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Nordic perspectives on the emerging biochar business

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A B S T R A C T

Biochar production offers various benefits related to climate change mitigation, circular economy, waste management, renewable energy, and reduced dependency on fossil carbon. Despite these advantages, the biochar market in the Nordic region is still developing. This study explores the current state and future potential of the Nordic biochar market, identifying existing and potential market segments, the role of biochar and its co-products, and factors affecting market growth. The study involved an online survey conducted in 2021, targeting key Nordic biochar stakeholders, including business actors, academic researchers, and other relevant groups (N = 72, representing 64 organizations). The findings reveal that the Nordic biochar market is in its nascent stages, with producers often considering biochar production as a side business. The market faces challenges such as inadequate legal and policy support, limited public awareness, lack of established norms, and uncertainties regarding profitability, technological efficiency, and market potential. However, the industry holds substantial growth potential due to its environmental and climate benefits, provided that current barriers are overcome. Key applications of biochar include carbon removal, water filtration, soil remediation, landscaping, and composting. Additionally, co-products such as energy-dense gases and bio-oil have the potential to enhance the economic viability of biochar production. To facilitate market development, integrating established scientific knowledge into industry standards and policies is crucial. The study underscores the importance of biochar networks and associations in advocating for industry development and highlights the need for enhanced collaboration among stakeholders to overcome existing barriers. Additionally, focused research on the varied applications of biochar is needed, with an emphasis on thoroughly evaluating its environmental, economic, and social impacts.

1. Introduction

Biochar, traditionally known as charcoal when produced from wood, has a history spanning several millennia. It is produced via pyrolysis, a thermal process whereby feedstock is heated in an oxygen-limited atmosphere, transforming it into a carbon-rich, highly porous substance called biochar (Lehmann and Joseph, 2015). Biochar is primarily known for its soil-improving properties and dates back over 2000 years, starting with its use by indigenous Amazonian people to enhance soil fertility (Glaser et al., 2001, 2002). In addition to biochar's role in improving soil properties, it can remain in soil for centuries and act as carbon storage (Lehmann et al., 2021). This has led to the production and application of biochar being recognized as one of the few immediately accessible strategies for large-scale carbon sequestration and removal (Fuss et al., 2018).

Recent advancements in biochar research have substantially increased understanding of its versatile properties, such as physical and chemical properties that enable it to retain nutrients and water but also adsorb contaminants such as heavy metals, organic pollutants, and microplastics (Kuoppamäki et al., 2016; Siipola et al., 2020; Tomczyk et al., 2020). These versatile properties enable various potential applications across different industries, ranging from soil amendment and environmental remediation (Guo et al., 2020; Nguyen et al., 2023) to metallurgical applications (Suopajärvi et al., 2017) and utilization as a cement additive or in construction (Roychand et al., 2023; Gupta et al., 2021, 2022). In addition to biochar, the pyrolysis procedure yields energy-dense gases and by-products like bio-oil and distillates, all of which entail promising new applications and market opportunities

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(Hagner et al., 2020; Qambrani et al., 2017).

Furthermore, the potential of biochar extends beyond its primary form; through physical or chemical activation processes, it can be transformed into high-value carbons such as activated carbon (Tiihonen et al., 2021), carbon black (Kane et al., 2022), or graphite (Guizani et al., 2023; Sagues et al., 2020). These products already have robust and expanding markets in diverse sectors, from water, gas, and air purification to energy storage systems and the automotive industry. The demand for different carbon types is intimately tethered to environmental regulation, industrial evolution, and factors such as electrification, population growth, and improving livelihood. Presently, the majority of activated carbon and graphite originates from fossil-based carbons—coal, natural graphite, and oil industry by-products (Andrews, 2021; Bosch et al., 2022). While coconut shells can be used as feedstock for activated carbon, they are often produced unsustainably, and the feedstock is limited by region-specific availability. In this context, biomass-derived biochar represents a sustainable and renewable alternative to fossil-based carbons that can be produced from a wide range of locally available biomass (Arena et al., 2016; Vilén et al., 2022; Yahya et al., 2015).

