REPORT ON CIRCULARITY MEASUREMENT AND ASSESSMENT OF CARBON RECOVERY AND REUSE FROM WASTEWATER

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ACTION: Methodology to support circularity measurement and assessment of carbon recovery and reuse from wastewater

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SUBJECT: D3.4 A circularity measurement and assessment methodology of resource recovery and reuse from sewage

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Executive Summary

Circularity measurement and assessment (CMA) is a new methodology that has been produced as part of a new family of ISO standards that provide guidance for the circular economy. These standards have yet to be applied in the production of bioproducts, therefore this report presents the methodology, which would capture the technical, economic, social, and environmental value for cellulose recovery from sewage. The study presents the methods for calculating the most relevant circularity indicators and provide the basis for identifying relevant life cycle assessment (LCA) indicators and sustainable development goals (SDGs) as complementary methods. Applying this methodology would provide a basis for CMA of activated biochar (AB) production as a circular resource in the wastewater extraction and treatment cycle.

The report provides an overview of the process of AB production from sewage pathways, extracting cellulose through screening in wastewater treatment plants (WWTPs) to the process of pyrolysis to transform the cellulose into activated biochar. It demonstrates the value of AB as a circular resource in the wastewater treatment process, as it can enhance constructed wetlands as a form of tertiary treatment by improving micropollutant removal, helping countries meet more stringent water quality standards.

The new family of ISO standards, ISO 59000, is introduced with a specific focus on ISO 59020 which will guide the development of the CMA framework in this report. There primary steps are outlined in the CMA process, namely setting the boundary condition, (ii) choosing appropriate indicators and data acquisition, and (iii) preparing the circularity assessment report. Complementary methods, such as LCA and SDG analysis, can be also applied to enhance the relevance of findings to all relevant stakeholders.

Seven core and additional indicators were identified for the CMA process that align with AB function and the overall goal of this study. The indicators reflected resource flows, energy, and water, as well as economic and social metrics. Formulae were prepared to ensure each indicator could be accurately assessment for one unit of AB. The complementary LCA process produced a subset of environmental indicators, and the SDG assessment considered several specific goals (#6, 8#, #9 and #10) in its assessment. Lastly, a simple comparison of AB and activated carbon demonstrated the differences in the associated environmental impacts of similar functioning materials, which could be considered as part of the decision-making process for producing AB or using AB in constructed wetlands.

Applying this methodology can provide evidence for key stakeholders, in this case wastewater treatment companies who have the cellulose as a circular resource and require installing advanced treatment processes to address the need for micropollutant removal. The circular performance of activated biochar as a product and its contribution to constructed wetlands for enhanced treatment can be evaluated, which can be of value to key stakeholders in their decision making to invest in infrastructure for cellulose treatment and activated biochar production. The application of a CMA methodology will provide a more holistic and balanced set of results to facilitate the wastewater sector demonstrating their capacity to become a more circular sector.

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1 INTRODUCTION

1.1 Biochar

Circular products have become a priority in recent years to support sustainable development and mitigate against climate change and water scarcity and address the energy and biodiversity crisis. Biochar represents a circular product that can be produced from waste streams, and it has significant capacity to act as a resource in different sectors and has notable benefits from sequestering carbon or to absorbing micropollutants (1). The origin of biochar is associated with a highly fertile soil from the Amazon region (so-called 'terra preta') which was originally used for agriculture (2). This application persists until present, as addition of biochar into soil improves its physiology and increases productivity (thanks to the presence of minerals such as Cu, Zn, Ca, K and Mg). To help address climate change (3), biochar can also be used in soil to sequester carbon, with an estimated removal capacity of up to 9.5 Gt/year by 2100 (4).

There are multiple ways of producing biochar e.g., torrefaction, hydrothermal liquefaction, hydrothermal carbonization (HTC), with the most common method being pyrolysis (5). Pyrolysis is a thermochemical process carried out under specific conditions (oxygen is completely absent or in under stoichiometric concentrations, temperatures range from 350-650 °C). A is slow degradation rate of the biomass with long residence times result in a carbon-rich material, with high temperatures ensures a higher active surface area due to deterioration of the pore blocking substances in the structure (6). Biochar produced under high temperatures is hydrophobic (i.e., insoluble), whereas biochar produced under lower temperatures is hydrophilic (dissolves in water). Biochar's properties depend on the incoming feedstock and production conditions (varying enrichment by different compounds, structural differences, etc.).

Biochar has gained a lot of attention as an alternative adsorbent for wastewater treatment, is a product of natural biomass that can often be produced from materials considered as waste (e.g., cellulose) making it a valuable circular resource. The usage of biochar in wastewater treatment is a very attractive solution, because of its low production costs as compared to conventional substrates, and its high surface area and related properties resulting in its ability to adsorb pollutants (contaminants, toxic compounds, heavy metals, lipids, pathogens, etc.) (7). The predicted lifespan of biochar varies based on its characteristics and applications, as it can vary from 50 years when used as a substrate in green roofs to 10 years when used as a biofilm for drinking water treatment (8). The fate of biochar after its end-of-life is normally it's decomposition into the natural environment (9).

1.1.1 Cellulose Extraction

Identifying natural materials that can be used in different applications to support sustainability and a circular economy is particularly important in today's society. Cellulose is one of the most abundant natural biopolymers, and is sourced from plants, bacteria, or algae. It is widely used due to its biodegradability, renewability, low carbon, and low-cost utilization (10). Cellulose, in contrary to other bio-based polymers (such as e.g., chitosan), which is recognised for its mechanical strength. Cellulose can be produced using materials like straw (e.g., wheat or rice straw), which is often burned as a waste by-product, even though it is a source of renewable lignocellulosic biomass (11).

