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LETTER

Biochar carbon removal from residues in Germany—assessment from environmental and economic perspectives

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Abstract

The topic of biochar carbon removal (BCR), which refers to the pyrolysis of biomass, is increasingly being discussed as a potential solution for the long-term removal of carbon dioxide from the atmosphere. However, BCR technology assessments in Germany, which are used as the basis for strategic decision-making, are often limited to woody biomass as an input material and are based on old data. Consequently, this study focuses on BCR from forest residues, straw and sewage sludge and assesses its contribution to negative emissions under current techno-economic framework conditions. Using life cycle assessment and annuity method, as well as complementary stakeholder engagement formats, the study provides a comprehensive analysis of BCR pathways in Germany based on an empirical, up-to-date data basis. The results highlight the environmental advantages of BCR, particularly in reducing greenhouse gas emissions compared to the conventional treatment of residues. The economic feasibility of BCR is uncertain, with profitability dependent on plant scale, biomass type and the integration of energy co-products. Stakeholder insights underscore the necessity for supportive policies and investment in BCR technology to enhance scalability. This interdisciplinary approach enriches the discourse on BCR's role in achieving carbon neutrality and offers a robust data foundation for future evaluations.

1. Introduction

In face of the expected long-term development of anthropogenic greenhouse gas emissions, the employment of carbon dioxide removal (CDR) technologies becomes necessary to reach carbon neutrality and global net negative emissions in the long-term [1]. A technologically mature option is biochar carbon removal (BCR), i.e. the pyrolysis of biomass for the production of biochar. Pyrolysis is the breaking up of organic substances at temperatures from 350 to 1000 °C in the absence of oxygen [2][4]. Used as soil amendment in agriculture, the product is a permanent carbon sink [3, 4] with additional potential positive impacts such as an increase in water retention capacity, soil organic carbon, or plant available nutrients [5]. As further co-benefits, pyrolysis plants can provide heat and power for the energy sector, by utilizing the exhaust heat generated in the process.

By the end of 2023, 171 BCR production plants were operating in Europe with a total annual production capacity of 75 000 metric tonnes (t) of biochar (or around 200 000 t of removed CO_2) of which 26% are located in Germany[5]. Studies for Germany assume BCR potentials of 2.9 [6] to 12 million metric tonnes (Mt) CO_2 $yr^{-1}$of removals [7] in 2050 if

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[4] EBC 2012–2023 *European Biochar Certificate—Guidelines for a Sustainable Production of Biochar* Version 10.3 from 5 April 2022 (Frick, Switzerland: Carbon Standards International (CSI)) [cited 15 May 2024]. Source: www.european-biochar.org/media/doc/2/version_en_10_3.pdf.

[5] European Biochar Industry 2023 *European Biochar Market Report 2023 × 2024* [cited 10 April 2024]. Source: www.biochar-industry.com/market-overview/.

biomass residues are used. For comparison: Luderer *et al* [7] estimate Germany's CDR demand to be between 41 and 74 Mt CO_2 yr^{-1} in 2050 for greenhouse gas neutrality. In the Key Principles of the German Government's long-term strategy on negative emissions of February 2024[6], BCR has also been mentioned as a viable CDR option.

Until 2023, the standard BCR case in Europe was the pyrolysis of woody biomass. The EU regulation on fertilising products (Regulation 2019/1009) excluded other substrates for soil additives from pyrolysis. Since July 2022, the restrictions are partly lifted. For the future, the industry is discussing agricultural crop residues, such as straw, and sewage sludge as inputs[7], both showing technical biomass potentials in Germany [8]. Although straw is approved as an input for soil additives and sewage sludge is still not under EU Regulation 2019/1009.

However, in research, comprehensive assessments of BCR beyond woody biomass represent a research gap. Broader, nationwide studies focussing on biomass utilization pathways for CDR [e.g. 9], or on CDR technologies in general [e.g. 10,11] typically model a generic pyrolysis plant using woody biomass. Teichmann [6] in turn focuses on a broader set of BCR pathways in a techno-economic analysis. However, in summary, the portfolio of nationwide studies is either built on technically and economically old secondary data, analyses cover only BCR via woody biomass or neglect co-benefits such as energy provision. On the other hand, more specific BCR case studies are rather based on empirical but case-related data [e.g. 12,13]. Thus, the potential for generalization is limited. Furthermore, interdisciplinary approaches and social science aspects are underrepresented in BCR assessments [14, 15].