The production and application of biochar and its co-products are considered to offer a broad range of potential solutions related to circular economy, waste management, climate change mitigation, and carbon removal (Lefebvre et al., 2023; Woolf et al., 2021; Qambrani et al., 2017). Furthermore, it presents opportunities for various innovative business models and strategies, including integrated biochar, heat, and power production (Azzi et al., 2019), as well as the processing of sewage sludge at wastewater treatment plants (Sarvi et al., 2023). According to the European Biochar Industry (2024) market report, there were 171 biochar production facilities in Europe in 2023, which together produce 75,000 tons of biochar annually. This number was projected to increase to 220 plants during 2024. In 2023, more than half of biochar was produced by facilities with an annual capacity of less than 2000 tons. Of the total European production, the Nordic countries contributed approximately 28%, corresponding to 21,000 tons of biochar annually.

Biochar is currently produced in small and pilot-scale facilities around Nordic countries using a variety of different feedstocks, processes, and business models. Stora Enso (2022) has a pilot plant in Sunila, Finland, which uses kraft lignin to produce hard carbon for battery applications, and the company is looking forward to beginning large-scale commercial production. In addition, Carbofex (2022), located in Nokia, Finland, has produced biochar from woodchips since 2017. Currently, the company produces 2000 tons of biochar annually and utilizes the excess energy from the pyrolysis process for district heating. Helsinki Region Environmental Services HSY (2022) has a pilot-scale plant in Espoo, Finland, that uses a mixture of woodchips and wastewater sludge to produce biochar. In Denmark, Stiesdal (2023) is currently operating a 2 MW SkyClean plant in Skive and building a 20 MW plant that would produce 15,000 tons of biochar from agricultural and forestry side streams and waste biomass.

In Norway, biochar production capacity is increasing significantly. Its first large-scale production plant has been operated by OBIO (2023) since 2021, producing biochar for soil amendment and animal husbandry. Vow (2023) is currently constructing a plant which will have an annual production capacity of 10,000 tons of biochar, targeting the metallurgical industry, with further plans to double the capacity. In Sweden, Nordvästra Skånes Renhållnings AB - NSR (2023) has established a biochar plant that uses locally available garden waste to produce 1500 tons of biochar annually. NSR has also developed a biochar competence center with laboratory infrastructure and has organized biochar-related exhibitions and training. In addition, there are various other biochar production facilities around the Nordic region.

Due to the diverse character of the biochar industry and the limited market data, the business environment in which the biochar market is developing, as well as the barriers and drivers of biochar development, are currently not well understood. The lack of reliable and accessible biochar market research that would consider regional approaches, market status, trends, and future outlook has been recognized as one of the key barriers that limit the widespread adoption of the industry by previous research (Thengane et al., 2021). This study aims to address this knowledge gap by examining the development and diffusion of the biochar business in the Nordics, including perspectives on its eco-innovation features. *Eco-innovations* refer to innovative products, services, and practices whose main objective is to mitigate environmental harm while fostering sustainable development (European Commission, 2011; Kemp et al., 2019). Additionally, this study considers the perspectives of Rogers' (2003) diffusion of innovations theory while examining the underlying factors and processes, and the speed with which novel ideas and technologies spread through the market.

In this exploratory study, we examine the biochar markets in the Nordics, including the current market status and the economic and environmental perspectives. A central aim is to address the information gap on how the business environment impacts the diffusion of biochar production processes and applications, as well as the driving forces behind this, barriers to growth, and future potential. Notably, this study, including its data collection process (surveying industry stakeholders), is among the first to comprehensively explore the biochar market with a particular emphasis on the Nordic region.

The study used a quantitative, online survey for data collection targeted at Nordic biochar stakeholders such as business actors, academic researchers, and other stakeholder groups. Furthermore, the study aims to explore differences in perceptions of the biochar market between different groups of actors.

The main research question of this study is.

- What is the current state of the biochar market in the Nordics, and what is the outlook for the future (until 2040)?

In addition, the following sub-questions were used to address the main question.

- What are the current and future biochar market segments, and what is the role of the co-products of biochar?
- What are the enabling and limiting factors for biochar market development?

