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Biochar production from late-harvest grass – Challenges and potential for farm-scale implementation

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ABSTRACT

Grasslands play a crucial role in European agriculture and ecology, but are often underutilized due to low-value end-products. The utilisation of late-harvest grass for biochar and heat generation on farm-level is being studied as a potential negative emissions technology. Technical (energy provision and carbon sink), economic (cost vs. benefit), political (regulatory framework) and social (SWOT) perspectives are being evaluated. Technical feasibility has been demonstrated with three different farm-scale technologies and the energetic and carbon-sink potential evaluated. When a continuously operating allothermal unit is evaluated, 35 % of the input biomass energy content can be utilized for heating a farm, in combination with the potential to provide a carbon sink. The cost-benefit analysis shows important monetary savings when including the agronomic value (based on the market price) of the produced biochar. An assessment of the regulatory framework of biochar production in Germany presents a multitude of regulations applying to such technologies some of which provide a hurdle to navigate and may incur excessive costs for farmers as small-scale biochar producers. A SWOT analysis of a case in Brandenburg, Germany highlights strengths and opportunities, but also obstacles such as lack of infrastructure and regulatory support. This study highlights the need for further development of suitable technology and research on the long-term economic and carbon sink potential of biochar.

1. Introduction

Grasslands are a major contributor to EU culture and agriculture covering 17 % of the surface area (Eurostat, 2018). Over the passing years, due to changing practices and abandonment, this value has decreased (Peeters and Osoro, 2016). Specifically in Germany the area of cultivated permanent grasslands has declined from $5.013 \cdot 10^6$ ha in 2001 (Landwirtschaftsverlag GmbH Münster-Hiltrup, 2003) to $4.729 \cdot 10^6$ ha in 2021 (Destatis, 2022). This decrease in cultivated area not only reduces the usable agricultural output, but also modifies cultural landscapes and the capacity of grasslands to provide vital ecosystem services for society and the environment (Park and Bieling, 2021). Furthermore, the potential of the excess grass biomass (unused, low yielding or low fodder quality grass) from rotational and permanent grassland in the EU28 in 2030 has been estimated to range from 20 to 111 Mt, depending on the grass availability (Meyer et al., 2018).

A considerable increase in biomass, mostly from the agricultural sector, coupled with a reduction of not- or under-utilized biomass, may be needed for a shift towards a sustainable bioeconomy as envisioned in many political strategies (Spies et al., 2022). However, through technological improvements the amount of input (biomass, land, energy) that is needed to produce a unit of output can be reduced (Pakseresht et al., 2023). In this context, the production of biochar as a soil amendment, and energy in form of heat, released during biochar production, from surplus dried grass (hay) could provide a solution that combines agricultural benefits, economic gains and environmental benefits. As energy supply in the agricultural sector is still mainly based on fossil fuels

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(Rokicki et al., 2021), the combined production of biochar and heat could provide an opportunity to reduce this dependency. In addition, the carbon sequestering nature of the process of biochar soil application (Jeswani et al., 2022) could foster its deployment by selling carbon credits on the voluntary carbon market (Bier et al., 2020; H. Schmidt et al., 2021). Thus, farms may make a profit from using surplus biomass and heating their farms (Haubold-Rosar et al., 2016), where else they would pay for fuel to run their heaters and in addition gain a potent soil amendment. Wood or woody biomass is almost the exclusively used biomass for this application (Jirka and Tomlinson, 2014). The technology utilises the thermochemical conversion route of pyrolysis, of which many potential technological process designs exist (Basu, 2013). The process may run heated via an external heat source (allothermal process) in an inert environment, with the addition of limited amounts of air (autothermal process), and either in batch or continuous mode of operation (Tagliaferro et al., 2020). Technologies for farm-scale production of biochar are scarce and existing once have not been tested for the utilization of grass as a feedstock. Previous research has shown that biochar of high quality for soil amendment purposes may be produced from grasses (Adesemuyi et al., 2020; Trippe et al., 2015) and specifically also from late-harvest grass (Heinrich et al., 2023). It is unclear if current technologies can also utilise agricultural residues such as grass as a feedstock and their energetic sensibility and carbon sink potential are yet to be determined.

While human use of biochar can be traced back to ancient times, with the dark earths of Amazonia as the most prominent remnant (Neves et al., 2003), regulatory frameworks for biochar are emerging only recently. Production, marketing, and use of biochar are governed by a number of policy areas such as agriculture, waste management, chemicals and emissions. Additionally, biochar relies on renewable raw materials, of which use may trigger competition in different use paths. Therefore, a well-aligned regulatory framework is necessary to facilitate the production and use of biochar (van Laer et al., 2015), enable the development of suitable business models (Adamseged and Grundmann, 2020), but also to ensure environmental and social sustainability (Neves et al., 2003; Shen et al., 2022). Furthermore, despite the environmental benefits of biochar, it is important that the amendment is economically profitable. Some studies have evaluated the viability of biochar in several crops including winter weed (Galinato and Yoder, 2010), horticultural crops (González-Pernas et al., 2022) or potatoes and beets (Keske et al., 2020), and the results depend on many factors such as the dose, the crop, the climate, the market price of biochar, and the cost of voluntary credits for CO_2 fixation. A live cycle assessment among seven negative emissions technologies, including bioenergy with carbon capture and storage (BECCS), direct air capture and storage (DACCS) or enhanced weathering among others, biochar incorporation in soils performs best in terms of greenhouse gas emissions per ton of CO_2 removed (Jeswani et al., 2022). This demonstrates the potential environmental benefit of the technology, while it has yet to be determined if economics and the regulatory framework support or hinder the implementation of biochar production from unconventional biomass feedstock.

The aim of this study is to (i) test the application of small-scale pyrolysis plants integrated in a farm using late-harvest grass and investigate the sensibility of energetic utilization, its potential to provide a carbon sink as well as economic feasibility, (ii) assess the regulatory environment and private certificates/label schemes in the EU and particularly in Germany in order to identify potential barriers to the implementation of these technologies on farm-scale, and (iii) illustrate the strengths, weaknesses, threats and opportunities (SWOT) for integrating biochar into current farming systems associated with the Lower Oder Valley (LOV) National Park in Germany as a framework. The results of this study may support decision making processes of potential biochar business owners as well as policymakers who seek to facilitate biochar production from residual biomass. This may finally contribute to achieving the main aims of the EU's common agricultural policy including increasing biomass use efficiency, reducing imports and dependency on fossil fuels as well as contribute to the EU's path to net zero carbon emissions.

2. Materials and methods

2.1. Biochar production

2.1.1. Feedstock

The feedstock consists of grass from periodically flooded polder area in the LOV National Park (53°02′32.6″N 14°17′50.0″E). The grass was cut, dried, turned, rowed and baled on the field. Square bales with dimensions of 1.35 × 1.2 × 0.9 m with an approximate weight of 650 kg are produced from the grass. Due to nature conservation management practices in the national park; the utilized grass was from areas harvested once a year, with a harvest date after the 15th of August for allowing bird nesting, leading to highly lignified grass that is not useful for animal feeding.