The extraction of cellulose (Figure 1.1) can generally be divided into three main pathways – biological, chemical, and physical (12). In general, cellulose can be derived from different types of solid waste (urban, industrial, clothing, agricultural). The extraction process depends on the source and is influenced by factors including the type of the source material, temperature and time variations, chemical concentrations, presence and type of pre-treatment, or centrifugal force during mechanical processes(13). Chemical hydrolysis, mechanical processes and pre-treatment represent the primary methods of extraction, with some mechanical methods e.g., cryo-crushing, or high intensity ultrasonication being more expensive, and dependent on the scale of processing. Cellulose extraction is generally an environmentally friendly process, but some steps require intensive chemical input resulting in increased pollutant loads (such as alkali boiling after ultrasonic wave producing pure cellulose fibres, or strong acid (sulfuric, nitric, hydrochloric) hydrolysis producing cellulose nanocrystals) (14).

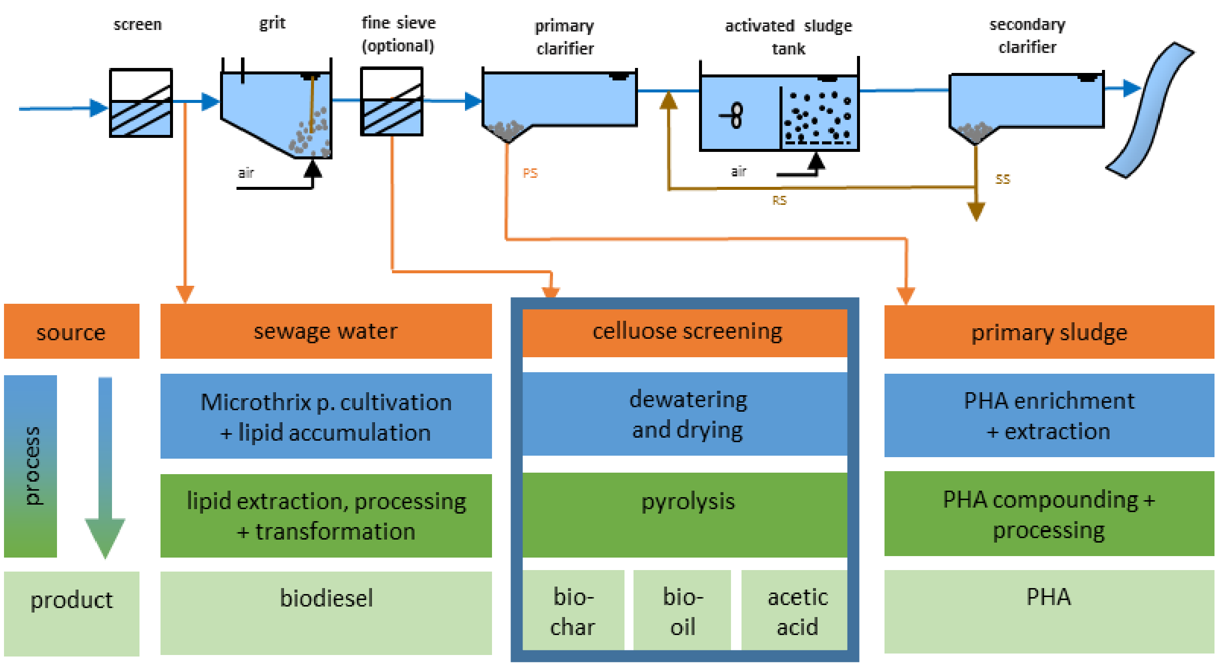

Figure 1.1. Recovery of carbon-based elements from sewage in the WoW! project, with blue highlighted area reflecting biochar production.

1.1.2 Biochar Production

Ensuring an efficient harvest and access to the feedstock of biochar represent challenges for biochar production. Improving the efficiency of production is also important, as well as the enhancement of economic performance and decrease of methane emissions. From an economic perspective, economy of scale is more sustainable as medium-to-large production facilities are favoured (> 30,000 tons per year of feedstock) (15). This required locations with a constant source of feedstock, placing small scale facilities at a disadvantage, although they can focus on producing a specific classification of biochar, with the classification process being time consuming and expensive. Biochar production also produces differently specified material, especially using unconventional sources of feedstock. Biochar can also support carbon sequestration. Biochar also has additional capabilities, as its interactions with microorganisms present a form of treatment, but it is unknown whether its production, transportation and application, its overall life cycle or circularity impacts outweigh the benefits of this product.

The economic appraisal of biochar production links to the feedstock, capital costs, operations, transport, and human resources, of which feedstock costs represents the most challenging (16). Depending on production, feedstock costs can range from 40-75% of the overall biochar production expenses.

The resource flows and processes associated with biochar production in the WOW project is detailed in Report '*D1. Report on the characterization of biochar obtained from recovered cellulose and evaluation of its potential for water purification.*'

1.1.3 Circular Economy Pathways

Sewage contains valuable substances that can be used as raw materials for biobased products. However, to date this potential has hardly been exploited to its full potential in North-West Europe (NWE). This results in loss of valuable materials, CO_2 emissions and less efficient use of natural resources. Cellulose represents an abundant global resource (17). Toilet paper is generally made from 'chemical pulp' which origin is paper. When broken down, the ingredients form creating chemical pulp are water, tree pulp, extraction chemicals for the fibre and bleach (to make the paper white). Wheat straw mainly consists of cellulose (up to 40%), followed by hemicelluloses and lignin (each up to 25% (18,19). Wood has a similar composition with 45% cellulose content, with hemicelluloses and lignin each around 25%. These three compartments (cellulose, hemicellulose, and lignin) can be labelled as general lignocellulosic biomass.

The production of biochar represents an opportunity to produce a circular product that could be used in to enhance the quality of treatment. As a circular resource, biochar used in some wastewater treatment processes can support the European's Commission's initiative to achieve good chemical and ecological status for ground and surface water bodies by 2027 (main principle of Water Framework Directive) (20,21).

Switzerland and Germany have already upgraded WWTPs for micropollutant elimination as part of long-term investments (22), but typically introduce advanced energy- or resource-intensive processes (e.g., adsorption on activated carbon and ozonation), thus constructed wetlands offers a passive nature-based solution with biochar as an embedded circular resource within the wastewater sector.