Based on this, we derive a need for up-to-date, empirical and comprehensive assessments of a broader set of BCR pathways including co-benefits.

To address this gap for the German context, we pose the following research question for forest residues (FR) as well as for straw and sewage sludge as two exemplary novel input biomasses from agriculture and wastewater treatment that are being considered for the further roll-out of BCR: can BCR based on these biomass residues contribute to achieving negative emissions under the current techno-economic framework conditions? More specifically, we address the following sub-questions:

- What are the environmental benefits and drawbacks of BCR compared to conventional reference processes?
- Is BCR economically feasible and how much do potential changes in the cost and revenue items influence the economic result?

The goal of this paper is to assess the sustainability of BCR from different residue streams yet to be developed in the prevailing techno-economic environment under consideration of potential co-benefits from energy provision. To achieve this objective, a life cycle assessment (LCA) and economic analysis (annuity method) are conducted for a generic pyrolysis plant. In the course of this, obstacles and options for action for the further BCR roll-out are discussed from the perspective of relevant stakeholders. By this, we aim to enrich the scientific and political discussion on BCR's role as a CDR option.

2. Methods

2.1. Focus, general approach and data basis

To address the outlined research questions, we apply an interdisciplinary approach including methods from environmental (life cycle analysis) and economic (annuity method) sciences.

Furthermore, we pursue a transdisciplinary research concept by actively involving relevant stakeholders from outside academia in the research process to explore specific topics, for data exploration, as well as for the verification and discussion of results [see 16]. For the latter, a guided online focus group discussion and a stakeholder workshop were conducted. The findings are considered in the discussion and interpretation of the analyses. Background information and detailed results are presented in the Supplementary Information.

In figure 1, the systems under consideration are displayed with their inputs, major processing steps and outputs. Biomass is pyrolyzed at high temperatures in the absence of oxygen using electrical energy for process initiation and resulting in the products biochar and pyrolysis gas. The gas can provide heat using a heat exchanger and electricity using an organic ranking cycle. The biomass is used on agricultural areas and thus becomes a C sink.

To create a current data basis for the quantitative analyses, primary data on techno-economic and environmental aspects of BCR was collected using questionnaires. A total of eight plant manufacturing companies from German-speaking countries were contacted in 2022/2023, four of which completed the questionnaire. The primary data was supplemented with data from literature, public manufacturer data and selected publications from a meta-study on environmental parameters. The consolidated data is published as separate data documentation [17]. It contains three generic process configurations covering

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[6] BMWK 2024 Langfristige Negativemissionen zum Umgang mit unvermeidbaren Restemissionen (LNe)—Eckpunkte [cited 26 April 2024]. Source: www.bmwk.de/Redaktion/DE/Downloads/E/240226-eckpunkte-negativemissionen.pdf?__blob=publicationFile&v=4.

[7] Bier H, Gerber H, Huber M, Junginger H, Kray D, Lange J, Lerchenmüller H and Nilsen P J 2020 EBI Whitepaper Biochar-based carbon sinks to mitigate climate change *EBI*. Source: www.biochar-industry.com/wp-content/uploads/2020/10/Whitepaper_Biochar2020.pdf.