2.1.2. Biochar production technologies

In farm-scale pyrolysis biochars were produced using a batch-fed autothermal Carbontwister (Prodana, Germany), coded as FA-BS, a batch-fed allothermal Vario L+ (SPSC, Germany), coded as FI-BB and a continuous allothermal C63-F (Biomacon, Germany), coded as FI-CP. Table 1 provides an overview of the performed experiments. The code provides the main differences of the three conversion units. While all are farm-scale units (F), the conversion in the autothermal unit (A) is sustained by addition of limited amounts of air, leading to the partial oxidation of released volatile pyrolysis products within pyrolysis reactor. In the allothermal units the volatile pyrolysis products are combusted downstream of the pyrolysis reactor and the design of the units fosters heat exchange into the pyrolysis reactor, where the process occurs in a presumably near inert environment (I). In all units excess heat from the combustion of pyrolysis volatiles is produced. The mode of operation, batch (B) or continuous (C), is also a defining feature. Depending on the thermochemical conversion reactor, biochars were produced from stalks (S), briquetted (B) or pelleted (P) grass, as indicated in the last letter of the code. All experiments were performed on farms in Germany in the states of Brandenburg, Baden-Württemberg and Lower Saxony respectively. More details on the performed experiments, the composition of the feedstock and produced biochar, as well as an assessment of the biochars suitability as soil amendment has been reported elsewhere (Heinrich et al., 2023).

2.2. Technology assessments

Calculations on the net energy production, the carbon sink (C-sink) potential and economic benefits from grass biochar production have been performed for hypothetical farms within the region of the Lower Oder Valley National Park. The basis of this case study is the performed experiments. For the batch units FA-BS and FI-BB the biochar is the only product, while for the continuous unit FI-CP the released heat may also be utilized.

2.2.1. Energy

Energy flows were calculated for one kilogram (dry basis) of grass. As stated in the introduction, the grass is harvested in August. Fertilization occurs naturally without additional fertilizer input, due to seasonal flooding of the polder area where the fields are located. Therefore, no energy requirements for fertilization are considered. Energy requirements for cutting, turning, rowing, bailing, loading and transport (20 km) were calculated on the basis of the processing machinery diesel consumption (Achilles et al., 2020), leading to a total of 5.0 L Diesel per ton of grass. The energy consumption for shredding the bale has been set to 6.4 kJ·kg^{-1} (Shinners and Friede, 2018), for briquetting to 252.0 kJ·kg^{-1} in a Biomasser press (ASKET, Poland) and for pelleting to 288.0 kJ·kg^{-1} (Tumuluru, 2019). Electricity requirements for running

Table 1
Specifications of the presented experiments. The input of grass feedstock and the output of produced biochar are included on a dry basis (db). The code is composed of: 1) farm-scale (F); 2) autothermal pyrolysis (A), or allothermal pyrolysis in an inert environment (I); 3) as batch (B) or continuous (C) process; and 4) from stalks (S), briquetted (B) or pelleted (P) grass (source: own elaboration).

Reactor	Mode of operation	Code	Replication	Total input (kg_{db})	Biochar output (kg_{db})
Carbontwister	Autothermal, batch	FA-BS	4	584.4	75.4
VarioL	Allothermal, batch	FI-BB	1	172.1	62.5
C63-F	Allothermal, continuous	FI-CP	1	2458.6	505.0

the reactors were based on manufacturer specifications of 12.0 kWh per batch, and 3.5 kW in continuous operation for the experiments FA-BS and FI-CP respectively, for FI-BB no electricity is required. The higher heating values (HHV) were measured using a C200 bomb calorimeter (IKA, PRC). While in case of the batch processes (FA-BS and FI-BB) all produced heat is released into the atmosphere, in case of the continuous operation in experiment FI-CP a usable heat output is achieved. This is determined via the lower heating value (LHV) of the pellets, which was calculated as described in (Kaltschmitt and Hartmann, 2009) at 16.6 $MJ \cdot kg^{-1}$. By assuming the LHV of wood chips of 15.6 $MJ \cdot kg^{-1}$ (Kaltschmitt and Hartmann, 2009) the usable heat output from the reactor was determined as describe in Eq. (1).

$$\text{Output} = \frac{\text{Unit Thermal Capacity}}{\text{Nominal Feed Rate} * LHV_{\text{WoddChips}}} * LHV_{\text{Grasspellets}} \qquad (1)$$

The utilized energy for the harvest, transport, and pelleting or briquetting are considered as input for the production of the grass feedstock. The heating value is the energetic defining feature for the thermal processes including biochar production. The energy released from the process, including energy transferred to the local heating system as usable heat, as well as the energy content of the biochar are considered as outputs.

2.2.2. Carbon sink

The potential C-sink of the produced biochar was calculated on the basis of the European Biochar Certificate (EBC) (EBC, 2022) and with regard to guidelines of Carbonfuture, Germany (Junginger-Gestrich, 2021), a potential broker for certificates in Germany, as per Eq. (2). Initially the CO_2 equivalent (CO_{2eq}) of the carbon contained in the produced biochar from the experiments was calculated, where $C_{Biochar}$ is the carbon content and $A_r°$ the standard atomic weight. The CO_{2eq} of the released emissions from harvest and transport are based on the Diesel consumption and 3.2 kg CO_{2eq} per liter Diesel (EBC, 2022). The annual decay is determined to be 0.3 % of the total CO_{2eq} of the biochar and deducted over a period of 50 years (Junginger-Gestrich, 2021). Electricity requirements, for pelleting and running the conversion reactor are considered either on the basis of the German energy mix of the year 2020 (Icha et al., 2021) with 366 $g_{CO2} \cdot kWh^{-1}$ or completely from renewable energies and thus carbon neutral. Potential greenhouse gas emissions from the conversion reactors are not considered. A total C-sink potential is calculated, as per Eq. (3), under the assumption, that all available grass from the late harvest from the LOV National Park were to be converted to biochar. In the LOV National Park, in the timespan between 2015 and 2021 a mean of 3941.0 ha consisted of managed grasslands of which a mean of 547.1 ha were released only for late harvest, after the 15th of August, as provided by the Association of Friends of the German-Polish European National Park Lower Oder Valley e.V. With an average dry matter grass yield of 7.6 $t \cdot ha^{-1}$ (Blokhina et al., 2011), this amounts to a total of 4158.0 t of late harvest grass (m_{Grass}) per year.

$$C\text{–Sink} = C_{Biochar} \frac{A_r^{\circ}(C)}{A_r^{\circ}(CO_2)} - CO_{2eqDiesel} - CO_{2eqDecay} - CO_{2eqElectricity} \left[t_{CO_2eq} * t_{Biochar}^{-1} \right] \qquad (2)$$

$$\text{Total C–Sink} = C - \text{Sink} * m_{Grass} \qquad (3)$$

2.2.3. Economic analysis

For an economic estimation, a basic cost-benefit analysis of the continuous unit FI-CP was performed. This analysis focuses on those tasks which are directly connected to the production of biochar and heat. Activities such as harvesting, and baling are not included as these are currently performed for environmental management purposes and input biomass is considered as excess for this study. The total annual heat demand was based on the experience of the pig farm where the experiment was performed at $330 \cdot 10^3$ $kWh \cdot year^{-1}$. Heat is required for heating pig barns as well as the farmhouse, from fall to spring over a total of 6000 h. The costs are divided into manual labour, infrastructure, and consumables. Manual labour is considered to be 5 h per week on average of a full-time employee at 21 $€ \cdot h^{-1}$ over 9 months per year (Achilles et al., 2020). The infrastructure consists of the conversion unit with an assumed investment cost of 108,900.0 € as well as investment cost for transporting the grass pellets into the conversion reactor and the biochar out of the conversion unit with 70.000 € as initial investment. Amounting a total annual amortization of 8945.0 € over a period of 20 years. Maintenance is assumed at 2 % of the initial investment of the conversion unit.

The consumables consist of the cost for pelleting the grass, the electricity cost for running the conversion reactor and annual C-sink certification fees. Pelleting is assumed to be performed at a pelleting mill at 30 $€ \cdot t^{-1}$ and an additional transporting distance of 10 km to current practices. Biochar prices per tonne were set according to literature and averaged to 700 $€ \cdot t^{-1}$ (González-Pernas et al., 2022; UNIDO (United Nations Industrial Development Organization), 2021). An important fluctuation in the market is expected in the next years, and further discussion about other possible prices is also included in the Discussion section.

