [8, 10].

The most prominent application of biochar is probably its application to soils. Biochar can be used as a soil amendment for agricultural soils, as it can improve their physicochemical properties and structure, increasing soil fertility and crop productivity [34, 37, 39]. At the same time, the production of biochar and its incorporation into soils sequesters carbon. More specifically, the thermo-chemical conversion of biomass into biochar increases the recalcitrance of carbon, enhancing its resistance to chemical and biological degradation [34]. Thus, when biochar is incorporated into the soil, the return of biomass carbon to the atmosphere as CO_2 is impeded [11, 40]. In this way, biochar can act as a carbon sink, thereby contributing to climate change mitigation, and for that reason, the production of biochar with its incorporation in soils has been recognized as a carbon dioxide–removal (CDR) technology [41].

Besides soil amendment and carbon sequestration, biochar has numerous applications across various sectors. Biochar can be used as an additive for production of cement [13], cement mortar [42] and concrete [43], adsorbent for wastewater treatment and water purification, coke replacement in metallurgical processes, raw material for the manufacture of activated carbon, and novel specialty materials for electronic devices, such as carbon nanotubes and nanosheets [10], and platform material for energy storage and conversion, including hydrogen storage and production, fuel cells and lithium/sodium-ion batteries [44]. It can also be used as a feed supplement for poultry or ruminants to improve the health and productivity of the animals, reduce odors and nutrient losses from the manure, and serve, in combination with the manure, as a slow-release fertilizer [45]. Moreover, the sorption properties of biochar have sparked an interest in the use of biochar for remediating soils contaminated with organic and/or inorganic pollutants [9, 46, 47].

4. Biochar systems for synergistic valorization of wood waste and contaminated soil

Contamination of soils from human activities is a widespread environmental problem around the globe [47]. Only in EU-28, it has been estimated that 2.8 million potentially contaminated sites exist [48]. A widely applied technique for remediating contaminated sites worldwide is the “dig and dump” technique, where the contaminated soil is excavated and landfilled, and the excavated site is usually backfilled with virgin material [49]. However, this technique is not sustainable because of high-energy requirements, scarcity of landfill space, high costs, and decreasing availability of natural resources for backfilling [49]. Hence, various alternative techniques are being explored, including the application of biochar to contaminated soils.

Biochar exhibits good sorption properties for organic compounds, such as polycyclic aromatic hydrocarbons (PAHs), and inorganic substances, such as heavy metals, because of their large surface area, porous structure, and cation-exchange capacity [9, 46, 47]. Therefore, the mixing of biochar with soils contaminated with these substances is considered a potential option for stabilizing the contaminants. The efficacy of this technique depends on the properties of the utilized biochar and the type and concentration of contaminants in the soil [50]. For example, the efficacy of biochar for sorption of PAHs and heavy metals, such as Cd, Zn, Pb, and Cu, have been reported as good [51, 52], while for negatively charged metal(loid)s, such as As and Mo, the sorption capacity of biochar is low [47, 50]. Furthermore, the interplay between positive and negative effects has been reported for contaminated soils with multiple contaminants [46]. This indicates that the utilization of biochar for remediation of contaminated soils may not be suitable for all types of contaminated soil and thus case–specific assessments are generally required.

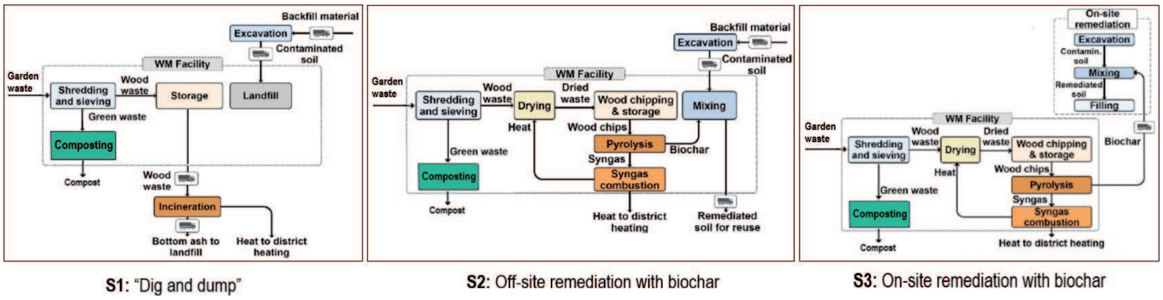
To explore the potential of using biochar for remediating contaminated soils with PAHs, heavy metals and metal(loid)s in Sweden, the research project “Biochar-RE: Source” was carried out between 2018 and 2020 [53]. The purpose of the project was to test and assess a new technique for remediation of contaminated soils excavated in urban areas, which is based on biochar made from urban wood waste. As part of the research, different biochar systems that use pyrolysis were designed and their environmental performance was assessed and compared to that of the “dig and dump” technique, which is the prevailing method for handling contaminated sites in Sweden [54]. The assessment of these systems is described by Papageorgiou et al. [55]. The following sections of this chapter (4.1 and 4.2) describe these systems and provide an overview of the methodological approach followed for the assessment and a summary of the results of the assessment. For more details see Papageorgiou et al. [55].