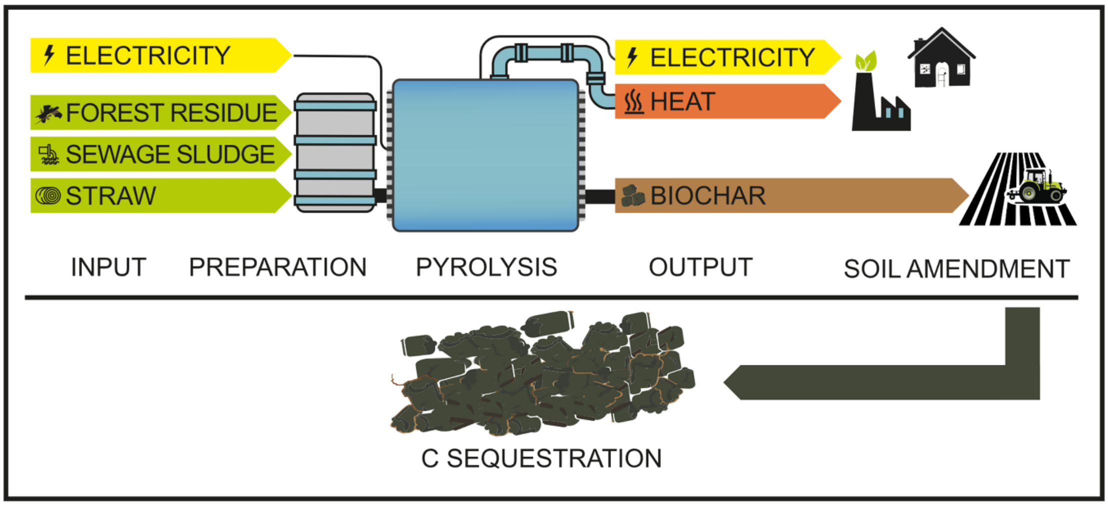

Figure 1. BCR system considered in the analysis.

key parameters on the production and use of BC in Germany[8]. The process configurations differ in size and type of decoupled energy and can be used as such or be adapted for individual analyses. In this research article, the configurations serve as a common starting point for the cases that are analysed in the LCA and the annuity method.

2.2. LCA

The environmental evaluation of the pyrolysis system is carried out using the standardized LCA method based on the ISO 14040/44 guidelines [18, 19]. We analyse three biomass scenarios which cover both electricity and heat extraction for the reference year 2020.

To deal with the multiple benefits of the pyrolysis the utility basket method is used [20]. Each benefit of the system is compared to a reference process. The benefits in the system and the reference should be equal, which can be achieved with offsets. In this case, the functional unit describes the following system: system output of 1600 t biochar and correspondingly specific biomass input depending on the type of biomass (FR: 6400 t of dry matter, straw: 6400 t of dry matter, sewage sludge: 4000 t of dry matter) per year. The benefits of the system are the utilization of residual materials and the provision of heat and electricity (8000 full load hours and continuous electricity and heat generation for industrial use). C sequestration is handled as an effect in the pyrolysis system.

For comparison, the pyrolysis systems are contrasted with a conventional system with the same biomass input benefits. For energy provision, this is CHP (FR, straw) and MI (sewage sludge), respectively. Since the reference processes provide more energy than the pyrolysis it has to be offset in the pyrolysis system using conventional mix for electricity and natural gas for heat. Multi-output of both BCR and reference systems is approached with system expansion. In so doing, credits are awarded for the provision of renewable energy in the form of electricity and heat, as these substitute the conventional energy mix. The German electricity mix is credited for electricity and generation with natural gas for heat. The system boundaries are set cradle-to-grave and cover the provision of biomass to the production of biochar and its application on the agricultural field, as well as transportation processes.

For a conservative approach, effects in the soil and following effects, such as higher yields or better water retention capacity, were not considered. A reduction in nitrous oxide emissions in the field is also not considered, as there is a lack of scientific evidence for this, especially when focusing on German soils. The empirical data basis for foreground processes was matched with background datasets from the Ecoinvent 3.9 database [21]. The impact assessment follows the EF 3.1 framework [22].

We focus on the impact category of global warming potential (GWP) in tonnes of carbon dioxide equivalents (t CO_2eq). The assessment for the other impact categories can be found in the supplementary information in table S2. The environmental impacts of biomass production, plant construction, plant operation, energy flows (including offsets) and transportation are shown, as well as the environmental benefits of the carbon sink function of biochar.

2.3. Annuity method

The economic efficiency of producing BC is evaluated using the annuity method according to German VDI standard 6025 [23] for the reference year 2023. The method compares investment in a technical installation for a given interest rate within certain

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[8] A detailed description of the data collection and derivation of the process configurations is given in the supporting document for the data documentation.

Table 1. Key assumptions for each case of the economic analysis. The profitability is calculated for an interest rate of 6% over an observation period of 15 yrs. Other general assumptions include heat revenue of 6 ct kWh^{-1}, BC revenue of 300 €/t BC (dry, untreated), CO_2 removal revenue of 130 €/t CO_2eq and electricity revenue of 18.6 ct kWh^{-1}.