This study offers insights with both practical and theoretical significance. On the practical side, it explores the current state and future outlook of the biochar market in the Nordic region, contributing to a deeper understanding of market dynamics. Since the business environment varies across different regions of the world, these impacts must be analyzed on a regional basis. This approach benefits stakeholders such as startups, investors, and policymakers by identifying current trends, potential growth areas, and market segments within each region. Focusing on the co-products of biochar allows for a more comprehensive approach to market development. Additionally, understanding the enabling and limiting factors for biochar market development is crucial for those aiming to establish and scale biochar production and applications. The insights from this study could also be used by policymakers and investors to make informed decisions regarding support, funding, and regulatory frameworks, thereby accelerating the adoption of biochar in the Nordic region. From a theoretical perspective, the research is related to the concept of eco-innovation and the theory of innovation diffusion. This provides knowledge on how specific eco-innovations can be researched and studied effectively. Overall, this paper enhances data gathering and analysis techniques by studying the scaling-up and diffusion of eco-innovations, which has been an under-researched topic in eco-innovation research (Losacker et al., 2023).

The structure of this article is organized as follows: It begins with an introduction, followed by a detailed theoretical background. The Materials and methods section describes the materials used and methodologies employed in the research. The Results section presents data from the survey, covering descriptive data about respondents, features of biochar production, applications, market drivers, and future directions. The Concluding discussion section provides an in-depth analysis of the results, exploring their implications and relevance to the field.

2. Conceptual and theoretical background: diffusion of eco-innovations

Various concepts and terms have been used to describe sustainability-oriented innovations (Carrillo-Hermosilla et al., 2010); examples include *eco-innovation* (Kemp et al., 2019), *environmental innovation* (Hemmelskamp, 1997), *green innovation* (Chen et al., 2006), and *sustainable innovation* (Clark and Charter, 2007). There have been several attempts by researchers to define and distinguish these terms based on innovation type, measurability of environmental impacts, and social dimensions (Schiederig et al., 2011). Nevertheless, the main objective of this relatively new terminology has been to differentiate and recognize the unique nature of sustainability-driven innovations compared to conventional innovations.

Eco-innovation can refer to novel or improved products, services, business models, patents, practices, processes, or other activities that reduce environmental impacts, pollution, and risks or increase environmental resilience and resource efficiency (European Commission, 2011; Kemp et al., 2019; Kemp and Pearson, 2008). One of the most recent definitions of eco-innovations was presented by Kemp et al. (2019): "An eco-innovation is a new or improved product or practice of a unit that generates lower environmental impacts, compared to the unit's previous products or practices, and that has been made available to potential users or brought into use by the unit." More generally, eco-innovations can be described as innovations that reduce the environmental impact caused by production or consumption activities (Carrillo-Hermosilla et al., 2010).

Perceptions on eco-innovations have evolved over the years, from eco-innovations being adopted mainly to comply with regulations to a more pro-active approach resulting from an increased understanding of the capability of eco-innovations to reduce costs and improve resource efficiency in addition to their pollution prevention capacities (Kemp et al., 2019).

2.1. Conceptual background

For the purpose of this paper the term *eco-innovation* was selected, as we believe it is the most relevant and suitable term for describing the features and development of biochar and related businesses. The production and application of biochar can provide multifield environmental benefits in different parts of the value-chain. Firstly, by using biomass waste materials biochar can contribute to waste reduction. Secondly, the excess energy from biochar can be used as renewable energy to replace fossil-based energy. Thirdly, biochar has various end-uses which contribute to emissions reduction or carbon removal and has application-specific co-benefits.

According to Kemp et al. (2019), eco-innovations can be further classified into various types, the four conventional types being product, practices, process technology, and organizational methods. Additional innovation types include but are not limited to market, social, and systemic eco-innovations. The development and adoption of eco-innovations are considered to play an essential role in promoting circular economy and enabling the transition to a climate-neutral and sustainable economy (Mohamedaly et al., 2022). The role of eco-innovations is considered critical to the European Union's policy strategies and to achieving the objectives of the European Green Deal (European Commission, 2019).

However, the concept of "eco-innovations" has been criticized for functioning as a modern "buzzword" that promotes a weak sustainability approach, prioritizing the creation of business opportunities focused primarily on enhancing eco-efficiency while failing to substantively question existing economic models which contribute to environmental issues (Colombo et al., 2019). One example of this is provided by Befort (2021), who examines the use of Polylactic Acid (PLA) as an eco-friendly alternative to petroleum-based plastics. While PLA was developed and marketed for its environmental benefits, its adoption does not adequately address critical sustainability issues such as overconsumption, waste generation, and consumer behavior patterns. On the contrary, promoting PLA might result in adverse effects, including potentially encouraging or increasing the production of unsustainable products such as single-use items while creating a misleading perception of environmental responsibility.