4.1 Systems description

Figure 1 depicts three different systems for the management of urban wood waste and contaminated soil. System 1 (S1) depicts how these two waste streams are currently managed in the urban area of Helsingborg in southern Sweden, which was the case study area for the research project. Systems 2 and 3 (S2 and S3) depict two alternative options for managing wood waste and contaminated soil based on biochar systems. More details for each system are provided below.

- *S1: “Dig and dump”*. In S1, contaminated soil with PAHs and metal(loid)s is excavated from various sites in Helsingborg and the excavated sites are backfilled with virgin material (gravel). The excavated soil is transported to the local waste management (WM) facility, where it is landfilled. Moreover, garden waste from the urban area is transported to the WM facility and is sorted, via shredding and sieving, into wood waste and green waste (mostly leaves and soil). The sorted waste is then transported to an incineration facility, where it is combusted for district heating. The green waste is processed through windrow composting.

- *S2: Off-site remediation with biochar.* In S2, the collected wood waste is first dried and processed into woodchips and then converted via pyrolysis (slow) into biochar and syngas. The syngas is combusted, and the generated heat is partly used for district heating and partly for drying the wood waste before pyrolysis.



S1: “Dig and dump” **S2**: Off-site remediation with biochar **S3**: On-site remediation with biochar

Figure 1.
The three studied systems for the management of wood waste and contaminated soil.

The biochar is mixed with contaminated soil (6% biochar, 94% soil, weight-to-weight), which is transported to the WM facility from excavation sites in Helsingborg. It is assumed that the excavated soil is transported for treatment to the facility due to technical or/and legislative restrictions that do not allow its mixing with biochar on-site and its direct reuse for backfilling. Instead, virgin soil (gravel) is used to backfill the excavated sites and the biochar-soil mix is reused in other applications (e.g., for noise barrier construction).

- *S3: On-site remediation with biochar.* The main difference between S3 and S2 is that the produced biochar is transported to the excavation sites and there it is mixed with the contaminated soil (6% biochar, 94% soil). The biochar-soil mix is then reused on-site for backfilling.

4.2 Environmental performance

4.2.1 Methods

The environmental performance of the three above–described systems was assessed by combining three Industrial Ecology tools, that is, Material and Energy Flow Analysis (MEFA), Substance Flow Analysis (SFA), and Life Cycle Assessment (LCA).

The goal of the MEFA was to map and quantify material and energy flows in the three systems in order to provide an understanding of the functioning of the systems and create the quantitative basis for the application of the LCA. The system boundaries of the MEFA included all processes for managing the contaminated soil (e.g., excavation and mixing) and wood waste (e.g., incineration and pyrolysis) and transportation between processes. However, they did not include the composting of the green waste, as the focus of the assessment was on the sorted wood waste, and the leaching of PAHs and metal(loid)s from the landfilled contaminated soil (S1) or the reused soil (S2 & S3), as it was studied through an SFA. The time boundary of the assessment was annual. The estimation of the material and energy flows was done by combining primary data and data from the literature.

The LCA was a comparative process-based LCA and its goal was to assess the life cycle environmental impacts of the studied systems. The system boundaries of the LCA were the same as those of the MEFA. They also included upstream impacts from the supply of backfill material, downstream impacts from the disposal of wood waste incineration ash, and impacts from capital goods (e.g., machinery). The functional unit was set as “1 year of operation of the pyrolysis plant (0.8 t/h dry wood, 1250 t/year biochar).” This functional unit is equivalent to the treatment of 5,650 t wood waste for district heating and remediation of 12,240 m^3 contaminated soil with biochar. To handle allocation issues and keep the functional unit constant the system expansion approach was followed. The modeling of the Life Cycle Inventory (LCI) was carried out using the LCA software Brightway2 [56] based on the Ecoinvent database (version 3.6 – cut-off) [57]. For the Life Cycle Impact Assessment (LCIA), the ILCD 2.0 impact assessment method [58] was used. From the 15 impact categories, the toxicity-related impact categories carcinogenic effects, non-carcinogenic effects, and freshwater eco-toxicity were not included, as the fate of the contaminants in the soil was investigated separately through an SFA.

The SFA was conducted to map and quantify the flows of the contaminants (PAHs and metal(loid)s) in the landfilled contaminated soil and the remediated soil.

The analysis was carried out taking a life cycle perspective, as the system boundaries included flows from all the processes included in the LCA. In addition, they included leaching of the contaminants from the soils, which was excluded from the MEFA and LCA. The amounts of contaminants leaching from the soils were calculated within a 100-year timeframe, using data from leaching experiments that were performed in the context of the "Biochar-RE: Source" research project and assuming a certain degree of water infiltration in the soils.

4.2.2 Results

The main results from the application of the MEFA are summarized in **Table 1**. The analysis revealed that on-site remediation with biochar (S3) can deliver significant fuel (diesel and biodiesel) savings, as it involves less transportation of materials than the "dig and dump" system (S1) and off-site remediation (S2). Moreover, on-site remediation minimizes the use of virgin material (gravel) for backfilling, as the remediated soil is directly reused on-site. By contrast, in S1 and S2, virgin material is required for backfilling. In addition, the analysis indicated that the pyrolysis of wood waste can supply less heat to the district heating network than incineration and that a considerable amount of auxiliary electricity is needed for the operation of the pyrolysis plant.