Table 2 gives a summary of the input parameters (including assumed costs) used for the different scenarios. Due to the volatility of the current electricity and natural gas market, a pre-war scenario considering average energy and gas prices (from 2017 to 2020) and a post-war scenario, considering prices from the first semester of 2022 were developed, in both cases specifically related to Germany (EUROSTAT Data). Similarly, diesel costs were calculated according two different scenarios including pre and post war prices. The price for C-sink certificates amounts to a minimum of 75 $€ \cdot t^{-1}$ of CO_2eq and maximum of 100 $€ \cdot t^{-1}$ (this maximum amount was calculated according to Carbonfuture guidelines: when the broker achieves a price over 100 $€ \cdot t^{-1}$, 75 % of the additional revenue goes to the producer). Several scenarios were set up based on current price fluctuations and all prices and values are set for Germany. Scenario 1 was the minimum scenario where an average price (2016–2020) for energy, gas and diesel was used. Scenario 2 was calculated according to the current energy and diesel prices (averaged price for the 1st semester of the 2022). Scenarios 3 and 4 were calculated assuming that previously to the implementation of the biochar pyrolysis unit, already external inputs of biochar were used in the farm (purchased biochar) as soil amendments, and therefore biochar costs would be saved when self-producing the amendment. Moreover, voluntary carbon credits were set as 75€ per tonne of biochar in Scenarios 1 and 3 and as 100 € per

Table 2
Input parameters for cost and benefit analysis (source: own elaboration).

Parameter	Amount	Unit
Area harvested	24.7	ha
Feedstock grass	189	t year^{-1}
Biochar output	35	t year^{-1}
C sink capacity	1.50	CO_2 equivalents t^{-1}
Revenues as C sink	75	€ CO_2 equivalent^{-1}
	100	€ CO_2 equivalent^{-1}
Total energy consumption	36,750	kwh year^{-1}
Diesel for field work (cutting, turning, rowing and bailing)	12.7	L ha^{-1}
Heat production	330,000	kWh year^{-1}
Electricity prices Non-household (Eurostat)	0.078	€ kWh^{-1} (avg 2017–2020)
	0.151	€ kWh^{-1} (1st semester avg. 2022)
Gas prices Non-household (Eurostat)	0.027	€ kWh^{-1} (avg 2017–2020)
	0.045	€ kWh^{-1} (1st semester avg. 2022)
Diesel prices	1.25	€ L^{-1} (avg 2018–2020)
	2.02	€ L^{-1} (1st semester avg. 2022)
Costs for pre-processing: pelleting the raw material	30	€ t^{-1}
Working days in Germany	190	9-months period
Price worker per hour	21	€ h^{-1}
Biochar Price	700	€ t^{-1}

tonne of biochar when considering scenarios 2 and 4 (considering that the increase in the price of raw materials would also lead to higher C-sink credits).

2.3. Regulatory framework and private standards

Analysis of regulatory frameworks and private standards was conducted by examining relevant regulations as well as private labels and standards that govern biochar value chains in a German context. This includes 19 regulations and policy documents of the European Union and Germany, and nine guidelines of private certificates and labels. We also reviewed publications on biochar regulations and policy in European and German context to ensure comprehensiveness of the analysis. The articles were searched by using keywords “biochar” AND (regulation* OR polic*) AND (Europe OR German*) in Scopus and by cited reference searching. Our focus is on the middle to downstream of the value chain: conversion of grass to biochar, use of grass as soil amendment, and carbon sink. Regulations related to upstream value chain, i.e., grassland management and other uses of biochar, such as animal feed, animal bedding and biomaterials are not dealt with in this paper. We analyzed the regulations and standards in order to identify regulatory barriers, which we define as (i) absence of regulatory support measures, (ii) restrictive regulatory measures, or (iii) misalignment of different regulations (across sectors/levels) that hinder production and marketing of grass biochar.

2.4. Case study – SWOT analysis

Firstly, we identified which factors may affect the use of pyrolysis in Germany from the literature. Secondly, using the LOV National Park as a case study, we identified the factors that hinder or support the integration of production of biochar in current farming systems.

We performed a Strengths Weaknesses, Opportunities and Threats (SWOT) analysis, which can be considered as a phase of the strategic planning process of a business or organization. Data was gathered within the frame of the H2020 GO-GRASS project (www.go-grass.eu) in three consortium meetings, which took place in Denmark and Sweden in 2021 and in the Netherlands in October 2022. Besides, two stakeholder board meetings took place at the LOV National Park with focus group discussions among entrepreneurs, researchers, technology developers, and agricultural producers.

3. Results and discussion

3.1. Suitability for farm level utilization

The results within this subsection are based on trials performed at farms that utilise the three described thermochemical conversion technologies (refer to Section 2.1.2) for the production of biochar and the technologies are tested for the utilization of grass as a feedstock. While an assessment of the physico-chemical characteristics of the produced biochar was previously performed (Heinrich et al., 2023). In all cases it is assumed that the units produce a biochar which conforms to guidelines proposed by the EBC (EBC, 2022). The presented results are limited by the low number of experiments performed as well as assumptions regarding farm size, circumstances and local infrastructure.

3.1.1. Energy

Fig. 1 presents an energetic balance of the input, the required input energy for the production and conversion of the feedstock, over the primary energy content of the feedstock (measured via bomb calorimeter, see Section 2.2.1) to the output, the released energy, as usable heat or waste heat, and the energy retained in the produced biochar. In each of the figures for the three investigated technologies (a) FA-BS, (b) FI-BB and (c) FI-CP, it can be seen on the lower left side that the energy requirement for the production of grass, a total of 0.11 MJ·kg^{-1}, of grass to briquettes, a total of 0.36 MJ·kg^{-1}, or of grass to pellets, a total of 0.46 MJ·kg^{-1}, requires 0.6 %, 2.0 % and 2.6 % respectively of the primary energy content of the respective feedstock for biochar production. Additionally, the electricity that is required for running the thermochemical conversion technology, in case of (b) FA-BS, 0.27 MJ·kg^{-1}, and (c) FI-CP, 0.4 MJ·kg^{-1}, is considered as input energy, while in case of (a) FI-BB no electricity is required for the conversion process. In both cases the electricity used for running the conversion device is the largest energy input. In case of (c) FI-CP, the unit from which parts of the released energy may be utilized, a total of 0.86 MJ·kg^{-1} of input energy is required to achieve a final heat output of 6.3 MJ·kg^{-1} to the farms heating system.

The output energy distribution is substantially different between the three technologies. One main factor is the yield of produced biochar, as it may retain up to 9.6 MJ·kg^{-1} and thus 53.0 % of the biomass energy in case of FI-BB (biochar yield 36.3 %, refer to Table 1), or as little as 2.8 MJ·kg^{-1} and thus 15.6 % of the biomass energy in case of FA-BS (biochar yield of 12.9 %, refer to Table 1). The second main factor is the produced heat: this may be completely released into the atmosphere, in case of the two batch units (FA-BS and FI-BB) or a part of the produced heat may be utilized in case of the continuously running unit (FI-CP). In both batch systems, exhaust heat exchangers are in development, but as these were not present in the performed experiments the potential of heat utilisation from these systems cannot be considered here. For the sustainable and energetic sensibility of biochar production the optimization of heat recovery should be a main focus of development. The usable heat, in case of (c) FI-CP amounts to 6.3 MJ·kg^{-1}, and thus 35.4 % of the biomass energy, which is transferred to the farms central heating system. The remaining heat, like all heat in both other cases (FA-BS and FI-BB) is utilized in the conversion, lost as latent heat of the char and of the exhaust gas, or losses from the reactor surface.