2.2. Diffusion of innovations

In the face of the wide variety of eco-innovations, researchers have adopted various methods and theoretical frameworks to study them. Eco-innovations can be explored more systematically, from the industry level down to individual case studies. One way to investigate how different factors, drivers, and barriers impact the market development of eco-innovations is using Rogers (2003) diffusion of innovations theory, which investigates how, why, and at what rate new ideas and technology spread across the market. Rogers (2003) provided one of the best known definitions of diffusion of innovation: "a process by which an innovation is communicated through certain channels over time among the members of a social system. It is a special type of communication, in that the messages are concerned with new ideas". Rogers (2003) describes the innovation diffusion process as an uncertainty reduction process that can be studied with a focus on its five most essential qualities: relative advantage, complexity, compatibility, observability, and trialability. Moreover, these qualities can be used to predict the rate at which an innovation will be adopted. In addition, other factors impacting the adoption rate include the decision type, social system, communication channels, and change agents have also been studied. Losacker et al. (2023) highlighted the significance of regional dimensions in fostering the development, initiation, and widespread adoption of eco-innovations. They also identified collaborations in regional R&D and partnerships between universities and industry as crucial driver.

Once innovations are introduced to market, they start developing through stages, also known as the innovation lifecycle. According to Rogers (2003), the innovation lifecycle can be classified based on individual speed of adoption: Innovators (2.5% of the population) are risk-takers and the first to adopt, and often have vast social networks. Early Adopters (13.5%) are socially forward, have higher status, and serve as role models in adoption. The Early Majority (34%) take longer to adopt, seeking more information and often interacting with peers before doing so. The Late Majority (34%) are usually skeptical, adopting due to economic necessity or peer pressure. Lastly, Laggards (16%) are the most resistant; they typically have the lowest social status and least financial resources and rely heavily on past practices and close-knit social circles. The adoption rate of innovations varies significantly between innovations; some may take years or even decades to reach widespread adoption while some may never be adopted at all.

While conventional innovations and eco-innovations face similar challenges during the diffusion process, eco-innovations are typically driven by environmental objectives, meaning some eco-innovations are less market-driven and rely on environmental policy as one of the main drivers (Horbach, 2008). According to Frondel et al. (2007), this is especially the case for end-of-pipe technologies, while cleaner production is often more market-driven due to achieved energy, material or other cost savings. The most relevant drivers of cleaner technologies include regulation, demand-pull factors, government subsidies, R&D intensity, organization capabilities, technological opportunities, taxes, voluntary agreements, economic risk and uncertainty, social pressure, general management systems, and competition, while specific market drivers vary depending on the specific eco-innovations (Hojnik and Ruzzier, 2016).

Eco-innovations are unique in that they create positive spillovers during both their development and adoption phases (Rennings, 2000). Positive spillovers are the additional benefits that reach beyond the entity that originally developed or implemented the eco-innovation. For example, a company that deploys a cleaner technology also contributes societal benefits, such as improved air quality or reduced waste. However, this leads to a unique issue known as the double-externality problem (Beise and Rennings, 2005). In this scenario, the innovators—companies or other actors that have invested in the development and adoption of eco-innovations—end up creating knowledge that can be freely applied by others, preventing them from fully realizing the financial benefits of their eco-innovations. Although certain effects may be mitigated by first mover advantage, patents, or policy interventions such as subsidies, grants, and regulations, the double-externality problem may still have a negative impact on diffusion and discourage investment in eco-innovations (Jaffe et al., 2005).

Kemp et al. (2019) describes eco-innovation drivers and barriers as factors that either facilitate or hinder the diffusion of eco-innovations and further divides them into four categories: market, policy/regulatory, social, and technology-specific factors. **Market** factors include the presence or absence of tax and regulations that mean market prices take into account external costs, R&D investments, financing, skilled labor and market demand. Furthermore, transition costs such as the initial costs of adopting the eco-innovation can negatively influence diffusion. **Policy/regulatory** factors include the presence or absence of regulation or policies that promote transition, obligatory or voluntary product standards, financial incentives such as grants and subsidies, pollution taxes, emission trading schemes and support for establishing infrastructure. **Social factors** include the presence or absence of political support from citizens, eco-literacy and environmental awareness, cultural aspects and peer-group dynamics, stakeholders' involvement, influential entities such as NGOs, media and political parties, and "soft measures" such as corporate social responsibility (CSR) to promote sustainability. **Technology specific** factors refer to facilitators and obstacles tied to specific technologies that have to be assessed on a case-by-case basis.