Table 2 presents the results of the LCA for the three systems and **Figure 2** shows the environmental impacts of S2 and S3, normalized to S1 (S1 = 100%), as well as the contribution of each process. Overall, biochar systems (S2 & S3) perform better than the "dig and dump" system (S1) in 10 out of 12 environmental impact categories. When comparing off-site (S2) and on-site remediation (S3), the former has lower environmental impacts in all impact categories. The main reason is that S3 entails less transportation of materials and saves virgin soil. Notably, both biochar systems have negative scores for climate change, as carbon sequestration in the biochar is 2.3 and 4.5 times higher than direct greenhouse gas emissions in S2 and S3, respectively. The biochar systems S2 and S3 had more impacts than S1 only in the impact categories Ionizing radiation and Fossils. The principal cause is the increased consumption of electricity for the operation of the pyrolysis plant, as a significant share of electricity in Sweden is from nuclear power, which is associated with these two impacts.

Material and energy flows	S1	S2	S3
Wood waste (t)	5,650	5,650	5,650
Contaminated soil (t)	19,580	19,580	19,580
Biochar produced (t)	—	1,250	1,250
Fossil fuels (diesel) used (t)	84.1	131	5,9
Biofuels (biodiesel) used (t)	90.3	15,8	13,1
Virgin material (gravel) used (t)	19,580	19,580	—
Landfilled contaminated soil (t)	19,580	—	—
Reused remediated soil (t)	—	19,580	19,580
District heating supply (TJ)	58.2	36	36
Electricity consumed (TJ)	—	14.2	14.2

Data source: Papageorgiou et al. [55].

Table 1.
Main material and energy flows of the three systems.

Impact categories	S1	S2	S3
Climate change (10^6 kg CO_2-eq)	1.01	−2.02	−2.31
Freshwater and terrestrial acidification (10^3 mol H+-eq)	25.35	7.2	5.96
Freshwater eutrophication (kg P-eq)	53.49	39.85	36.63
Marine eutrophication (10^3 kg N-eq)	13.76	2.78	2.34
Terrestrial eutrophication (10^3 kg N-eq)	124.96	27.84	23.71
Ionizing radiation (10^3 kg U235-eq)	169.42	781.07	763.55
Ozone layer depletion (kg CFC-11)	0.19	0.18	0.12
Photochemical ozone creation (10^3 kg NMVOC)	26.63	6.67	5.54
Respiratory effects, inorganics (Disease incidences)	0.27	0.09	0.07
Fossils (TJ)	17.46	30.4	26.13
Land use (10^6 points)	115.64	24.46	17.73
Minerals and metals (kg Sb-eq)	44.18	18.45	11.29

The negative scores for Climate change mean that the uptake of greenhouse gases is larger than direct emissions to the atmosphere (Data source: Papageorgiou et al. [55]).

Table 2.
Life cycle environmental impacts of the three systems.

Moreover, transportation and the incineration of wood waste are the most significant contributors in almost all impact categories for S1 (c.f., **Figure 2**). For the biochar systems S2 and S3, pyrolysis of wood waste and heat substitution are significant contributors. Heat substitution represents the additional heat that needs to be generated to compensate for the reduced heat production in S2 and S3, as pyrolysis produces less energy than incineration because a large share of the initial energy content in the biomass remains in the biochar. For S2, transportation is another significant contributor, as off-site remediation requires transportation of large quantities of materials, for example, virgin soil for backfilling.