3.1.2. Carbon sink

Fig. 2 presents the potential of the produced biochar to provide a carbon sink (C-sink) in CO_2 equivalent (CO_{2eq}) terms. As CO_2 is captured by the grass when growing and stabilized during the thermochemical conversion process, it is returned in this stable form to the ground when used as soil amendment (Zhang et al., 2019). This evaluation is only an estimate as site-specific factors, such as conversion reactor emissions or intermediary uses of biochar (Zhang et al., 2019), impact the real value.

In Fig. 2, the CO_{2eq} of the biochar based on its carbon content, is presented in bar (1) Biochar. In bar (2) the emissions, the production of briquettes or pellets and running of the conversion reactor are

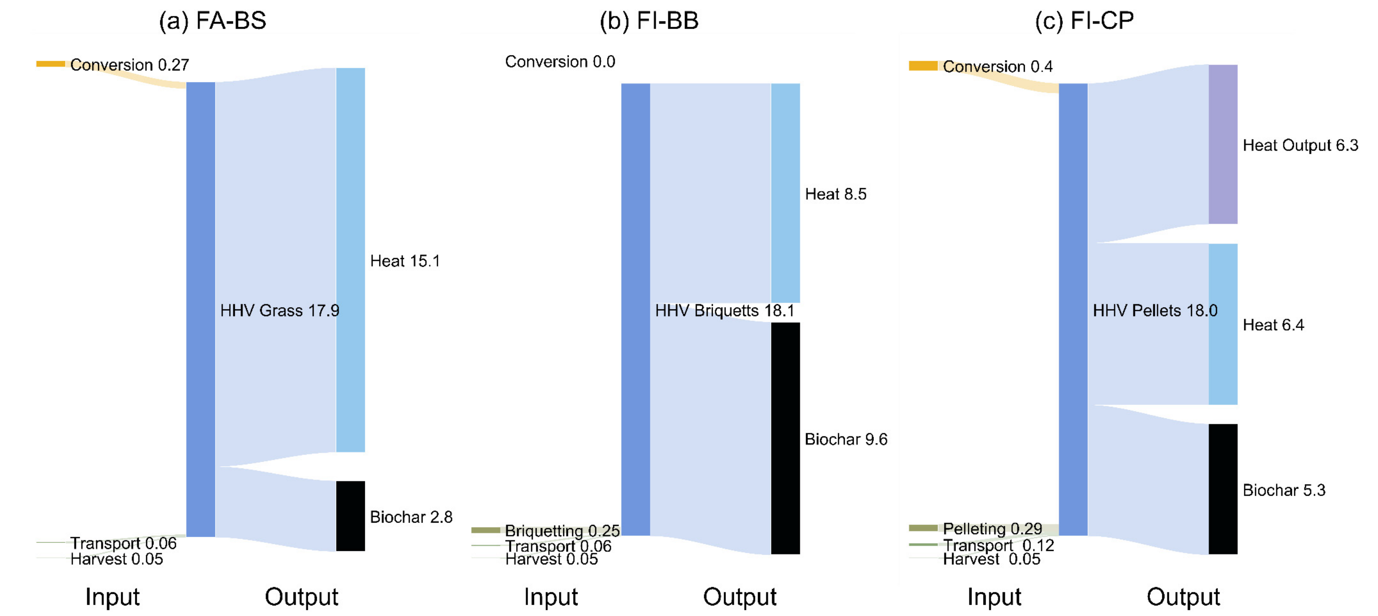

Fig. 1. Energy flow in biochar production via three conversion technologies, (a) the autothermal batch unit FA-BS, (b) the allothermal batch unit FI-BB and (c) the allothermal continuous unit FI-CP. The code is composed of: 1) farm-scale (F); 2) autothermal pyrolysis (A), or allothermal pyrolysis in an inert environment (I); 3) as batch (B) or continuous (C) process; and 4) from stalks (S), briquetted (B) or pelleted (P) grass. Provided values in MJ·kg^{-1} (source: own elaboration).

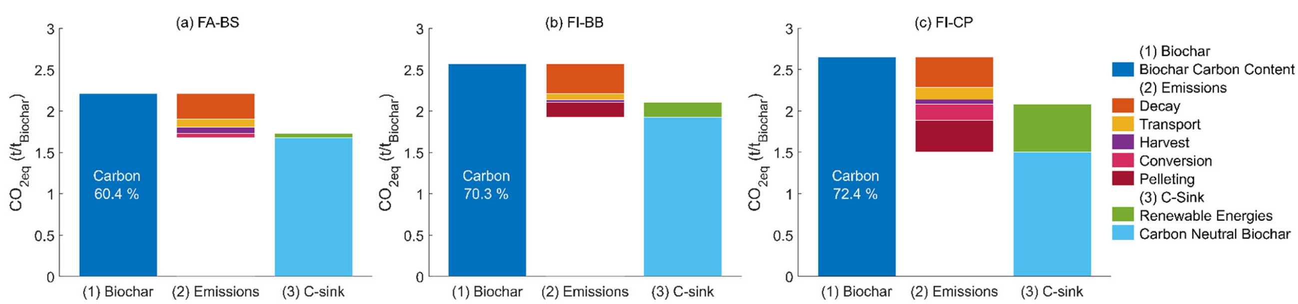

Fig. 2. The bar (1) carbon content, bar (2) related emissions with its production and utilisation, and bar (3) the carbon-sink potential of the produced biochars, from the three different conversion units (a) FA-BS, (b)FI-BB and (c) FI-CP (source: own elaboration).

considered on the basis of the Germany energy mix, which releases high amounts of CO_2 due to the high fraction of fossil coal based electricity production (Icha et al., 2021). A carbon neutral biochar can provide a C-sink of 1.68, 1.92 and 1.50 t of CO_{2eq} per t of the biochar for units FA-BS, FI-BB and FI-CP respectively (see light blue bar (3)). If the electricity for pelleting and running the conversion reactor was to be supplied entirely by renewable energies, preferably from own production (e.g. rooftop photovoltaic) the C-sink potential of the biochar would increase up to 2.08 t of CO_{2eq} per t of the biochar for FI-BB ((b) light blue plus green bar). If the CO_2 emissions from diesel consumption during harvest and transport could be reduced for example through the use of biodiesel the C-sink potential could be further increased, which is not considered in the presented assessment.

In the LOV National Park, in the period of 2015 to 2021 on average (Blokhina et al., 2011) 4179.84 t of late-harvest grass were harvested annually. With a carbon yield as presented in Table 3 and a carbon sink per t of biomass as calculated via Eq. (3) a total carbon sink of in the range of 9112.04 to 2925.90 $t_{CO2\ equivalent}$, as presented in Table 3. Based on the unit FI-CP where a total of 189 t of biomass would be need to heat a comparable farm. Thus additionally to the achievable carbon sink 22 such farms could cover their energy demand for heating.

Table 3
The yield of carbon from the biomass feedstock in the produced biochar, the $CO_{2\ equivalent}$ from the biomass which is retained in the biochar and the total $CO_{2\ equivalent}$ if all late-harvest grass from the LOV National Park were to be converted to biochar (source: own elaboration).

	FA-BS	FI-BB	FI-CP
Carbon yield [wt-%$_{db}$]	16.82	55.18	32.20
$CO_{2\ equivalent}$ [t_{CO2}·$t_{Biomass}^{-1}$]	0.22	0.70	0.31
Total CO_2 sink potential [t_{CO2}·a^{-1}]	912.04	2925.90	1306.20

3.1.3. Economic assessment

The costs and benefits for the example farm are presented in Table 4. The economic calculation is based on the assumption that unlike in the previous sections, the harvest is not considered, as this is the current practice, and that the supply of the biomass is cost free. This situation of a cost-free input material is similar to the situation at the farm, where the experiment FI-CP was performed.