1.1.4 Application of Biochar in Constructed Wetlands

Constructed wetlands can be considered as a nature-based solution for post-treatment in small to medium-sized WWTPs (< 20,000 PE) (23,24). A wetland with 15% activated biochar substrate effectively removed most compounds. This can improve compliance with discharge standards (e.g., 80% elimination between the influent and effluent required in Luxembourg). Given the more stringent treatment standards in place for 2027, the use of biochar for micropollutant removal is necessary in constructed wetlands used for tertiary treatment.

The variability of biochar's sources can be a limiting factor for some applications e.g., constructed wetlands as it may require different pre-treatment techniques (grinding, chopping, pre-drying (depending on the moisture) or different temperatures for pyrolysis, etc. (25). When applied in the constructed wetlands, the temperature for the pyrolysis is crucial when producing biochar from sources previously used for remediation – as the presence of hazardous compounds (esp. persistent ones, such as heavy metals, PAHs, free radicals) poses a risk to the environment and human health due to potential wash-out of these compounds. To assess this risk, preliminary toxicity tests of the substrate should be carried out, so that the wetland's substrate doesn't act as a pollution carrier. Ash content is a by-product of biochar production and can also impact the performance of biochar in constructed wetlands. Further process of biochar to remove ash content makes the product more expensive. Optimal applications of biochar in a wetland, with particles of 1-2 mm, can lead to a substantial decrease of ammonia and nitrogen concentrations. However, this small particle size can lead to unwanted clogging, thus limiting the wetland's operation (26).

1.2 Circular Measurement and Assessment Methodology for biochar application

The methodology of circularity measurement aims to quantify the technical, economic, and environmental value of resource recovery and reuse to produce biochar from sewage. The case study example within the WOW! project on activated biochar from cellulose provides a context for applying the methodology in this guidance document.

The methodology is based on the new ISO 59000 family of standards for the Circular Economy, which is summarised in Chapter 2. The procedure is presents in Chapters 3 & 4 to support the evaluating of biochar production and application by comparing circularity performance, accounting for resource flows, as well as economic and environmental impacts in the form of different core and additional circularity indicators.

To undertake the circularity measurement and assessment for each scenario, the following steps are defined:

- Setting an overarching context of application for the circularity measurement and assessment within a strategic framework.
- Defining clear boundaries for the system in focus, i.e., biochar production and application to ensure a sustainability-driven outcome is effectively captured.
- Measuring circularity for defined indicators based on specified primary and secondary data requirements.
- Assessing the circular performance and reporting on the economic, social, and environmental aspects of the system in focus (biochar production and application).

Based on these steps, the findings could inform decision-makers or stakeholders on the value of biochar production for use in wastewater treatment.

2 CIRCULAR ECONOMY ISO STANDARDS

2.1 Overview of Standards

In 2020, expert representatives from national bodies around the world were brought together to begin the task of producing a set of circular economy standards to provide a harmonised approach and a universally agreed set of terminology and principles to support the transition to and measurement of circular systems.

As shown in Figure 2.1, three primary standards within the ISO 59000 family were initially defined: ISO 59004 focusing on terminology, principles and guidance for implementing circular principles; ISO 59010 providing guidance on implementing circular business models and creating value chains or networks; and ISO 59020 presenting a consistent approach to measuring and assessing circular performance of systems. Several additional complementary standards are in earlier stages of development and will provide supporting guidance for organisations to align environmental management responsibilities, tracing of material flows, and appropriate methods for organisations to implement circular business models.

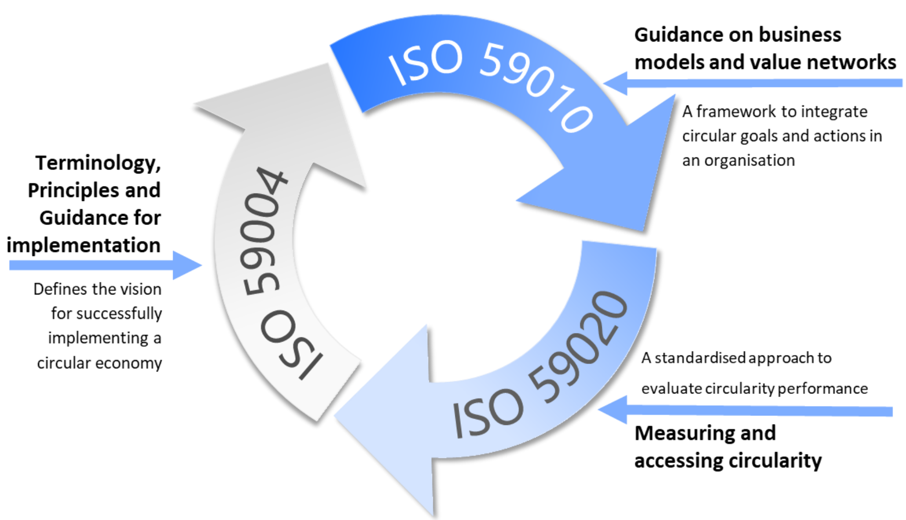

Figure 2.1. Current structure and connectivity of ISO 59000 family of standards.

The standards will be published in 2023. These standards will provide an organisation with the appropriate guidance to transform linear supply chain activities into circular value chains that enables organisations to contribute to sustainable development.

2.2 Relevant Circularity Economy Standards

In this report, ISO 59020 Measuring and Assessing Circularity will represent the primary standard to follow for this study, with ISO 14040 and ISO 14044 acting as complementary methods for life cycle assessment (LCA) to quantify the environmental sustainability of biochar production and application as the system in focus. However, the overarching guidance that is provided in ISO 59004 and the relevant indicators that are outlined in ISO 59010 will inform the measurement and assessment of activated biochar production.

ISO 59004 – Terminology, Principles and Guidance for Implementation

This standard provides the conceptual framework governing the concept of circular economy and this family of standards. This includes all the relevant terms and definitions, a rationale for circular economy and its fundamental principles, and guidance for organisations to implement circular economy values in practice.

ISO 59010 – Guidance on Business Models and Value Networks

This standard provides guidance to support an organisation prepare its vision for transitioning its existing linear business model and supply chain to a circular business model. This can be achieved by mapping the interdependencies within the value chain or value network, which can help define actions and determine strategies for implementing circularity within an organisation.