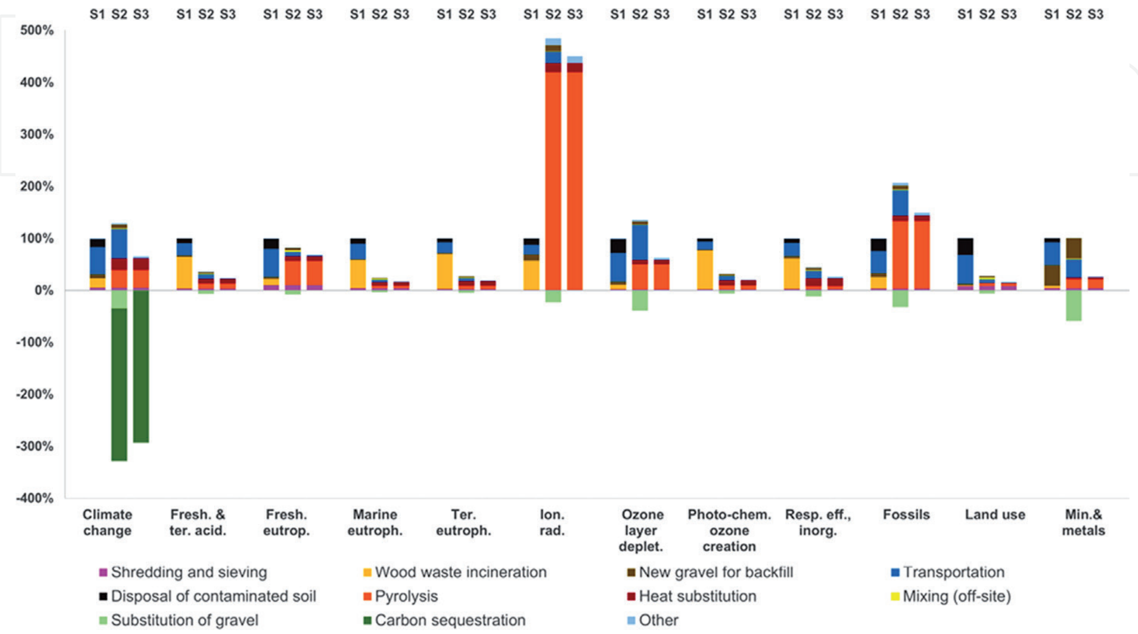


Figure 2.
Life cycle environmental impacts of the biochar systems (S2 and S3), normalized to the "dig and dump" system (S1) (S1 = 100%) with process contributions (Data source: Papageorgiou et al. [55]).

The results of the SFA for PAHs are summarized in **Table 3**. The analysis showed that for all PAHs, except benzo(a)pyrene, the leached amounts from the contaminated soil and the biochar-remediated soil are significantly higher than their life cycle emissions from the other processes of the systems. However, the leached amounts of PAHs constitute only a small part of their initial content in the soils. The analysis showed that remediation with biochar can stabilize PAHs in the soil, as less than 0.1% of the initial content of these contaminants in the soil will leach out within a 100-year period.

For the metal(loid)s the results of the SFA are presented in **Table 4**. Contrary to PAHs, the leached amounts of most metal(loid)s from the landfilled or remediated soil are lower than their life cycle emissions. The only exceptions are Mo and Ba. Moreover, the analysis showed that less than 0.8% of the initial content of metal(loid)s in the contaminated soil leaches out, except for Ba where 1.1% leaches out in S2 and S3, and Mo where 4.7% and 25% of the initial content leaches out in S1, S2, and S3, respectively. Furthermore, the SFA indicated that the application of biochar can reduce the leaching of Cu, Zn, Ni, and Hg, while it does not have the same positive

PAHs	**Life cycle emissions, without emissions from disposal of contaminated soil or reuse of biochar-remediated soil (kg)**			**Initial amount in the contaminated soil (kg)**	**Amount released from the disposed contaminated soil (kg)**	**Amount released from the reused remediated soil (kg)**
	S1	**S2**	**S3**		**S1**	**S2 & S3**
Naphthalene	1.0E–04	3.2E–05	2.1E–05	2.9E+01	9.4E–02	1.4E–02
Acenaphthylene	1.9E–05	6.0E–06	3.5E–06	1.6E+01	1.9E–02	5.5E–03
Acenaphthene	1.6E–04	8.8E–05	4.4E–05	1.4E+00	1.6E–02	9.3E–04
Fluorene	6.9E–05	3.3E–05	2.1E–05	4.3E+00	3.5E–02	6.6E–04
Phenanthrene	1.7E–04	8.0E–05	5.1E–05	7.0E+01	2.5E–01	4.1E–03
Anthracene	7.6E–06	4.2E–06	2.6E–06	2.7E+01	8.7E–02	5.4E–04
Pyrene	1.1E–04	6.4E–05	4.0E–05	2.5E+02	5.7E–01	5.8E–03
fluoranthene	1.5E–04	8.5E–05	5.3E–05	1.9E+02	7.1E–01	6.0E–03
Chrysene	2.8E–07	5.5E–08	4.2E–08	1.3E+02	1.6E–01	9.9E–04
Benz[a]-anthracene	1.9E–07	6.4E–08	4.6E–08	1.5E+02	1.7E–01	1.0E–03
Benzo[k]-fluoranthene	1.1E–07	3.7E–08	2.7E–08	7.1E+01	2.1E–02	2.5E–04
Benzo[b]-fluoranthene	1.5E–07	5.2E–08	3.7E–08	1.1E+02	4.7E–02	6.5E–04
Benzo[a]-pyrene	1.6E–01	8.6E–02	7.7E–02	9.6E+01	4.9E–02	6.5E–04
Benzo[ghi]-perylene	3.1E–08	6.7E–09	5.1E–09	7.5E+01	3.5E–02	1.1E–03
Dibenz[ah]-anthracene	4.0E–08	2.0E–08	1.4E–08	1.8E+01	1.1E–02	3.0E–04
Indeno[1,2,3-cd]-pyrene	3.1E–08	1.2E–08	8.6E–09	9.4E+01	3.0E–02	8.4E–04

Data source: Papageorgiou et al. [55].

Table 3.
Results of the SFA for PAHs.