	Unit	S(H)-FR	S(H)-ST	M(H)-FR	M(H)-ST	I(H&P)-FR	SLUDGE
Type of biomass		Forest residues	Straw (pelletized)	Forest residues	Straw (pelletized)	Forest residues	Sewage sludge (dried and pelletized)
Biomass throughput	t ds yr^{-1}	760	760	1904	1904	6400	347
Conversion rate biomass to BC	% (ds)	0.25	0.25	0.25	0.25	0.25	0.41
Biomass price	€/t ds	100	226	100	98	100	−98
Rated thermal power	kW	160	160	400	400	1.200	0
Rated electrical power	kW	0	0	0	0	220	0
Operating hours	h yr^{-1}	8000	8000	8000	8000	8000	7700
Hours of heat decoupling	h yr^{-1}	6000	6000	6000	6000	8000	6000
Investment cost	€/t ds biomass	721	747	692	705	971	6497
Operating cost	€/t ds biomass	58.4	60.6	38.1	40.3	34	151.9

investment period by calculating the annuity. The annuity is a constant annual payment that is determined by summing the present values of all cost and revenue streams that occur during the investment period, including one-time investment cost, periodic cost, such as maintenance costs or biomass procurement costs, as well as periodic revenues, i.e. from selling BC or energy. A positive annuity means that an investment is economic, while the annuities of different plant designs can also be compared with each other.

For the economic analysis, six cases are created from the biomass types considered and the process configurations derived in the data documentation [18]. The process configurations are referred to as S(H), M(H) and I(H&P), the biomass types as FR, ST (straw) and SLUDGE (sewage sludge). As depicted in table 1, each process configuration was evaluated for FR. For straw, only two cases for the smaller process configurations were evaluated, since supplying the largest process configuration with straw was considered to be too costly. For sewage sludge, data from [24] was used to derive a single case (SLUDGE), because it provided a data basis that also included energy and cost data for pre-processing the sewage sludge. The realisation of the cases S(H)-FR, S(H)-ST, M(H)-FR and M(H)-ST are considered to be possible on medium to large farms in Germany, where the decoupled energy is used to heat agricultural buildings or a local heating network. The case I(H&P)-FR evaluates a pyrolysis plant which supplies industrial production with thermal and electrical energy. Lastly, the case SLUDGE analyses sewage treatment using pyrolysis. The tables S1, S3 and S4 in the supplementary information provide detailed data on the biomass considered and all techno-economic assumptions.

3. Results

3.1. LCA results

Overall, the forest residue system provides the most energy, while the sewage sludge system provides the least (due to different calorific values). The conventional treatment of the three residual materials is in general more beneficial from an energy supply perspective and directly translates to higher offsets for BCR cases (depicted as 'energy offsets' in figure 2) according to the utility basket method.

Considering the overall GWP (figure 2) result, all considered biomass treatments, both BCR and conventional, deliver environmental benefits (from −560 up to −5392 t CO_2eq) due to achieving negative emissions in form of biochar and substituting nonrenewable electricity and heat.

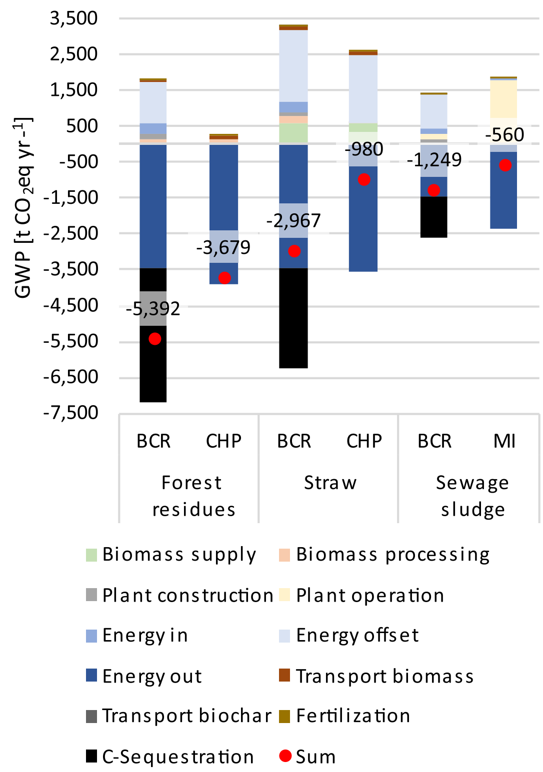

Figure 2. Global warming potential (GWP) in t CO_2eq yr^{-1} for the treatment of forest residues, straw and sewage sludge by pyrolysis and CHP/MI. *Source*: own calculations.