ISO 59020 – Measuring and Assessing Circularity

This standard provides a methodological process for circularity measurement and assessment for a given system in focus. This system in focus may represent a product, service, or process, and sits within an economic system, and is connected to external social and environmental systems. By considering circular goals and actions in this framework, the outputs support broader sustainable development goals.

Complementary Methods – ISO 14044 & 14044 for Life Cycle Assessment

These LCA standards act as a complementary means to evaluate the environmental burdens attributed to the system in focus, providing a means of enhancing the circularity assessment process. Complementing circularity measurement and assessment with LCA can avoid uninformed negative impacts attributed to the system in focus to strengthen its sustainable performance.

3 FRAMEWORK FOR CIRCULARITY MEASURING AND ASSESSING CIRCULARITY

3.1 Introduction

The methodology for undertaking a circularity measurement and assessment (CMA) requires the application of specific principles that are relevant to the system in focus and is conducted within a specified timeframe. In this case, Figure 3.1 provides an illustration of the CMA framework for the system in focus in this study, specifically the valorisation of activated biochar production from cellulose.

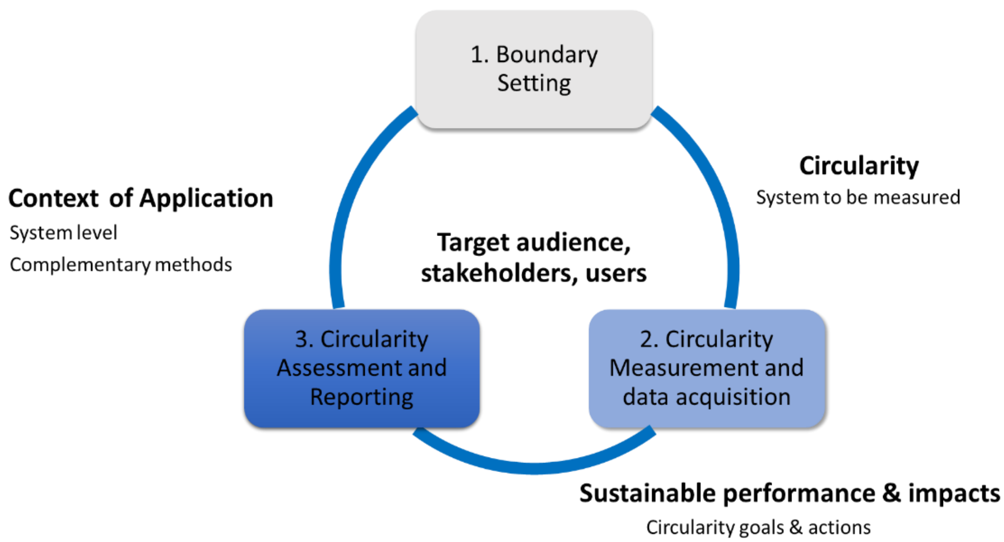

Figure 3.1. Framework overview for circularity measurement and assessment of the valorisation of activated biochar production from cellulose.

As described, the CMA framework proposed three steps for determining the valorisation potential of the carbon recovery and reuse; (i) set boundary conditions; (ii) undertake a circularity measurement and data acquisition exercise; and (iii) evaluate results through a circularity assessment and reporting. A brief overview is provided within Section 3.2, with more detailed information and guidance in relation to the activated biochar production in Chapter 4.

3.2 Context of Application

3.2.1 Purpose and Intended Use of CMA Results

The primary purpose of this activity is to apply the CMA methodology to compare the valorisation potential of activated biochar production as a circular resource.

This report represents one of the first studies to apply new circular economy principles from the forthcoming ISO 59000 family. Following the methodology presented will provide unique insights into the potential for cellulose for biochar production, going beyond complementary methods of assessment such as LCA. The methodology will also provide evidence to allow for a critical evaluation of the appropriateness of the CMA methodology on its suitability for application for resource recovered from wastewater streams. To achieve this goal, the results must reflect a range of economic, environmental, and social indicators, collectively addressing sustainability, with the findings to provide insights and value to different stakeholders representing the target audience of the study.

3.2.2 Applicable System Level(s)

The circular activated biochar as a final product is produced from cellulose fibres (coming from cellulose) from a WWTP. This novel approach defines the need for clear regional or national considerations to be considered depending on the management structures of WWTPs in a specific country. Waterboards and water authorities can represent either public or private organisations, and the consideration that contractors may take some responsibilities in the management, biochar production processing or cellulose transport activities, there is scope for both inter-organisational and organisational impacts in the value chain. Similarly, the CMA results can provide an insight into the circular and life cycle credentials of the final product itself i.e., activated biochar.

3.2.3 Circular Goals, Aspects and Actions

The circular goal aims to position the capacity of the system in focus in support a circular economy, whilst also addressing social and environmental objectives using complementary methods. The creation of a new valorisation pathway of biochar from cellulose represents the goal to be measured.

The circular aspect to be considered of importance in achieving this circular goal is to produce activated biochar (AB) for the purposes of its role in a substrate for a constructed wetland to enhance its treatment capacity of micropollutant removal from wastewater effluent.

The actions that can be derived by the results of the CMA study of biochar production from cellulose and its potential for valorisation will inform the range stakeholders (Section 4.2.4) on their options and clarify their role within the value chain. This will be created with regards to the biochar resource potential of the system in focus, and the associated economic, social, and environmental impacts as compared to a different adsorption material (activated carbon) that could be used in a similar setting.

The functional unit for assessment of biochar production will reflect 1 unit of activated biochar.

3.2.4 Relevant stakeholders in the value chain

The target audience will include a range of stakeholders within the value chain including biochar producing companies, local water authorities / waterboards, and policy makers. Each stakeholder plays a different role or has a unique impact on the value chain, with this project focusing on producing cellulose pellets, biochar and activated biochar.