Metal(loid)s	Life cycle emissions, without emissions from disposal of contaminated soils (kg)			Initial amount in the contaminated soil (kg)	Amount released from the disposed contaminated soil (kg)	Amount released from the reused amended soil (kg)
	S1	**S2**	**S3**		**S1**	**S2 & S3**
As, Arsenic	2.5	8.1	7.9	144.9	0.3	1
Ba, Barium	61.8	75.7	64.6	5180.3	13.0	68.2
Cd, Cadmium	1.8	2.3	2.2	7.3	0.05	0.1
Cr, Chromium	74.3	387.5	386.7	285.2	0.3	2.3
Co, Cobalt	293.6	1629.7	1625.3	90.8	0.3	0.6
Cu, Copper	357.4	768.1	749.1	4132.6	12.8	2.7
Pb, Lead	119.8	151.4	137.1	8265.3	0.1	0.5
Hg, Mercury	0.2	0.4	0.4	29.1	0.002	0.001
Mo, Molybdenum	3.6	7.0	6.3	36.7	1.7	9.3
Ni, Nickel	41.9	39.6	37.0	232.8	1.4	0.8
V, Vanadium	6.3	5.5	4.7	372.5	0.3	1.3
Zn, Zinc	250.4	326.7	306.1	7275.8	27.6	20.7

Data source: Papageorgiou et al. [55].

Table 4.
Results of the SFA for metal(loid)s.

effects for the other metal(loid)s. A sensitivity analysis showed that the results for metal(loid)s were sensitive to the assumed degree of water infiltration in the soils, contrary to the results for PAHs, which showed low sensitivity.

Overall, the SFA showed that the treatment of contaminated soils with biochar is effective for stabilizing PAHs. For metal(loid)s, however, the results of the SFA were more varied and sensitive to modeling assumptions. Therefore, further investigation is required to evaluate the effectiveness of this technique for remediating contaminated soils with metal(loid)s and identify and assess potential ecological and human health risks associated with it.

5. The role of biochar systems in the circular economy

To explore the role of biochar systems in the CE, the definition of the CE by Kirchherr et al. [5] (see Section 2) is used as a conceptual basis. More specifically, it is examined how the studied biochar systems can satisfy key elements of the definition.

The definition has an explicit reference to the 4Rs (Reduce–Reuse–Recycle–Recover) principle highlighting that, in the CE, a top priority is given on reducing the use of materials, and then on reuse, recycling, and recovery. On-site remediation with biochar (S3) can contribute to both reduction and reuse of materials, as the remediated soil can be reused on-site preventing the use of virgin soil for backfilling. Moreover, on-site remediation can generate significant fuel savings, as it involves less transportation compared to off-site remediation (S2) and landfilling of contaminated soil with the incineration of wood waste (S1). Off-site remediation cannot offer the same benefits as on-site remediation, as the remediated soil is not used on-site for backfilling. Nonetheless, the remediated soil can be reused in other applications (e.g., construction of noise barriers), preventing the use of virgin soil for these applications. In addition, both off-site and on-site remediation recover energy from the sorted wood waste and at the same time prevent the landfilling of the contaminated soil. Hence, it is evident that both biochar systems, especially S3, contribute to fulfilling the 4Rs principle of the CE.

The definition also indicates that a multi-level implementation of the CE model at the micro, meso and macro level is required for the transition to the CE. The versatility of biochar systems offers opportunities for the operationalization of the CE model at different system levels. The studied systems in this chapter demonstrate how biochar systems could form the basis of circular models for valorizing different waste streams in urban areas (macro level). Nonetheless, similar systems based on pyrolysis of biomass waste or other biomass feedstocks could also be developed in symbiosis with other industrial facilities in eco-industrial parks (meso level). For example, biomass waste (e.g., from a paper or pulp mill) could be pyrolyzed to supply heat and/or electricity for industrial processes within the eco-industrial park, while the produced biochar could be used as a resource for the manufacture of other materials, such as concrete, steel or activated carbon (see Section 3). In addition, biochar systems offer circular economy pathways at the micro level. It has been reported that decentralized biochar systems using agro-industrial wastes could be deployed in farms and small and medium enterprise (SME) activities to generate bioenergy and produce biochar that can be used as amendment of agricultural soils [12] or feed supplements for poultry or ruminants [45]. For example, a pyrolysis-biochar system could be integrated into an olive–grove farm in symbiosis with an olive mill, where residues from the olive grove and oil extraction are used as feedstock for the pyrolysis to produce heat and power for olive milling operations and biochar for amending the soil in the olive grove [37].

Moreover, according to the definition, the ultimate goal of operationalizing the CE model at different levels is to achieve sustainable development. One aspect of this goal is the creation of environmental quality. The assessment of the environmental performance of the biochar systems described in this chapter highlighted that these systems have great potential to improve environmental quality. First, they can contribute substantially to climate change mitigation through carbon sequestration in the biochar. Moreover, when compared to the conventional "dig and dump" system, the biochar system for on-site remediation can provide additional greenhouse gas emission savings, as it delivers fuel and virgin material savings. Apart from contributing to climate change mitigation, the assessed biochar systems can also provide additional environmental benefits, as they perform better than the "dig and dump" system in 10 out of 12 analyzed impact categories (see Section 4.2.2). However, there are also trade–offs associated with these systems, as they cause more impacts in the impact categories of ionizing radiation and fossils. The reason is that the technology for pyrolysis of wood waste used in this specific case requires considerable amounts of auxiliary electricity, which in Sweden is derived to a large extent from nuclear power, which is associated with these environmental impacts. Furthermore, the efficacy of biochar to stabilize certain metal(loid)s was not as high as for PAHs, and, in general, the extent of potential ecological and human health risks from the reuse of the remediated soil is still unknown.