In direct comparison per biomass, the BCR of FR achieves better results compared to CHP, with a difference of 1712 t CO_2eq. Also, straw and sewage sludge perform better when pyrolyzed, with −2967 compared to −980 t CO_2eq for straw and −1249 compared to −560 t CO_2eq for sewage sludge.

On a life cycle level, the generation of negative emissions and the energy flows (especially the substitution of electricity and heat) have the biggest impact on the results. All three biomasses provide different amounts of negative emissions (when pyrolyzed), depending on the C content of the biochar produced (see table S1 in the supplementary information). The carbon sequestration function of biochar has the greatest influence on the GWP result of straw and forest residue pyrolysis. Since more energy can be decoupled in the conventional energy treatment of FR and straw, the credit for energy substitution also plays a decisive role in this context. For sewage sludge, process operation plays a significant role in MI (direct process emissions). The different data quality of the systems investigated should also be noted here, which can result in corresponding differences. Other life cycle stages, such as plant construction and transportation play a subordinate role in the results.

Since the substitution of electricity and heat is a crucial factor in the comparison of pyrolysis and conventional treatment, we performed a sensitivity analysis which considered a future renewable energy system, and the results changed significantly. The feed-in of energy and corresponding credits play a much smaller role and the generation of negative emissions dominates the comparison between the pyrolysis system and conventional energy use of the residues. Concerning sewage sludge effects such as phosphorus recycling, which are not included in the quantitative analyses, also play a role in the future and can be approached with pyrolysis. In addition to the GWP, other environmental impact categories were also calculated (see table S2 in the supplementary information). Land use for the straw-based BCR system stands out in particular, which is attributable to the cultivation. Resource use (minerals and metals for the plants) is also noticeable, while the transportation of the biomass to the plant plays a subordinate role in general.

3.2. Economic results

Figure 3 shows the composition of the specific annuity in € per ton of produced BC for each case. The specific annuity allows for an assessment of the economic viability of a business model and for a comparison of the profitability of plants with different amounts of BC production. Five key results derive from the figure: First, economic production of BC via slow pyrolysis is uncertain in Germany. Four cases are not profitable, one is at the edge and only case I(H&P)-FR is economically viable under the assumed conditions. Secondly, all pyrolysis products (BC, renewable energy and carbon removal) are important for an economic business model. Thirdly, economies of scale occur, as larger plants are more profitable than smaller plants that utilise the same biomass type. Scale advantages do not only occur for the pyrolysis unit itself, but also with regards to the necessary infrastructure typical for bioenergy plants, such as biomass storage, pre-processing or conveyor technology. Fourthly, the use of FR is more economic than using straw. This is due to higher biomass supply cost for pelletized straw in case S(H)-ST, where external pelletising is assumed, and due to higher capital and electricity cost in case M(H)-ST, where own pelletising is assumed. Lastly, BC production from sewage sludge is the least favourable economic option, as the assumed capital cost for pre-treatment facilities, for instance drying, are much higher. This reflects the fact that sewage sludge treatment is a municipal task of waste disposal, which generates costs.

To address uncertainty regarding key cost, revenue and operation parameters, figure 4 shows the results of a sensitivity analysis. The analysis is depicted for I(H&P)-FR, but other cases showed similar results. A decrease of the operating hours by 20% has