For biochar producing companies, the CMA will support current and future decision-making with regards to pursing a centralised or decentralised system based on resource flows and a range of sustainability (economic, environmental, and social) indicators. It will also evaluate the quality of the cellulose pellets prior to transforming them into the biochar.

Waterboards or water authorities will be able to determine the optimal valorisation method of cellulose as a resource, depending on the size and spread of their WWTPs. For these water bodies, their boundary condition represents the provision of the feedstock (cellulose) to biochar production, depending on what infrastructural investment is implemented at WWTP sites for centralised or decentralised systems. It also allows for informed decision making on whether to support the production of biochar as opposed to using alternative adsorption materials used in other wastewater treatment processes.

Lastly, policy makers play an important role in driving standards or setting requirements for wastewater effluent treatment and end-of-life pathways for cellulose. Quantifying the circular performance of biochar production will provide evidence with regards this option for using cellulose.

4 EXAMPLE OF CIRCULARITY MEASUREMENT AND ASSESSMENT PROCESS

4.1 Step 1: Setting Boundary Conditions

4.1.1 Case Study Requirements

A case study should provide details of the case, such the scale of the WWTP for recovering toilet paper to produce cellulose, and the size of constructed wetland to effectively remove micropollutants for the WWTP. Information as to the value of activated biochar and its production are taken from literature and evidence provided by stakeholders in the value chain for the product.

The production of activated biochar from cellulose covers two valuable assets: production of a sorbent out of waste (toilet paper from WWTP screens) and application of the sorbent as a post-treatment wastewater treatment solution in constructed wetland. As such, the interest generally lies on two stakeholder groups: (i)- companies focusing on production of such sorbents (biochar, activated biochar or other types of circular sorbents) and (ii) WWTP representatives/operators as the application of the wetland unit for post-treatment and micro-pollutant removal (23, 24). The challenges with micropollutants in surface water bodies has been an emerging topic for a few decades now, and broad audience starts to be aware about this problem (toxicity of the aquatic fauna and flora and secondary toxicity to humans), inclusion of dissemination activities introducing the project to broad public are needed to deepen the knowledge about this issue.

4.1.2 Goal and Scope

The circular goal is to valorise activated biochar as a product from cellulose and provide a benchmark for production in a case study region. The circular aspect to be considered of importance in achieving this circular goal is to use a waste pathway as a resource to recover cellulose and produce biochar for micropollutant removal, as opposed to using alternative adsorption materials used in other wastewater treatment processes.

The actions that can be derived by the results of the CMA study of biochar production from cellulose and its potential for valorisation will inform the range stakeholders (Section 4.2.4) on their options and clarify their role within the value chain.

This quantity of cellulose will produce biochar can be compared to activated carbon production and impacts from carbonaceous feedstock.

4.1.3 Boundaries of the system in focus

The boundary conditions for the system in focus is to produce activated biochar from cellulose. This includes primarily production of the biochar, in particular the feedstock, the production steps, energy demands of the production, etc. For example, the geographical border of the project is restricted to NWE, thus the raw materials, production of cellulose and straw pellets, carbonization and activation of the biochar, and application of the biochar in a wetland would need to be captured in this regional boundary in the study.

4.1.4 System perspective at different levels

Biochar production could encompass a range of different levels, depending on the governance structure for wastewater treatment, the specific location of focus, and scale of production in question. Table 4.1 provides an overview specific to this assessment, providing commentary of variable factors in terms of their relevance to different levels for the system in focus.

Table 4.1. Levels of relevance for biochar production and application for the system in focus.

Level	Relevance	Outside of boundary
Organisational	For production of cellulose biochar is necessary involvement of WWTP with cellulose screen, which can provide the feedstock – the WWTP becomes the only stakeholder. The consequent process and production steps involving creation of biochar from cellulose include several contractors (other organisations contributing to these steps).	For an application of the biochar is then required to find a WWTP, where the wetland can be installed as a post-treatment step.
Product	The data required to measure and assess the circularity of producing biochar from cellulose, or undertake an LCA, can be obtained from a single organisation i.e., the WWTP/contractor as they represent the entire value network.	Incorporating the impacts attributed to the production of the equipment (components) itself that are used to produce the biochar, not just the energy they require over time.

4.2 Step 2: Circularity measurement and data acquisition

4.2.1 Circularity measurement taxonomy

The production of biochar from cellulose aims to add value to the pathway for the toilet paper present in wastewater, offering an alternative pathway to recognised management and disposal. Given the role of biochar is to replace conventional adsorbents (activated carbon) as a more sustainable product, a set of relevant circularity indicators will be defined, and an LCA and SDG mapping will be undertaken as supplementary methods of assessment to quantify biochar's environmental performance and value for a sustainable future.

4.2.2 Choice of indicators for circularity measurement

The following seven indicators were selected to be applied in the CMA, as presented in Table 4.2, which includes three core indicators and four additional indicators.

The data requirements for this assessment includes the collection and treatment of raw cellulose to produce cellulose, the provision of straw and the pyrolysis process to produce the activated biochar.

From the seven indicators, one core indicator was deemed relevant to enable a sustainability impact measurement and assessment, specifically the percentage energy from renewable energy sources.

Table 4.2. Core and additional circularity indicators from ISO 59020 and other supporting documentation to assess the valorisation of activated biochar production from cellulose.

Type	Category	Indicator Description
Core (Shall)	Outflow	Average lifetime of product or material relative to industry average
Core (Should)	Energy	Average % of consumed energy from renewable source
	Water	Percent water discharged in accordance with quality requirements
Additional	Economic	Value per mass
		Investment costs
		Production costs
	Social	Labour

Life cycle assessment indicators to complement circularity measurement

Complementary to this, a LCA was also undertaken which provides a range of relevant indicators to support an in-depth assessment of the broader range of impacts that may be associated with biochar production. Seven impact categories were selected from the EF v3.0 impact assessment method and will be applied in line with ISO 14040 and 14044 standards. These environmental burdens that should be evaluated in an assessment of producing activated biochar should include environmental, ecotoxicological status, human health, and resource usage impact categories.