Main costs contributors are pelleting and electricity to run the conversion reactor together with manual labour (see Table 4). The main factor for benefits is the heat provision, which is translated into a reduction in external inputs such as natural gas, leading to lower fuel expenses: in the minimum scenario considered (Scenario 1), benefits from energy savings are almost 4-fold higher than benefits from C-sink credits.

Considering the increase of energy prices in 2022 (comparing Scenario 2 with Scenario 1; Scenario 4 with Scenario 3), economic losses are more than 4000 € lower per year than those calculated for the previous 2017–2020 period (due to the increase in gas prices compared to electricity prices). Only when a scenario where savings by avoiding

Table 4
Cost and Benefit analysis of biochar production and use. Scenarios were calculated based on farm data (electricity and diesel consumption and heat production; infrastructure costs) and estimated assumptions (biochar and C credits prices). A short description of the differences between the scenarios is provided below the table (source: own elaboration).

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Unit
Costs					
Manual labor	3985	3985	3985	3985	€ year^{-1}
Infrastructure					
*Annual lineal amortization (constant euros)	8945	8945	8945	8945	€ year^{-1}
**Annual maintenance	2178	2178	2178	2178	€ year^{-1}
Consumables					
Pelleting	5670	5670	5670	5670	€ year^{-1}
C-sink certification	2000	2000	2000	2000	€ year^{-1}
Electricity	2874	5557	2874	5557	€ year^{-1}
Diesel	364	590	364	590	
Total costs	26,016	28,924	26,016	28,924	€ year^{-1}
Benefits					
Biochar savings			24,500	24,500	€ year^{-1}
Fuel / energy savings	8903	14,685	8903	14,685	€ year^{-1}
C credits as C sink	3943	5258	3943	5258	€ year^{-1}
Total benefits	12,846	19,943	37,346	44,443	€ year^{-1}
Balance	−13,169	- 8981	+ 11,331	+ 15,519	€ year^{-1}

*Unit price: 108.900 €. In addition to the pyrolysis unit costs, the estimated costs for the units transporting the feedstock into the unit (about 30.000) and the biochar out of the unit (about 40.000) are included. Amortization calculated for a lifetime period of 20 years
**Maintenance (including reparation): approx. 2 % investment cost

Scenario 1	Averaged 2016–2020 prices and C credits 75 € t^{-1}
Scenario 2	1st semester 2022 averaged prices and C credits 100 € t^{-1}
Scenario 3	Averaged 2016–2020 prices for energy and diesel and C credits 75 € t^{-1}
Scenario 4	2022 prices and diesel 1st semester 2022 averaged prices and C credits 100 € t^{-1}

external biochar purchase in the farm is considered (that means biochar is self-produced at the farm instead of being bought, Scenario 3 and Scenario 4), a total positive balance of benefits is found. Moreover, in this case benefits up to 11,331 € per year are found considering the prices for 2017–2020 (scenario 3) and up to 15,519€ in the scenario 4, considering the current energy, gas, prices (together with higher C credits).

3.2. Regulatory framework and private standards

Biochar production and sales are governed by a number of regulations and private standards. In each value chain step, different regulations may apply (refer to Fig. 3). In this section, we address regulations in relevant policy areas (e.g., agriculture, emissions) as well as private certificate guidelines and how they facilitate or hinder biochar production and marketing.

3.2.1. Agriculture

The amendment to the EU regulation on fertilizing products (EU) 2009/1009 in 2021, which provides requirements for fertilizing products to be marketed as EU-fertilizing products, includes biochar as a component material category. The delegated regulation (EU) 2021/2088 sets conditions on input materials, conversion process and product quality that ensure the safety and agronomic efficiency of biochar. The grass feedstock addressed in this paper fulfills the requirements for biochar input material i.e., “(a) living or dead organisms or parts thereof, which are unprocessed or processed only by manual, mechanical or gravitational means […]”. The thermochemical conversion process is also compatible with the requirement of oxygen-limiting conditions and a temperature of at least 180 °C for at least two seconds. According to the regulation, biochar must comply with the requirements in the component material category ‘pyrolysis and gasification materials’ which include hydrogen-to-carbon (organic) ratio and polycyclic aromatic hydrocarbons. When it comes to organic farming in the EU, biochar use as a soil conditioner has been authorized by implementing regulation (EU) 2021/1165, as long as the plant materials after harvest are treated with permitted materials. Thus, the grass biochar can be used in organic production in principle. Values for contaminants in (EU) 2009/1009 apply.

On the contrary, the German fertilizer ordinance (Düngemittelverordnung) that exists in parallel with the EU regulation on fertilizing products restricts the origin of charcoal to chemically untreated wood to be used as a raw material for soil amendment (van Laer et al., 2015), and excludes grass-based biochar. Therefore, producers of grass biochar via pyrolysis in Germany who wish to market the product as soil amendment (both conventional and organic) in Germany or elsewhere in the EU must obtain an individual approval to the product or go through with a conformity assessment by a designated assessment body outside Germany. A conformity declaration process through an inspection body (e.g., Carbon Standards International or CerTrust) takes between six to eight weeks. Costs vary depending on the audit team's travel expenses and could amount to several thousand euros. These options require time and resources, which may discourage potential producers, especially of small-scale.

With regard to carbon sequestration in agriculture, the Commission's recommendation to the Common Agricultural Policy (CAP) strategic plans in 2020 highlights the potential in agriculture and forestry. Member states may choose carbon sequestration as one of their eco-schemes (European Commission, 2020), which is a new tool in the CAP for supporting sustainable agricultural practices (European Commission, 2021a). Although the CAP strategic plan of Germany takes up this point, major emphasis was given to permanent grassland management as a source of carbon sequestration while biochar use was not explicitly dealt with in the plan (Bundesministerium für Ernährung und Landwirtschaft, 2022).

3.2.2. Chemicals

According to REACH (Registration, Evaluation, Authorization and Restriction of Chemicals, (EC) No 1907/2006) regulation, biochar producers are required to gather data on the chemical substances of the char and submit a dossier to European Chemicals Agency, if their production is over 1 ton per year. Biochar can be registered under the charcoal dossier (EC / List no.: 240-383-3) (Fachverband Pflanzenkohle, 2019; The European Biochar Industry Consortium, 2020). The registration incurs cost, and reduced fee is applied to micro-, small- and medium-sized enterprises ((EC) No 340/2008). No further chemical regulations apply for biochar production in Germany.