To understand the role of biochar systems in CE it should be noted that CE, as defined here, does not imply "re–circulation of everything." One of the key benefits of biochar is to remove carbon from the atmosphere, thus contributing to climate change mitigation, by turning biomass into a stable material with a long lifetime in soils. Thus, the carbon cycle from atmospheric carbon dioxide to organic matter and back to the atmosphere is not closed, but slowed down, fitting into the CE concept of "slowing loops" [31].

Apart from environmental quality, other aspects of the desired goal to achieve sustainable development are the creation of economic prosperity and social equity. These aspects were not included in the scope of the above–described assessment, as it was focused only on the environmental sustainability of the studied systems. Nevertheless, it has been reported in the literature that biochar systems can generally have positive economic effects, as they can create new revenue opportunities, cut costs by reducing resource use and improving logistics, and create new business opportunities [34, 37]. Moreover, they can deliver social benefits, as they can create employment, promote food security through improved crop production from enhanced soil productivity, and offer energy diversification and security of supply [34, 37]. Moreover, the creation of new job opportunities and the associated increase in income are important factors for poverty reduction, which can help in reducing inequalities in society [59].

The above–mentioned environmental, social, and economic benefits of biochar systems are good indications that these systems have the potential to contribute to achieving sustainable development, which is the ultimate goal of the CE. Nevertheless, further research is required to identify and assess potential risks and drawbacks with these systems. From an environmental perspective, it is essential to investigate further various types of biochar systems to ascertain whether they could create risks to environmental quality. For example, in the case of the studied biochar systems, in this chapter, further research could be directed toward identifying and assessing the magnitude of potential risks associated with the reuse of the remediate soils within urban environments. From a social and economic perspective, further research is needed to identify and assess potential socio-economic implications of biochar systems, including those described in this chapter.

6. Conclusion

The CE has emerged as an alternative development model to the unsustainable "take–make–waste" approach that characterizes the contemporary economic systems. The transition toward the CE requires the implementation of new innovative technological solutions that can foster CE principles and help operationalize the CE model at different system levels. One emerging technology that can have a role in the transition toward the CE is biochar systems. These are multifunctional systems that can be deployed for biowaste treatment, and bioenergy and biochar production. As the produced biochar has versatile physicochemical properties, it can be used in various applications. Perhaps, the most prominent application of biochar, is its incorporation into soils, as it can contribute to climate change mitigation through carbon sequestration and at the same time amend the properties of soils. Overall, the multifunctionality of biochar systems, in combination with the versatility of the produced biochar, makes them suitable to function as a basis for developing circular models of waste management.

This chapter describes two biochar systems that could be developed for valorizing wood waste and contaminated soil in an urban area in Sweden. In the studied systems, wood waste is converted via pyrolysis into syngas and biochar. The syngas is used as the energy source for district heating supply. The produced biochar is applied to contaminated soil, either on-site or off-site, to sequester carbon and at the same time to remediate the soil to enable its reuse and prevent its landfilling.

The environmental performance of the two biochar systems was assessed and compared to the conventional “dig and dump” system, where the wood waste is incinerated for energy recovery and the contaminated soil is disposed of in a landfill. The assessment was carried out by combing LCA with MEFA and SFA. The MEFA showed that the biochar system for on-site remediation could provide large fuel and virgin soil savings, compared to the biochar system for off-site remediation and the “dig and dump” system. The LCA revealed that the two biochar systems performed better than the “dig and dump” system in 10 out of 12 analyzed impact categories. The two biochar systems performed remarkably well in the climate change category, as they can achieve net negative GHG emissions, because of carbon sequestration in the biochar. Between the two biochar systems, on-site remediation with biochar performs better than off-site in all impact categories, as the former provides fuel and virgin soil savings. However, there are also trade–offs with the biochar systems, as the pyrolysis of wood waste contributes to ionizing radiation and fossils depletion due to increased consumption of auxiliary electricity. Moreover, the SFA showed that the efficacy of biochar to stabilize certain metal(loid)s is not as good as for PAHs. Hence, the extent of potential risks (e.g., ecological and human health) associated with the reuse of biochar-remediated soils is still unknown.

Based on the findings from the assessment of the studied biochar systems and using the definition of the CE by Kirchherr et al. [5] as a conceptual basis, it was highlighted that these systems can have an important role in the transition toward the CE. It was established that these systems, especially the one for on-site remediation, fulfill the 4Rs principle of the CE. It was also suggested that the versatility of biochar systems creates opportunities for operationalizing the CE model at different system levels. Furthermore, based on the findings of the environmental assessment and findings from the literature, it was inferred that the biochar systems have the potential to provide environmental, social, and economic benefits and thus to contribute to achieving sustainable development, the ultimate goal of the CE. Nevertheless, further research is required to assess whether the reuse of the biochar-remediated soil creates potential risks to ecosystem quality and human health. Moreover, further research could assess potential social and economic implications from the development of these systems.