Contributing towards sustainable development

To provide a link between the production of biochar and its role in contributing towards sustainable development, an evaluating of the sustainable development goals, and their related targets and indicators, was undertaken. Table 4.3 provides an overview of relevant SDG targets and indicators that relate to the biochar focus of this study and aligns with the core and how this aligns with circularity indicators considered in this report. The SDG indicators encompass social, environmental, and economic dimensions that a region could improve upon where organisations implemented biochar production to produce a circular resource.

Table 4.3. Relevant SDG targets and indicators as defined in 59020 that are relevant to the core and additional circularity indicators of the valorisation of activated biochar production from cellulose.

SDG	Target	Indicator
#6	Clean water and sanitation	6.3.1 Proportion of domestic and industrial wastewater flows safely treated.
#8	Decent work and economic growth	8.4.2 Domestic material consumption (DMC), DMC capita, and DMC per GDP

#9	Industry, innovation, and infrastructure	9.2.1 Manufacturing value added as a proportion of GDP and per capita
#10	Reduce inequalities	10.4.1 Labour share of GDP

4.2.3 Data acquisition

The data required for the CMA can be obtained from producers of the activated biochar.

Resources

To quantify a unit of activated biochar, which can be produced using toilet paper collected at the screen of a WWTP, this must be combined with an equal measure of straw to produce a 15% of that combined quantity as activated biochar (i.e., 1 unit AB). The toilet paper is used to produce raw cellulose fibres, with a dry matter content 94-95%, which decreases to circa 90%. From this, cellulose pellets are produced and mixed with the straw. The mixture is than carbonized (270 °C for 210 minutes), with material loss 70%. Finally, the pellets are activated (biological fermentation under 25-35 °C for 2-4 weeks with addition of nutrients, minerals, and microorganisms). Figure 4.1 shows the resource flows for the final biochar product.

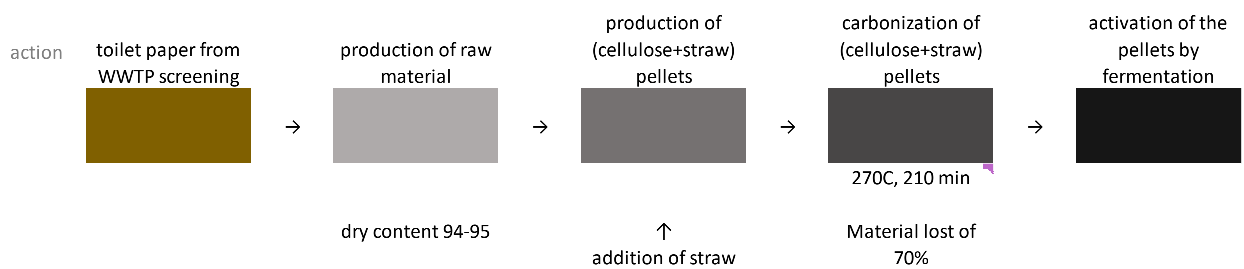

Figure 4.1. Resource flows for WOW! Activated biochar production.

Energy

The energy required to produce the activated biochar production from cellulose, specifically electricity, heat and steam must be collated. The electricity for a given country needs to be broken down into its different sources, reflecting the percentages of fossils, nuclear, and renewables (wind, solar and hydro) in a given year of focus. If heat or is produced from different sources, this breakdown of energy transformations must be quantified. Details relating to the total electricity, heat and power requirements relate to CMA are required in Table 4.4.

Table 4.4. Electricity, heat, and steam consumption to produce 1 unit of activated biochar (AB) from cellulose.

	Electricity (kWh/ unit AB)	**Heat (kWh/ unit AB)**	**Steam**	
			(ton/ unit AB)	**(kWh/ unit AB)***
All Scenarios				

Transport

The energy associated with transport can be omitted from the assessment because of the low quantity of resources being considered, and the likely negligible impact of this factor.

Additional information on operational requirements

In addition to resources, energy and transport, technical and economic data would need to be estimated based on national data. Table 4.5 details are required for the CMA, LCA and SDG evaluation.

Table 4.5. Details of modified costs specific to product.

Item	Cost	Unit	Details
Electricity		€/MWh	Average € per MWh in a given year
Natural gas		€/MWh	Average € per MWh in a given year
Labour		€/hr	€ hourly Minimum/Living/Specialist wage (for a given year)

4.3 Circularity Assessment and Reporting

4.3.1 Calculation of circularity indicators and complementary methods

Resource Outflows

To provide evidence that the production of activated biochar (AB) as opposed to an alternative resource of activated carbon (AC), this core circular indicator requires the calculation of the average lifetime of activated biochar (AB) as a product relative to the industry average, which in this case is considered as activated carbon (AC) (Eqn. 4.1).

$$LR_M = LS_{AB} / LS_{AC} \qquad \text{Eqn. 4.1}$$

Where:

- LR_M *is the lifespan ratio of the AB versus AC*
- LS_{AB} *is the lifespan of the AB (years)*
- LS_{AC} *is the industry average lifespan of AC (years)*

The link between resource outflows with LCA and SDG indicators is outlined in Table 4.6.

Table 4.6. Relationship between resource outflows as a CMA indicator with complementary LCA and SDG indicators.

Indicator type	Specific indicator	Relationship to resource outflow indicator
LCA	Seven EF 3.0 midpoint impact categories.	The production of AB will inevitably impact all EF impact categories investigated.

SDG	SDG 6.3.1 Proportion of domestic and industrial wastewater flows safely treated.	Using AB in constructed wetlands can remove micropollutants and reduce pollution.

Energy

One circular indicator focuses upon energy, which quantifies the proportion of renewable energy consumed in production (Eqn. 5.2). In addition, the quantities, forms, and sources of energy has an impact on the following LCA indicators as outlined in Table 4.7.

$$RE_{\%} = ((I_{RE} - O_{RE}) / (I_{TE} - O_{TE}))*100 \qquad \text{Eqn. 5.2}$$

Where:

$RE_{\%}$	*is the average renewable energy consumed for AB production (%)*
I_{RE}	*is the inflow of renewable energy per unit production of AB (kWh/unit AB)*
O_{RE}	*is the outflow of renewable energy per unit production of AB (kWh/unit AB)*
I_{TE}	*is the total energy inflow per unit production of AB (kWh/unit AB)*
O_{TE}	*is the total energy outflow per unit production of AB (kWh/unit AB)*

Table 4.7. Relationship between renewable energy as a CMA indicator with complementary LCA and SDG indicators.