3.2.3. Emission control

Plants for the disposal or recycling of solid, liquid or gaseous waste by pyrolysis with a capacity of less than 3 tons of non-hazardous waste per hour (plant category 8.1.1.4 in the fourth ordinance for the

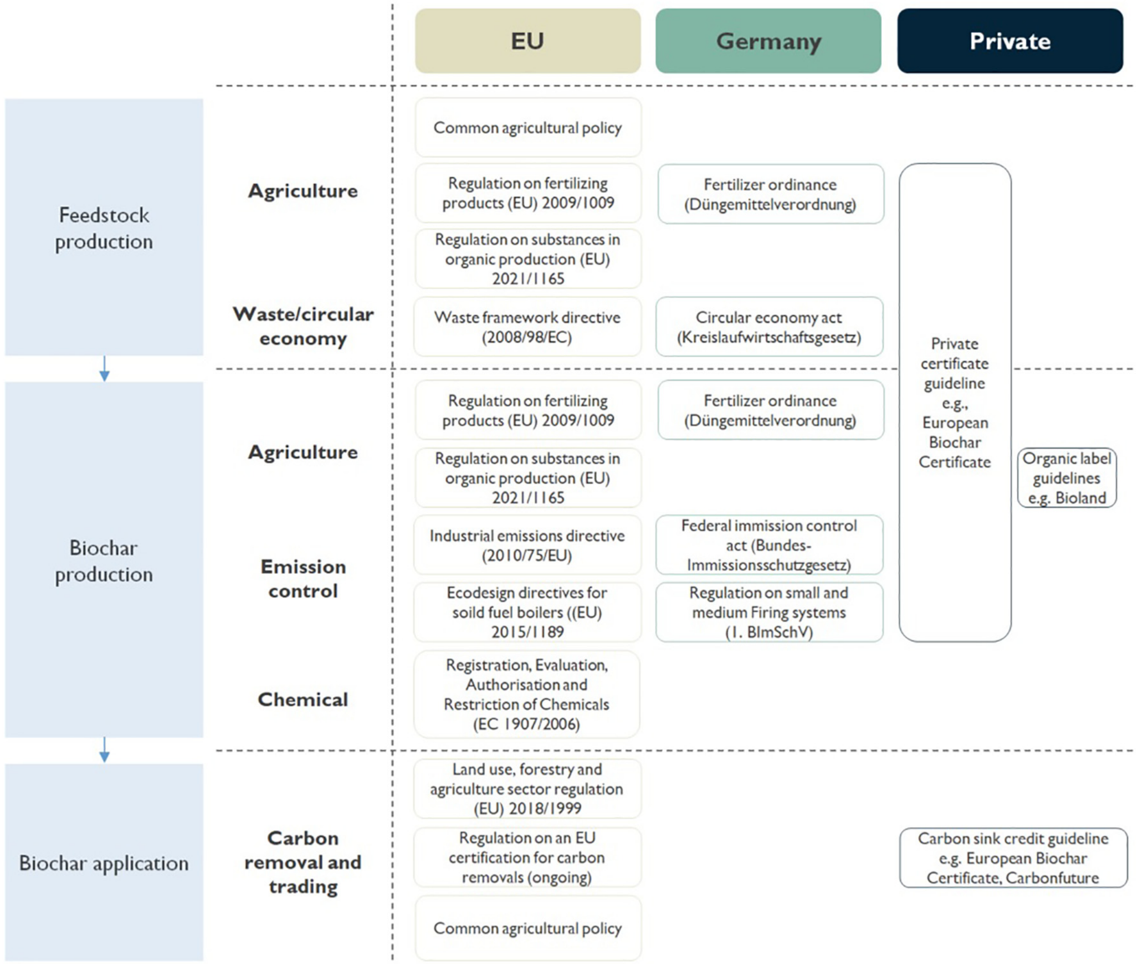

Fig. 3. Relevant regulations and private certificates/labels for farm-scale biochar production (source: own elaboration).

implementation of the Federal Immission Control Act) require a simplified approval process. Plants with a capacity of 1 MW or more must comply with the emissions limits according to the 44th ordinance for the implementation of the Federal Immission Control Act. In addition, building approval may be required depending on the construction type of the plant. The building regulations vary from state to state in Germany. In the EU, emissions requirements for solid fuel boilers under 500 kW capacity is addressed in the Ecodesign directives. However, the directives for solid fuel boilers ((EU) 2015/1189) do not apply to non-woody biomass boilers due to insufficient data availability for Ecodesign requirements (Padua et al., 2022). The Commission planned to review the inclusion of non-woody biomass boilers under the directive by January 2022.

3.2.4. Emission reduction and trading

In 2018, the European parliament and the council of the European Union included emissions and removals of GHG from land use, land use change and forestry (LULUCF) in its 2030 climate and energy framework. In Germany, the land use, land use change and forestry sectors have a target of 40 million tons of carbon dioxide equivalent reduction by 2045 compared to 1990 levels. The proposal for amending the LULUCF regulation sets an ambitious target of achieving climate neutrality by 2035 in the LULUCF and non-CO_2 agricultural sector and aims to set up a certification system for carbon removals (European Commission, 2021b). The European Commission submitted a proposal on carbon removal certification in 2022 (European Parliament, 2022b), which offers opportunities for biochar. Nonetheless, it is yet uncertain to what extent biochar will be included in the certification scheme. In a report prepared for "A cleaner planet for all" communication (COM (2018)773), the European Commission excluded biochar from negative emission technology that can be used for achieving its GHG scenario. It addresses the uncertainty in the potential to provide a carbon sink and environmental effect of biochar as tests on the effect on the soil should be scaled up from laboratory- to the field-scale. Also, production of biochar involves usage of land, water, and energy that may trigger competition with other uses (European Commission, 2018). In the pre-legislative synthesis of European Parliament for the carbon removal certification, use of biochar was introduced as one of promising carbon removal strategies. At the same time, it points out that effect on carbon sequestration still remains unclear and its potential may be limited as much of the feedstock is already utilized (European Parliament, 2022a). In the proposal, biochar was mentioned as a carbon farming practice that has not been fully consolidated (European Commission, 2022a).

3.2.5. Private certificates and labels

The grass grown in the national park fulfills the feedstock requirement of the European biochar certificate (Heinrich et al., 2022). On its positive list of feedstock, biomass from nature conservation areas can be used for the production of all kinds of biochar except for feed purposes (European Biochar Certificate, 2020). As long as the grass is produced from well-documented sources, the biochar made from the grass can be used as feed, which offers an opportunity for extending the value chain before the char is applied to the soil at the end.

Limitation on the transportation distance of the feedstock that existed in the previous guideline was removed in the updated guideline in 2022 (EBC, 2022). While International Biochar Initiative and Biochar Quality Mandate do not provide list of permitted feedstock, Biochar Quality Mandate requires a "seed to seed" life cycle assessment (International Biochar Initiative, 2015; Shackley et al., 2014). A number of private actors offer carbon sink certificates including European Biochar Certificate (Schmidt et al., 2020), which certifies carbon sink potential and Carbonfuture (Junginger-Gestrich, 2021), which tracks carbon sink.

The grass biochar can be used in agriculture that is certified by the major organic labels in Germany. Bioland allows the use of biochar ("pyrolysis product from organic materials of vegetable origin"), as well as Naturland. Demeter allows the use of biochar as an organic fertilizer and a mulching material as long as its heavy metal values are under the limit of EBC AgroBio standard. All the labels require conformity of the biochar to the regulation (EU) 2021/1165 including its contaminants level. The raw materials can be both from organic and conventional agriculture (Bioland e.V. Verband für organisch- biologischen Landbau, 2022; Demeter e.V., 2022; Naturland Verband für ökologischen Landbau e.V., 2021).

3.3. Integrating biochar into farming systems: socio-economic challenges and opportunities

Despite the increasingly diverse documented benefits of biochar applications, impediments to the adoption of biochar in sustainable agriculture are many. Empirical research on practical integration of biochar into conventional farming systems is scant. Here we use the LOV National park as a case study to identify strengths, weaknesses, opportunities and threats with respect to the integration of biochar in current farming systems.

Integrating Biochar in Traditional Farming Systems: Case Vignette LOV National Park

The Lower Oder Valley is the only wetland national park in Germany with extensively managed polder grasslands and is an internationally protected area for birds. The protection management involves late harvesting (after mid-august) which leads to highly lignified grass with low nutritional value and low quality for animal feed or feedstock for biogas production. The harvested grass is therefore mostly either used as bedding material for livestock (if stables are still suitable for such bedding material), or not used at all and left to decompose.