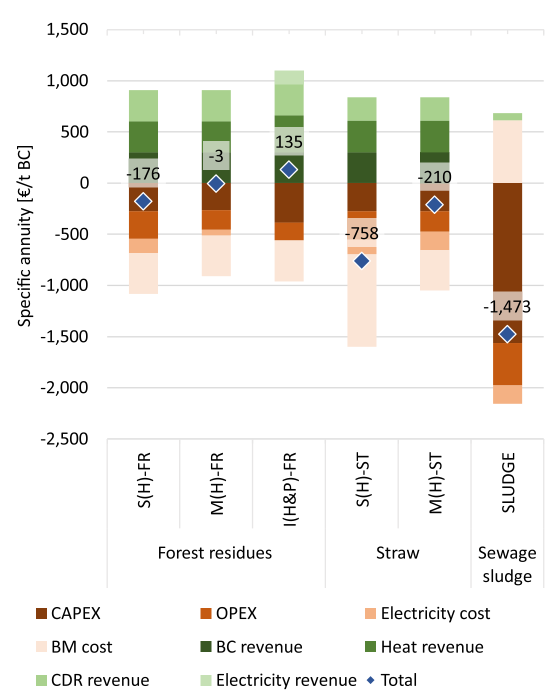

Figure 3. Composition of specific annuity in € per ton of produced BC for the analysed scenarios. The green bars indicate revenues, the red bars indicate costs. In case of sewage sludge, the costs for biomass are disposal costs and thus positive. The blue diamonds and their labels represent the total annuity. If the annuity is below zero, investment is not economic. *Source*: own calculations.

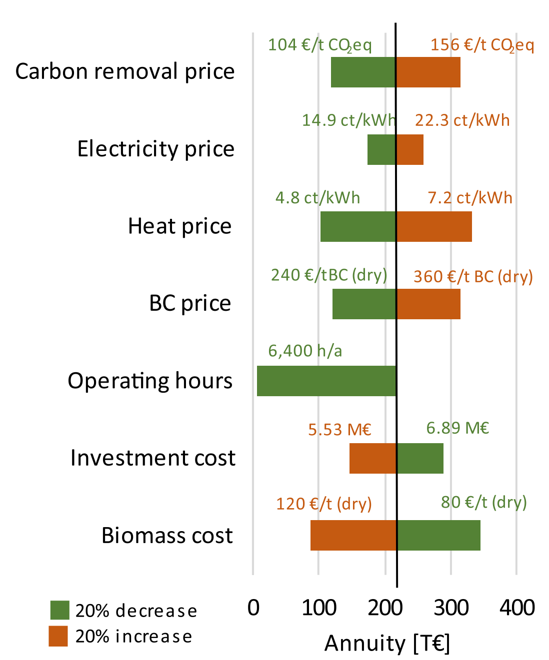

Figure 4. Sensitivity analysis of key cost, revenue and operating parameters for scenario I(H&P)-FR. The abscissa shows the absolute annuity in thousand € for a 20% increase (orange bar) and a 20% decrease (green bar). *Source*: own calculations.

the strongest effect on profitability and almost turns the case unprofitable. The biomass supply cost shows the second strongest effect on the economic viability. On the revenue side, the price achieved for BC, heat and carbon removals has an almost equally strong effect, followed by investment cost and lastly the achieved price for electricity sales. The dependence of the BC production costs on the revenues from carbon removal certificates is further evaluated: Assuming an average carbon removal price of 130 €/t CO_2eq[9], BC production costs between 165 and 1058 €/t BC could be achieved in case I(H&P)-FR and case S(H)-ST, respectively. An assumed price of 300 €/t CO_2eq for carbon removal results in a range of BC production costs between −235 and 759 €/t BC for the same cases, meaning that in the most profitable case, the BC could be sold for free.

4. Discussion

4.1. What are the environmental benefits and drawbacks of BCR compared to conventional reference processes?

In a comparison between the three biomasses under consideration, FR perform best concerning the generation of negative emissions. However, if the difference between reference and pyrolysis system is compared, straw has the highest potential over the conventional treatment.

From an energy perspective, the reference processes provide more renewable electricity and heat than BCR and, thereby, ensure valuable GWP effects as they substitute the conventional national energy mix. However, as (especially) the electricity mix becomes less CO_2-intensive in the future, its substitution becomes less and carbon sequestration more important. BCR therefore not only already provides GWP benefits today, but these will potentially increase in the future. Thus, prioritising biomass flows between BCR and other processes implies a (political) prioritisation between energy and negative emissions.

Net negative CO_2 emissions via carbon sequestration are achievable in all pyrolysis systems considered (−1249 t CO_2eq (sewage sludge), −2967 t CO_2eq (straw), −5392 t CO_2eq (FR)), thus confirming previous LCA literature. Due to the different presentation of the results (e.g. in relation to input quantity or biochar output) in previous studies and different system boundaries, our results are not directly comparable. However, our mass-specific results per ton of BC are in line with previous studies: −2932 kg CO_2eq/t BC [25] vs. −3370 kg CO_2eq/t BC for FR, −1854 kg CO_2eq/t BC [26] vs. −1854 kg CO_2eq/t BC for straw. As for sewage sludge, comparisons to previous LCAs are not possible because of methodological differences (system boundaries, functional unit, allocation).