Indicator type	Specific indicator	Relationship between energy and indicator
LCA	Climate change, incl. biogenic carbon (kg CO_2 eq.)	Reflects the climate change impact associated with the energy required to produce AB.
	Fossil fuel depletion (kg oil eq.)	Accounts for the non-renewable component of the total energy mix required in AB production.

Water

One circular indicator focuses upon water, which quantifies the percentage of water discharged in accordance with quality requirements (Eqn. 5.3). The quantities and sources of water has an impact on the following LCA & SDG indicators (Table 4.8).

$$P_{TW} = (100 . V_{CSE}) / V_{ASE} \qquad \text{Eqn. 5.3}$$

Where:

P_{TW}	*is the average circular water discharges (%)*
V_{CSE}	*is the volume of circular water discharges (m^3/yr)*
V_{ASE}	*is the volume of water inflow from all sources (m^3/yr)*

Table 4.8. Relationship between water as a CMA indicator with complementary LCA and SDG indicators.

Indicator type	Specific indicator	Relationship between energy and indicator
LCA	Climate change, incl. biogenic carbon (kg CO_2 eq.)	Reflects the climate change impact associated with the energy required to produce AB.
	Fossil fuel depletion (kg oil eq.)	Accounts for the non-renewable component of the total energy mix required in AB production.
SDG	6.3.1 Proportion of domestic and industrial wastewater flows safely treated.	Treated wastewater in which AB provides a means of enhancing water quality to meet stricter water quality requirements.

Economics

Three economic circularity indicators are considered in this assessment and relates to the value per mass of producing AB (Eqn. 5.4). This can provide an estimation of resource use efficiency and validate the production of AB as a valued product to support micropollutant removal. In addition, the associated investment costs (i.e., capital expenditure or CAPEX costs) and production costs (i.e., operational expenditure or OPEX costs) can be estimated using Eqns. 5.5 and 5.6, respectively.

$$C_{AB} = C_T + O_T \qquad \text{Eqn. 5.4}$$

Where:

C_{PS} *is the cost per unit mass of AB production (€/unit AB)*

C_T *is the total investment costs (€/unit AB)*

O_T *is the total operational costs to produce one unit of AB (€/unit AB)*

$$C_T = C_E + C_c \qquad \text{Eqn. 5.5}$$

Where:

C_T *is the total investment costs (€/unit AB)*

C_E *is the total equipment costs including piping and instrumentation (€/unit AB)*

C_C *is the total civil engineering installation works (€/unit AB)*

$$O_T = O_E + O_T + O_R + O_c \qquad \text{Eqn. 5.6}$$

Where:

O_T *is the total operational costs to produce one unit of AB (€/unit AB)*

O_E *is the total energy costs to produce one unit of AB (€/unit AB)*

O_T *is the total transport costs to produce one unit of AB (€/unit AB)*

O_R *is the total resources costs to produce one unit of AB (€/unit AB)*

O_P *is the total personnel costs to produce one unit of AB (€/unit AB)*

The economic implications of producing AB should also evaluated to align with relevant SDGs as outlined in Table 4.9.

Table 4.9. Relationship between economic CMA indicators with complementary SDG indicators.

Indicator type	Specific indicator	Relationship between economics and indicator
SDG	8.4.2 Domestic material consumption (DMC), DMC per capita, and DPM per GDP	The quantity of AB to be produced to offer enhanced water quality requirements for a given population equivalent.
	9.2.1 Manufacturing value added as a proportion of GDP and per capita	Creation of new value chain and jobs for AB production to impact GDP.

Social

A social indicator proposed to account for fair labours costs in the production of AB in Europe is the provision of a Living Wage rather than applying a minimum wage. This impact of providing a Living Wage within the cost of AB production is evaluated, thus the percentage impact on overall production costs can be considered in Eqn. 5.7. This is based on the data taken from Eqn. 5.5 and Eqn. 5.6.

$$LW_{\%} = ((O_{AT} - O_T) / (C_T + O_T))*100 \qquad \text{Eqn. 5.7}$$

Where:

- $LW_{\%}$ *is the average renewable energy consumed in AB production (%)*
- C_T *is the total investment costs to produce one unit of AB (€/unit AB)*
- O_T *is the total operational costs to produce one unit of AB (€/unit AB)*
- C_T *is the total investment costs to produce one unit of AB (€/unit AB)*
- O_{AT} *is the total adjusted operational costs to produce one unit of AB (€/unit AB)*

The social implications of producing AB can be evaluated to align with relevant SDG as outlined in Table 4.10.

Table 4.10. Relationship between labour as a CMA indicator with a complementary SDG indicator.

Indicator type	Specific indicator	Relationship between labour and indicator
SDG	10.4.1 Labour share of GDP	Increasing the labour costs to align with Living Wage requirements would increase the labour share of GPD in the region.

4.3.2 Comparative Resource

The alternative resource considered within the CMA is AC, as it offers a similar product that delivers similar treatment outputs when added to the substrate for a constructed wetland. The LCA would provide some comparative results of the biochar production from cellulose by carbonization, and the comparison of AB and AC in terms of environmental impacts . Midpoint indicators will be presented using the EF 3.0 impact assessment method to represent the direct and final impacts of AB production and its comparative to AC production.

The relevant SDGs relating to biochar production, are presented, and evaluated in comparison to AC production in Table 4.11 with respect to their impact on relevant circularity indicator results.

Table 4.11. Impact of alternative circularity pathways to produce energy (carbonization) or offset activated carbon on SDG indicators used to assess biochar resource recovery from cellulose.