The objective of the German GO-GRASS demonstration site is to valorize the late-harvested grass by converting it into biochar through the process of pyrolysis. The biochar produced can be applied site-specific as a soil amendment to agricultural fields outside the national park. Moreover, the heat released during the production process can help reduce dependency on fossil fuels and help farmers to become more independent regarding the energy usage.

The LOV National Park is currently developing this innovation together with farmers from the region and with technical, scientific and business advice from the ATB (Leibniz-Institute for Agricultural Engineering and Bioeconomy).

3.3.1. SWOT analysis

In this section, we summarize the strengths, weaknesses, opportunities and threats by applying the small-scale biochar production system in a potential farm in the region of the Lower Oder Valley National Park. The results were generated from the focus group discussions with multiple stakeholders as described in Section 2.3 (Table 5).

Strengths

The farmers at LOV National Park could utilise low-quality grass biomass and valorise it for higher value added products rather than current farming practices in which the grass biomass is left unused. One of the benefits of the locally sourced biomass is the shortened logistics route which can reduce transportation costs and the environmental impact of biomass production. In addition, the implementation of the pyrolysis technology at the farm to produce the biochar and reduce fertiliser or amendments input which could close the loop for nutrients cycle. The soil quality in the German state of Brandenburg is not optimal for farming activities, specifically the sandy soil type with low water holding capacity. When applying biochar for soil amelioration, farmers could benefit from an improved soil quality. Alternative income due to the substitution of fossil energy, and potentially carbon credits which is high on the political agenda, may be generated. Essentially, when taking into account the potential to provide a carbon sink at the farm level, this valorisation pathway for biochar from locally sourced low quality grass biomass can largely contribute to climate change mitigation.

Table 5
Summary of the results from the SWOT analysis on a farm-scale biochar production system (Source: own elaboration).

Strengths	Weaknesses
• Short transportation/ lower production cost • Reduction in fertiliser and soil amendment inputs • Close loop for nutrients cycle/ soil amelioration for sandy soil type in the region • Potential economic benefits for local farmers • Renewable energy	• Current fertilizer regulations in Germany • Limited interests from local farmers to invest in this business model • Unfitness of current biochar production technologies for grass as feedstock • Lack of production infrastructures • Additional training required / capacity building
Opportunities	**Threats**
• Access and availability to grassland biomass • Increasing fossil fuel prices • Growing demand for carbon credits	• Misalignments in the regulatory framework • Variability of biomass quality and supply • Competing end-users for underutilized grass

Weaknesses

The weaknesses for implementing this biochar system at farm level were identified mainly associated with the current biochar regulations and limited interests from local farmers (Vochozka et al., 2016) (for a detailed overview of the legal barriers please refer to Section 3.2). An additional weakness is that current technologies for biochar production have not been designed for the use of grass, but rather for woody biomass, and the impact on of this alternative feedstock on the technology is currently unclear (Heinrich et al., 2023). Furthermore, current technologies require pre-treatment either for the production of grass briquettes or pellets. This pre-treatment requires a substantial effort in terms of investment for technology as well as in terms of labour for the production. Farmers may not be willing to perform additional tasks and the economy of such pre-treatment on farm-level may also not be favourable. Infrastructure for farms to be able to outsource this pre-treatment may be necessary to co-evolve with the establishment of biochar production from non-woody biomass on farm level. Another concern is post-treatment, after the production of biochar. Its direct application to the field is not recommended, while a treatment before field application, such as co-composting, utilization as bottom layer for bedding material in barns, or its addition to anaerobic digestion have been found beneficial (El-Naggar et al., 2019; Fertiplus et al., 2019; H. P. Schmidt et al., 2021). All these post-treatment steps do require additional effort from farmers, may require additional specialised equipment and in all cases an adaption of the farmer's practices.

Opportunities

Large amounts of grassland biomass in the LOV National Park are currently disposed, causing lost benefits for the society and the environment. With increasing fossil fuel prices, unlocking the potential of grass biomass as feedstock and of technologies that can convert it into energy becomes more promising. The regenerative capacity of grassland biomass as an alternative to fossil fuels addresses the problem of non-renewable resource scarcity, serves to mitigate climate change and represents opportunities to develop self-reliance energy schemes.

Threats

Perhaps the most prominent threat identified for the integration of biochar into current farming systems is the misalignments in the institutional framework (for a detailed overview of the legal barriers, please refer to Section 3.2). Additionally, from a business perspective, securing a regular supply of feedstock is a challenge in the production of large amounts of biochar. In addition, there are several competing end-users for the underutilized grass in the National Park. Companies producing grass-based products are currently in close contact with the park administration for the biomass. Moreover, biochar production requires certain infrastructure conditions. For example, having a close by briquetting or pelleting company appears necessary to achieve a positive cost-benefit balance.

4. Discussion

From an energetic perspective the utilization of grass as a feedstock for heat and biochar production appears promising. Even when pre-processing, for the production of briquettes or pellets, is included the provision of the feedstock is small when compared with the amount of energy released. A farm's heat requirement should determine the capacity of the utilised technology, although this may substantially limit the amount of biochar that can be produced, and therefore, further development to enable and maximise the amount of energy which can be utilised in form of heat on the farm would be desirable. The integration of the farms heating system within district heating infrastructure may increase the potential capacity as well as the amount of biochar production. It is important to highlight that, most of the available technologies for biochar production on the market are optimised for wood as feedstock (Jirka and Tomlinson, 2014) and improved technologies for grass are needed, which could substantially improve the potential for implementation.

With the addition of the utilization of the produced biochar as a soil amendment this is a technology that provides a carbon sink up to 1.92 t of CO_{2eq} per t of the biochar. To maximise the potential to provide a carbon sink a reduction of the amount of fossil fuels used in the feedstock provision and the conversion process are desirable. The carbon sink potential could also be increased by maximising the yield of biochar from the process, while this approach has the trade-off of lower heat release. In an ideal scenario the utilised technologies could be controlled to adapt the biochar yield, depending on the availability of excess biomass. Although our experiments show the feasibility and sensibility of biochar production from grass its continuous operation is questionable, as discussed elsewhere (Heinrich et al., 2023), and as identified here, further technology development is a basic necessity for its application.

The economics of biochar systems is a nascent field of research. Up to now, the economics of process inputs and outputs of industrial-scale biochar systems have been analysed in greater detail (e.g. (McCarl et al., 2009; Roberts et al., 2010)) than the economics of small-scale biochar systems, such as cook stoves at household-level or heaters on farm-level, for which such analyses are almost non-existent. Meyer et al. (2018) show that the potential for excess grass as feedstock is high in Europe. This may contribute to address the great challenge of designing farming systems that combine production of food and energy with an overall negative carbon footprint. Zabaniotou et al. (2015) recommend farm-scale biochar system which utilise agricultural wastes as feedstock to produce biochar and energy for on-farm use and state that this scale has efficiency advantages over industrial-scale biochar production (Zabaniotou et al., 2015) Biomass production has an environmental impact, however residual biomass available on farms or agricultural wastes may reduce this impact (Azzi et al., 2021). Unfortunately, the long-term benefits for soil fertility from biochar application (Bundesministerium der Justiz, 2022) are not usually connected with short-term economic gains for farmers. However, when producing biochar via pyrolysis, substantial amounts of heat are released that could be utilized (Rokicki et al., 2021). In this study, we found that heat use is the key for the economic feasibility. This is even more important in the context of the current unstable geopolitical situation together with the related fluctuations in energy or raw material prices. It is necessary to implement production systems that ensure greater autonomy for countries but also for the society (including farmers). However, the savings are only considered for natural gas and may be greater in locations where the infrastructure for this fuel is less available (such as more isolated rural areas). The use of excess local biomass for heat production can decrease a farmer's reliance on fossil fuels and thus reduce the effects of fluctuating fuel prices. In addition, heat production from natural gas would create costs of 8900 and 14,800 Euros just for fuel with pre- and post-war prices respectively. When comparing this with Scenarios 1 and 2, these appear much more feasible since already just the production of heat seems to be competitive with fossil fuels. In addition, the on-farm production of grass, followed by on-farm consumption and the connected nutrient recycling when utilizing the biochar as soil application, could also be promising to decrease a farmer's dependence on mineral fertilizer. Although biochar production is not the most effective route for nutrient recycling it has been shown that a large fraction of the biomass' nutrients may remain in the biochar (Heinrich et al., 2023). At the same time the utilized biochar contributes to the establishment of sustainable management practices within a circular economy and bioeconomy as desired in current European policies (Maroušek et al., 2019).