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[9] Average market price for BC carbon removal on puro.earth from 08/23 to 01/24. Source: https://puro.earth/corc-carbon-removal-indexes, accessed on 1 February 2024.

The focus group and stakeholder workshop highlighted the limited experience with non-woody biomass and the need for scientific research on the quality of biochar from different raw materials and the amount of carbon sequestered. Setting quality standards, conducting field experiments, promoting co-products and cascading use, and identifying alternative BC applications were proposed as measures to mitigate or ensure the envisaged environmental effects.

The provision of energy in the form of heat and/or electricity has not been taken into account in many studies to date [25, 27, 28]. Our results show, that the supply of energy is indeed relevant in the GWP balance in addition to the negative emissions generated. In many LCA studies, the reduction of field emissions from the agricultural use of biochar is also taken into account (see [29–32]). However, the actual reduction of field emissions has not yet been observed in climate zones typical for Germany with a realistically low application rate of biochar, which is why they were not considered in this LCA.

Other effects of biochar on the soil, such as water retention capacity and humus formation, could not be considered in the LCA. Further products of the pyrolysis system (e.g. pyrolysis oil or flexibility service in the electricity system) or other functions (phosphorous recycling when pyrolyzing sewage sludge) were also not considered.

4.2. Is BCR economically feasible and how much do the cost and revenue items contribute to the economic result?

The results of the economic analysis show that BC production is largely unprofitable under the assumed conditions. The stakeholders who participated in the focus group and stakeholder workshop confirmed these results. They mentioned high production costs and investment risks, as well as the need for information on viable business models and for financial support. The stakeholders proposed options for action like organisational measures (such as mergers to achieve economies of scale), a reduction of investment costs via learning curve effects, and direct financial support. Furthermore, the stakeholders emphasized the need for embedding BCR in an official regulatory framework to achieve a more predictable price for carbon removals. This is supported by our economic analysis: The only profitable case in the economic analysis requires a carbon removal price of at least 72 €/t CO_2eq on a voluntary market to break even and BC production costs inversely proportional to the carbon removal price. The analysis considers a price of 300 €/t BC for untreated BC in intermediary trade, which was partially considered as too low by stakeholders. However, this price is considered for intermediary trade and will increase for ready-to-use BC. Furthermore, the stakeholders identified high BC prices as a significant economic obstacle. They suggested two options for action: time-limited subsidies for BC prices funded by public institutions and the own production of BC by farmers using residual materials.

The sensitivity analysis shows the strong influence of the operating hours and the biomass cost on the economic feasibility, the former indicating a conflict of interest between uptime maximization and flexible energy generation, the latter indicating the high risk of usage competition for biomass that increases the cost. The necessity of revenues from all pyrolysis products reflects the results of current literature [12, 24, 33, 34]. Economic benefits from larger pyrolysis units explain why economic operation of a pyrolysis unit on a farm level is currently not feasible, which is in line with a current study on farm-scale BC production from late-harvest grass in Germany [35]. Our analysis further showed economic advantages of FR in comparison to straw and sewage sludge, due to higher capital and operating cost for pre-treatment, such as drying and pelletizing. This corresponds with the findings of a current study that evaluates the economic feasibility of pyrolysis in a local heating network in Germany [12]. However, two other studies find that BC production from straw is cheaper than from FR due to differences in the underlying assumptions [36, 37]. Concerning the cost of BC production from sewage sludge the results of these studies are different, as [37] states, corresponding to our results, significantly higher costs than from straw and FR, while [36] finds significantly lower costs[10]. The BC production cost range identified in this paper is within the costs identified in recent literature (−89–1031 €/t BC [12, 24, 33, 34]) and observed current market prices of between 288 and 1740 €/t BC[11]. The ranges in production cost reflect that BC is not a homogenous product with varying prices depending on the quality standard (i.e. the EBC certification class) and that the costs are dependent on the plant-specific context.