SDG Indicator	Alternative Pathway (Activated Carbon)
6.3.1 Proportion of domestic and industrial wastewater flows safely treated.	AB and AC both offer treatment performance, but which one achieves this with the lowest environmental burdens.
8.4.2 Domestic material consumption (DMC), DMC capita, and DMC per GDP	Biochar produces a product for the economy, carbonization presents an end-of-life for the resource.
9.2.1 Manufacturing value added as a proportion of GDP and per capita	Increased regional manufacturing to support biochar production, thus increasing manufacturing added value as a proportion of GDP as compared to other cellulose/carbon? resources pathways.
10.4.1 Labour share of GDP	More jobs required to support biochar production, thus increasing labour share of GDP as compared to other cellulose/carbon resource pathways.

4.3.3 Complementary Methods

Environmental - Life Cycle Assessment

Selected midpoint category boundaries for LCA of this case are cradle-to-grave ‘limited’, as the end substrate’s application in the wetland configuration is novel and the lifespan of the technology is unknown. The geographical boundary is federal state of Saarland, Germany, area typical with high abundance of small WWTPs.

Typical impact criteria for this case are freshwater ecotoxicity (EF); climate change (CC); land use (LU); human toxicity (carcinogenic (HC) and non-carcinogenic (HN)); water use (WU); and non-renewable energy resources (ER). The environmental burdens associated with each of these impact categories are in this case considered for the substrate. The inventory data are normally obtained from the Ecoinvent database, with a comparison of one unit of substrate.

Such an assessment, as show in Figure 4.2, can provide informative evidence of the environmental impacts of activated biochar production as compared to activated carbon. It offers an addition to conventional substrates for similar wastewater treatment applications (activated carbon as a substrate for post-treatment step) but offers improve treatment. Biochar produced from cellulose sourced from toilet paper, typically generates environmental impacts for land use are higher for biochar, as wood sources (trees, etc.) cover bigger area, then activated carbon sources (coal).

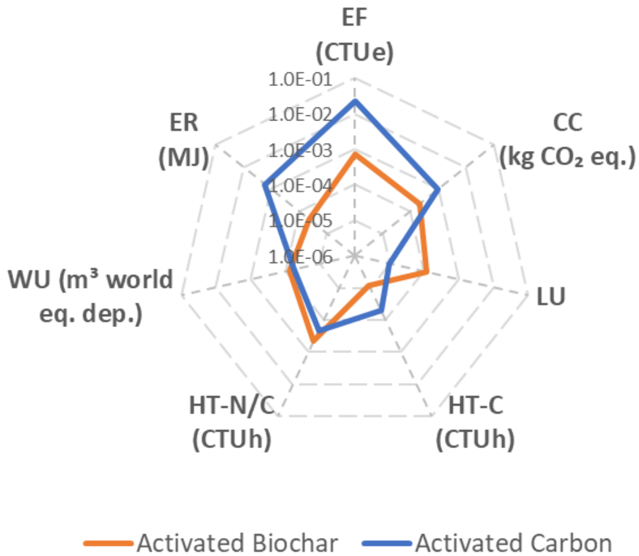

Figure 4.2. Comparison of LCA results for one unit of activated biochar and activated carbon.

When considering one unit of activated biochar versus one unit of activated carbon, four of the seven impact categories presented lower burdens for activated biochar as opposed to activated carbon as a resource to add to the substrate of a constructed wetland: ranging from 30-40 times higher for non-renewable energy resources (ER) and freshwater ecotoxicity (EF) to 4-6 times higher for climate change (CC) and carcinogenic human toxicity (HT-C). Water use (WU) and non-carcinogenic human toxicity (HT-N/C) were 1.4-2.1 times higher for the activated biochar than for the activated carbon, with land use (LU) over 11 times higher for activated biochar.

It is foreseen that with the upscale of the technology the substrate will represent main impact category in these systems, so improving the production of this resource can help control its associated burdens.

4.3.4 Stakeholder reporting

The CMA outputs can provide the technical, economic, and environmental value of resource recovery and reuse to produce biochar from sewage. This can inform stakeholder decision-making to implement biochar in constructed wetlands and strengthens the case for using biochar as a sustainable product.

This information is of value to wastewater treatment companies who would finance and deploy constructed wetlands as a sustainable nature-based solution.

5 CONCLUSIONS

This study presents the circularity measurement and assessment (CMA) methodology that would allow for a carbon recovery product from wastewater to be evaluated. To provide a context, forthcoming ISO standards and its governing framework are presented within this study to support a case study example to be evaluated in the future. Current limitations of data availability limit the current capacity for a CMA of activated biochar (AB) to be undertaken, with guidance provided in this report outlining the most relevant indicators to capture the technical, economic, environmental, and social impacts in producing AB.

The framework presented in this report provides the governing principles for the CMA. This includes (i) setting the boundary of the system in focus, (ii) defining the goals, aspects, and actions to be measured or derived using acquired data, and (iii) providing appropriate guidance on the details required within the assessment and reporting phase to address all relevant stakeholders. The CMA focuses on a set of relevant indicators, and in addition the process applies both life cycle assessment (LCA) and sustainable development goal (SDG) mapping as complementary methods to produce additional outputs.

From the CMA, seven indicators were selected as the most appropriate for the evaluation of AB, with one representing a core indicator and six additional indicators, all of which align with newly formed standards (ISO 59020). These indicators reflect resource flows, energy, and water, as well as economic and social metrics. A subset of environmental indicators within an LCA, and a group of specific SDGs (#6, 8#, #9 and #10), were selected as complementary outputs for the CMA.

A comparative analysis between AB and activated carbon considered one unit of both materials and demonstrated the differences in the associated environmental impacts due to differences in sourcing and production of both materials.

A complete circularity measurement and assessment (CMA) can provide evidence for key stakeholders on the environmental performance of activated biochar as a product and its contribution to constructed wetlands for enhanced treatment. Furthermore, this can be of value to key stakeholders to inform their decision making in relation to investing in infrastructure for cellulose treatment and activated biochar production. This methodology can allow stakeholders to collate relevant data to produce CMA results that provide a benchmark for activated biochar production and enhance the circularity of wastewater sector.

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