Additional revenue is important to the economic feasibility of biochar production. This can be achieved due to payments from the sale of carbon credits. Due to the stabilisation of carbon during pyrolysis and the fixation when applying biochar to the soil, the production of biochar can be viewed as a negative emissions technology, resulting in pyrogenic carbon capture and storage (PyCCS) (H. P. Schmidt et al., 2021; Shinners and Friede, 2018). In this study, based on the Carbonfuture guidelines, two possible values for C-credits were considered (75 and 100 € per tonne of biochar), however, due to the growing interest and demand on C-credits, this value could even being higher in the next close years (personal communication). However, while there is a growing political interest in carbon sequestration in land, carbon removal credits at the EU level are still under development and it is unclear if biochar will be included in this mechanism. The first reason is the perceived uncertainty in the amount/duration of carbon sequestered (European Commission, 2018). Despite this uncertainty, carbon sequestration via biochar can be better quantified than other methods such as permanent soil cover and reduced tillage (Verde and Chiaramonti, 2021). Therefore, more support for long-term and real-life setting experiments are called for. The second reason is potential competition in land and biomass use (European Commission, 2018). However, this can be to some extent avoided by setting sustainability criteria for the accepted feedstock, which is similar to the German biomass electricity/biofuel sustainability ordinance, or a positive list of accepted feedstock. For instance, the late-harvest grass in the LOV National Park or other feedstock from marginalized grasslands or herbaceous biomass from rewetted moors can substantially contribute to carbon storage and emissions reduction without competition in biomass use or land use change. Via proper sustainability criteria or positive feedstock list, feedstock can be steered to residues, waste, and ecologically valuable plants. While biochar producers can participate in the voluntary carbon market, upfront investment, informational barrier, and environmental and economic uncertainties may discourage small-scale business owners (Hansen-Connell et al., 2022).

However, at the moment neither carbon credits or direct use as soil amendment is included in the biochar related directives or regulations, largely still due to lack of empirical data on these topics. This makes it essential, to continue with the research and investigations on the long-term carbon sequestration capacity of biochar as well as its short- and long-term effects in soils through its use as a soil amendment.

Despite the benefits involving energy savings from heat production and potentially carbon credits, biochar production did not seem to be profitable at farm-scale due mainly to the high costs of the initial investment and the 20-years amortization period considered. Only when considering that biochar was already used on the farm by external purchase, and this was changed to self-production the system becomes highly profitable. In this regard, the sale of biochar seems to have a huge potential for the business development (from an economic perspective). However, the business environment for such small-scale producers, as investigated in our study, is currently unfavorable in many regards with one main issue being the complexity of regulations, as stated previously in the manuscript. As currently most farms are not utilising biochar as a soil amendment the assumed value of the biochar would need to be reflected in long-term economic gains for the farm. In this study the potential increase in yield production and/or possible reductions in fertilizer needs wasn't accounted. However, the increases in crop/grass productivity or fertilizer savings are also a strong factor influencing feasibility: for example in Spain, researchers found an improvement in yield of tomato, radish, lettuce, and sweet pepper after application of 1 kg biochar m^{-2}, which brought economic benefits, ranging from 3500 to 32,000 EUR·ha^{-1} (González-Pernas et al., 2022). Although biochar amendment is considered in some study as potential P fertilizer; this role is still in discussion since it highly depends on external parameters such as soil properties, feedstock characteristics, technical parameters etc. (Jindo et al., 2020). Therefore, in this study, the economical savings on external inputs of mineral fertilisers were not considered, although this aspect should be further evaluated in future studies.

While the European Commission aims to support the use of organic fertilizer produced from residues and waste due to the increasing price of mineral fertilizer influenced by the supply chain interruptions and energy crisis (European Commission, 2022b) direct use of biochar included in fertilizer products has not been actively promoted, largely still due to lack of empirical data on this topic. Therefore, continued research efforts on the short- and long-term effects in soils through its use as fertilizer or soil amendment, particularly from self-produced biochar, are desirable. Further research to clearly demonstrate the long-term economic gains resulting from the application of biochar for a variety of farming systems may be necessary to convince farmers to adopt its application and invest in the required technology.

Although it was not included in the economic calculation, REACH registration ((EC) No 1907/2006) procedure may be an economic hurdle to especially small to medium producers due to the costs and time involved despite the support measures for small producers. If biochar is a promising option for sustainable agriculture and energy production in a decentralized manner, better advisory service should be provided for small to medium scale producers. In addition, a severe misalignment between fertilizer regulations in EU and Germany requires the producers to take unnecessary steps to be able to produce and market the grass biochar, which generates additional burden. The regulation should provide clear guidelines for biochar products to be able to achieve by-product or end-of-waste status. In the call for a project in the area of "Application of biochar for agriculture in climate change", the Federal Ministry of Food and Agriculture stresses the potential of biochar as a source of carbon sequestration in the LULUCF sector (Bundesministerium der Justiz, 2022). The policy gap should be closed in order to exploit this potential.

Besides the potentialities of grass-based products (Orozco et al., 2021) and particularly biochar, as identified in this paper, its deployment at farm level seems still to be limited due to technical, economic, and regulatory issues. In the end, to valorize the low-nutritional quality grass, not only supports the management of the grasslands but also provides opportunities for additional socio-economic benefits in the region such as developing local self-reliant energy schemes. Yet, missing specialized technologies, accompanied with lack of proper infrastructure and mis-alignments of the institutional framework have been identified as the most prominent challenges for the integration of biochar into current farming systems.

5. Conclusions

In this paper, multiple benefits for the combined production of biochar and heat from underutilised grass as a feedstock are identified. These include independent and local negative emissions heat production, in conjunction with the production of biochar, a high value soil amendment. Yet, many linkages are missing in the value chain to make this a prospective business for farmers. An energetic assessment shows that during the biochar production process large amounts of energy are being released which may be utilised for heating. From an economical perspective, the establishment of the biochar technology at farm-scale could be feasible (and even highly beneficial) when a theoretical scenario of savings of external inputs of soil amendments (or potentially mineral fertilizers) together with income of C-credits are considered. Moreover, the establishment of local technologies that can guarantee self-production of energy seem to be the key for the adaptation to the current global scenario of energy crisis and price fluctuations. Furthermore, regulatory barriers generate additional economic and time burdens or block potential revenue stream. Specifically, misalignment of co-existing European Union's regulation on fertilizing products and German fertilizer ordinance may increase the effort and uncertainty for implementation. utilization of grass as feedstock for biochar production on farm level can be a promising way to valorise low quality grass with the beneficial side effects regarding energy production and providing a carbon sink, but there is a need for the development of suitable technologies for this application. In order to better exploit the potential of farm-scale biochar production, further research on long-term economic gains and carbon sink potential in real settings is essential. Also, alignment of regulations at different levels as well as regulatory measures to ensure the sustainability of the feedstock is recommended.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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