Important limitations include the fact that the economic analysis is highly dependent on cost and price assumptions with unpredictable future development. Furthermore, the positive impacts of BC application on ecosystem services, such as increasing phosphor availability and the reduction of N_2O leaching and emissions [38, 39], are not considered in the economic analysis. This is important to consider in future research, but is beyond the scope of this paper, as the monetary impact on the business perspective of an individual actor is yet unclear.

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[10] This very positive economic result for sewage sludge is based on assuming high avoided treatment cost as additional income and comparatively low capital cost [37].

[11] Source: Own web research of BC sellers in Germany.

4.3. Can BCR based on FR, straw and sewage sludge contribute to achieving negative emissions under the current techno-economic framework conditions?

BCR via FR, straw and sewage sludge show significant potential per tonne of biomass for achieving negative greenhouse gas emissions. Environmental advantages over reference processes with higher energy output can even improve in the future. However, the economic framework for BCR is not yet favorable enough to support the investment decisions needed for broader market diffusion. Furthermore, stakeholder interactions revealed multiple non-financial challenges for further scaling such as a lack of awareness of BCR and regulatory barriers.

Moreover, the results for straw, as an agricultural residue, and sewage sludge, as residue stream from municipal wastewater treatment with a specialized business model, are very different from the results for woody biomass. Thus, the results support our motivation to carry out more specific technology assessments on BCR. On the other hand, in March 2024, the German Scientific Advisory Board for Fertilization Issues recommended, with reservations, using FR for biochar production as soil amendment due to competition with material and energetic use, but no use of straw due to competing uses for soil organic carbon and also no use of sewage sludge because of 'uncertain pollutant removal and unsatisfactory phosphorus availability'[12]. However, in the case of straw, we point out that existing regional surpluses may allow for pyrolysis, that non-agricultural usage with carbon release (e.g. incineration) is already in place instead, and that returning biochar might compensate for soil organic carbon losses resulting from straw removal [40]. As for sewage sludge (which is still not allowed under European fertilizer law), pyrolysis should be considered as a viable utilization path if legal limits for substances and nutrient recovery can be met. If not, BC might still be used for other purposes than soil application. Thus, although biomass-specific, the board's recommendations still appear too generalized. Nevertheless, the continuing recommendation list of biomass residues for BCR issued by the advisory board[7] can serve as a starting point for further specific technology assessments.

This leaves the general question of the role of BCR as CDR method in Germany. The focus group and stakeholder workshop showed that both the demand and the supply side have depended on each other's pioneering goodwill to buy and provide a sustainable product in evolving framework conditions. Under these circumstances, however, scaling is limited. To pass from the still ongoing market introduction phase (partly even research and development phase for novel types of biomass residues) to the market growth phase, an empowering political framework for providing negative emissions and realizing BCR, as well as active regional and local actors, need to come into play.

Since, on the one hand, relevant CDR volumes are needed by 2045 and Germany is starting from practically zero today, and on the other hand, BCR is one of the most mature CDR options, it should be promptly addressed at the political level. As BCR touches various political domains (e.g. national and EU strategies and regulations on negative emissions, biomass utilization, energy, waste, fertilizer), creating a consistent policy framework will be particularly challenging. Nevertheless, as a result, CDR stakeholders in general can learn from BCR introduction and ramp-up.

5. Conclusion

We carried out an inter—and transdisciplinary assessment of BCR from three residues in Germany: woody biomass (as standard case) as well as straw and sewage sludge as potential novel biomasses. The analyses are based on an up-to-date data basis including empirical results from a questionnaire and manufacturer data.

The LCA results show that all three BCR pathways can provide negative emissions and (except in the case of sewage sludge) greater GWP mitigation than reference processes. However, from an economic perspective, BCR is either marginally profitable in the medium and industrial cases with usage of FR or not profitable in the remaining cases. Furthermore, BCR faces multiple non-financial challenges, which calls for an adjustment of the economic and legal framework in the domains of CDR, energy, as well as waste and fertilizer legislation if BCR is to be deployed.

For future research on BCR, we recommend carrying out further biomass-specific and transdisciplinary assessments, analyzing concrete business models under consideration of co-benefits and researching inner-annual effects (e.g. price fluctuations and changing emission factors for electricity), as well as the impact on different soil types.

Data availability statement

The data compilation, which provides the basis for the analyses in this study, is openly available at https://zenodo.org/records/11079949.

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare that they have no conflict of interest.

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