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References

[1] Kristensen HS, Mosgaard MA. A review of micro level indicators for a circular economy: Moving away from the three dimensions of sustainability? Journal of Cleaner Production. 2020;**243**:118531

[2] Korhonen J, Honkasalo A, Seppälä J. Circular economy: The concept and its limitations. Ecological Economics. 2018;**143**:37-46

[3] Moraga G, Huysveld S, Mathieux F, Blengini GA, Alaerts L, Van Acker K, et al. Circular economy indicators: What do they measure? Resources, Conservation and Recycling. 2019;**146**:452-461

[4] Petit-Boix A, Leipold S. Circular economy in cities: Reviewing how environmental research aligns with local practices. Journal of Cleaner Production. 2018;**195**:1270-1281

[5] Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling. 2017;**127**:221-232

[6] Paiho S, Mäki E, Wessberg N, Paavola M, Tuominen P, Antikainen M, et al. Towards circular cities: Conceptualizing core aspects. Sustainable Cities and Society. 2020;**59**:102143

[7] Homrich AS, Galvão G, Abadia LG, Carvalho MM. The circular economy umbrella: Trends and gaps on integrating pathways. Journal of Cleaner Production. 2018;**175**:525-543

[8] Moreira MT, Noya I, Feijoo G. The prospective use of biochar as adsorption matrix: A review from a lifecycle perspective. Bioresource Technology. 2017;**246**:135-141

[9] Yuan P, Wang J, Pan Y, Shen B, Wu C. Review of biochar for the management of contaminated soil: Preparation, application and prospect. Science Total Environment. 2019;**659**:473-490

[10] Nanda S, Dalai AK, Berruti F, Kozinski JA. Biochar as an exceptional bioresource for energy, agronomy, carbon sequestration, activated carbon and specialty materials. Waste and Biomass Valorization. 2016;**7**(2):201-235

[11] Woolf D, Lehmann J, Ogle S, Kishimoto-Mo AW, McConkey B, Baldock J. Greenhouse gas inventory model for biochar additions to soil. Environmental Science & Technology. 2021;**55**(21):14795-14805

[12] Fytili D, Zabaniotou A. Circular economy synergistic opportunities of decentralized thermochemical systems for bioenergy and biochar production fueled with agro-industrial wastes with environmental sustainability and social acceptance: A review. Curr Sustain Energy Reports. 2018;**5**(2):150-155

[13] Dixit A, Gupta S, Pang SD, Kua HW. Waste valorisation using biochar for cement replacement and internal curing in ultra-high performance concrete. Journal of Cleaner Production. 2019;**238**:117876

[14] Marin J, De Meulder B. Interpreting circularity: Circular city representations concealing transition drivers. Sustainability. 2018;**10**(5):1310

[15] Boulding KE. The economics of spaceship earth. In: Jarrett H, editor. Environmental Quality Issues in a

Growing Economy. Baltimore: Johns Hopkins University Press; 1966

[16] Georgescu-Roegen N. The Entropy Law and the Economic Process. Cambridge MA: Harvard University Press; 1971

[17] Stahel WR, Reday G. Jobs for Tomorrow: The Potential for Substituting Manpower for Energy. Brussels: Report to the Commission of the European Communities; 1976

[18] Frosch RA, Gallopoulos NE. Strategies for manufacturing. Scientific American. 1989;**261**:144-153

[19] Lyle JT. Regenerative Design for Sustainable Development. New York: John Wiley & Sons; 1996

[20] Chertow MR. Industrial symbiosis: Literature and taxonomy. Annual Review of Energy and the Environment. 2000;**25**:313-337

[21] McDonough W, Braungart M. Cradle to Cradle: Remaking the Way We Make Things. 1st ed. New York: North Point; 2002

[22] Stahel WR. The Performance Economy. New York: Palgrave Macmillan; 2010

[23] Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ. The circular economy: A new sustainability paradigm? Journal of Cleaner Production. 2017;**143**:757-768

[24] EMF - Ellen MacArthur Foundation. Towards a Circular Economy: Economic and Business Rationale for an Accelerated Transition. Cowes, UK: EMF; 2013

[25] Suárez-Eiroa B, Fernández E, Méndez-Martínez G, Soto-Oñate D. Operational principles of circular economy for sustainable development: Linking theory and practice. Journal of Cleaner Production. 2019;**214**:952-961

[26] Schroeder P, Anggraeni K, Weber U. The relevance of circular economy practices to the sustainable development goals. Journal of Industrial Ecology. 2019;**23**(1):77-95

[27] Pauliuk S. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resources, Conservation and Recycling. 2018;**129**:81-92

[28] Velenturf APM, Purnell P. Principles for a sustainable circular economy. Sustainable Production Consum. 2021;**27**:1437-1457

[29] Cambridge University Press. Cambridge Dictionary [Internet]. [cited 2022 Jan 24]. Available from: https://dictionary.cambridge.org/dictionary/english/principle

[30] Reike D, Vermeulen WJV, Witjes S. The circular economy: New or Refurbished as CE 3.0?: Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resources, Conservation and Recycling. 2018;**135**:246-264

[31] Bocken NMP, de Pauw I, Bakker C, van der Grinten B. Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering. 2016;**33**(5):308-320

[32] Kalmykova Y, Sadagopan M, Rosado L. Circular economy - From review of theories and practices to development of implementation tools. Resources, Conservation and Recycling. 2018;**135**:190-201

[33] Korhonen J, Nuur C, Feldmann A, Birkie SE. Circular economy as an essentially contested concept. Journal of Cleaner Production. 2018;**175**:544-552

[34] Lehmann J, Joseph S. Biochar for Environmental Management: Science and Technology. Sterling, VA: Earthscan; 2009

[35] Mandal S, Kunhikrishnan A, Bolan NS, Wijesekara H, Naidu R. Application of Biochar Produced From Biowaste Materials for Environmental Protection and Sustainable Agriculture Production. Environmental Materials and Waste: Resource Recovery and Pollution. 2016:73-89

[36] Weber K, Quicker P. Properties of biochar. Fuel. 2018;**217**:240-261

[37] Zabaniotou A, Rovas D, Libutti A, Monteleone M. Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis-biochar based system integrated in an olive farm in symbiosis with an olive mill. Environment and Development. 2015;**14**:22-36

[38] Azzi ES. Biochar Systems across Scales in Sweden: An Industrial Ecology Perspective. KTH Royal Institute of Technology; [PhD thesis] 2022

[39] Joseph S, Cowie AL, Van Zwieten L, Bolan N, Budai A, Buss W, et al. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. GCB Bioenergy. 2021;**13**(11):1731-1764

[40] Smith P, Adams J, Beerling DJ, Beringer T, Calvin KV, Fuss S, et al. Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. Annual Review of Environment and Resources. 2019;**44**(1):255-286

[41] IPCC. In: Calvo Buendia E, Tanabe K, Kranjc A, Baasansuren J, Fukuda M, Ngarize S, Osako A, Pyrozhenko Y, Shermanau P, Federici S, editors. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Switzerland: IPCC; 2019

[42] Gupta S, Kua HW, Low CY. Use of biochar as carbon sequestering additive in cement mortar. Cement and Concrete Composites. 2018;**87**:110-129

[43] Kua HW, Gupta S, Aday AN, Srubar WV. Biochar-immobilized bacteria and superabsorbent polymers enable self-healing of fiber-reinforced concrete after multiple damage cycles. Cement and Concrete Composites. 2019;**100**:35-52

[44] Liu WJ, Jiang H, Yu HQ. Emerging applications of biochar-based materials for energy storage and conversion. Energy & Environmental Science. 2019;**12**(6):1751-1779

[45] Hagemann N, Spokas K, Schmidt H-P, Kägi R, Böhler M, Bucheli T. Activated carbon, biochar and charcoal: Linkages and synergies across pyrogenic carbon's ABCs. Watermark. 2018;**10**(2):182

[46] Beesley L, Moreno-Jiménez E, Gomez-Eyles JL, Harris E, Robinson B, Sizmur T. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environmental Pollution. 2011;**159**(12):3269-3282

[47] Zama EF, Reid BJ, Arp HPH, Sun GX, Yuan HY, Zhu YG. Advances in research on the use of biochar in soil for remediation: A review. Journal of Soils and Sediments. 2018;**18**(7):2433-2450

[48] Pérez AP, Eugenio NR. Status of local soil contamination in Europe:

Revision of the indicator "Progress in the management Contaminated Sites in Europe". Luxemburg: Publications Office of the European Union; 2018

[49] Hodson ME. The need for sustainable soil remediation. Elements. 2010;**6**(6):363-368

[50] Hilber I, Bastos AC, Loureiro S, Soja G, Marsz A, Cornelissen G, et al. The different faces of biochar: Contamination risk versus remediation tool. Journal of Environmental Engineering and Landscape Management. 2017;**25**(2):86-104

[51] Beesley L, Marmiroli M. The immobilisation and retention of soluble arsenic, cadmium and zinc by biochar. Environmental Pollution. 2011;**159**(2):474-480

[52] Thomas E, Borchard N, Sarmiento C, Atkinson R, Ladd B. Key factors determining biochar sorption capacity for metal contaminants: A literature synthesis. Biochar. 2020;**2**(2):151-163

[53] Enell A, Azzi ES, Dan Kleja SD, Ekblad A, Flyhammar P, Fröberg M, et al. Biochar - from organic waste to a resource for utilization of soil waste, Synthesis Report (Report in Swedish: Biokol - från organiskt avfall till resurs för nyttiggörande av jordavfall, Syntesrapport). Linköping: SGI (Statens geotekniska institut); 2020

[54] Anderson R. Efficient Remediation of Contaminated Sites: A Literature Review. Göteborg: Chalmers, University of Technology; 2017

[55] Papageorgiou A, Azzi ES, Enell A, Sundberg C. Biochar produced from wood waste for soil remediation in Sweden: Carbon sequestration and other environmental impacts. Science Total Environment. 2021;**776**:145953

[56] Mutel C. Brightway: An open source framework for life cycle assessment. Journal of Open Source Software. 2017;**2**(12):236

[57] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. International Journal of Life Cycle Assessment. 2016;**21**(9):1218-1230

[58] European Commission, Joint Research Centre, Institute for Environment And Sustainability. Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment Methods. Luxemburg: Database and Supporting Information - First Edition; 2012

[59] Kamali M, Sweygers N, Al-Salem S, Appels L, Aminabhavi TM, Dewil R. Biochar for soil applications-sustainability aspects, challenges and future prospects. Chemical Engineering Journal. 2022;**428**:131189