3. Materials and methods

This research targeted biochar businesses, researchers, and other stakeholders in the Nordic biochar field. The survey questions (Appendix 1) were developed in collaboration with the Nordic Biochar Network (NBN, 2023), the Finnish Biochar Network (Bioenergia, 2023), the Norwegian Biochar Network (Norsk Biokullnettverk, 2023) and the European Biochar Industry Consortium (EBI, 2023). Moreover, the survey was distributed through these networks. The survey questions were influenced by diffusion of innovation theoretical frameworks and earlier studies on the diffusion and business potential of new bio-based production methods and products (Hurmekoski et al., 2019; Kunttu et al., 2020; Näyhä, 2019; Näyhä and Pesonen, 2012). In addition, ideas and feedback regarding survey questions were gathered from representatives of biochar associations and networks. For the purpose of the survey, biochar was defined as a solid product of biomass pyrolysis or other thermochemical conversion processes that result in a carbonaceous solid with a porous structure. The definition was communicated to respondents at the beginning of the survey form (Appendix 1).

The survey consisted of a total of 30 questions, including both quantitative and qualitative questions. The survey was divided into three sections: background information, biochar production (for current producers), and the biochar market and future perspectives. The answer time for the survey was approximately 20–25 min. The survey was carried out using the Webropol (2021) survey tool during April 2021. Respondents were asked to provide their position and organization at the beginning of the survey. This information was used to ensure that a sufficient number of key biochar actor responded to the survey. Survey data was anonymized before the actual analysis. The survey respondents were classified into three groups: researchers, business actors, and other actors (e.g., from the public sector, NGOs, and investors). The statistically significant differences in opinions between the three groups were compared using Pearson Chi Square analysis with Cochran's and Mantel-Haenszel statistics using the SPSS statistical package (IBM, 2021). For questions 17 and 18, which asked about the importance of biochar market areas currently and by 2040, original six-point answer categories were combined into three: 1) fairly to very important, 2) important to slightly important, and 3) not relevant to not at all important, for analytical purposes.

Respondents' answers to the open-ended questions of the survey (Q23 – Q30) varied significantly in length. Data from each question was analyzed separately using the thematic analysis method (Boyatzis, 1998; Creswell, 2014) following Braun and Clarke's (2006) phases: data review and screening (including anonymization), coding, categorizing into themes and sub-themes, and refining themes. The results are presented in Section 4.5.

The data collection and analysis process for this study is presented in Fig. 1 below.

4. Results

4.1. Descriptive data

A total of 72 respondents participated in the survey: 43 business actors, 20 researchers, and 9 respondents who were categorized as "others". Representatives from the business sector included actors such as biochar producers, pyrolysis technology providers, and biochar resellers. Representatives from research included actors conducting academic research at universities or other research organizations. The "others" group included investors, public sector actors such as city representatives, and members of non-governmental organizations. The respondents were distributed geographically as follows: Finland 31, Sweden 19, Norway 12, and Denmark 10. Almost all the business actors were representatives of small companies (with under 50 employees), while most researchers represented large organizations (with over 250 employees).

4.2. Features of biochar production

Nearly half of the survey participants (49%, 35 respondents) expressed an interest in establishing new biochar production facilities in the future, while 20 respondents were actually involved in biochar production at the time the survey was conducted. Among the biochar producers, 60% described biochar production as a side business, 25% as their main business, and the remaining 15% were producing biochar mainly for research and process and product development purposes. Most biochar producers (over 50%) used different types of woody biomass as feedstock although other feedstocks including wheat straw, manure, wastewater sludge, and animal bones were also used. Several respondents pointed out legal constraints and challenges related to the use of specific waste feedstocks, especially those classified with official waste status. When biochar producers were asked to estimate the average price of biochar per ton, the responses ($n = 12$) varied within the range of €400 to €1950. Biochar producers identified the domestic market as the foremost market area of importance. Moreover, the Nordic regions and their respective local markets were considered important while other EU and outside-EU markets were perceived as not at all or only slightly important.

There was a strong consensus across all groups that the technological challenges related to biochar production and uncertainties concerning the profitability of biochar production create investment insecurities. There were no statistically significant differences among the groups (researchers, business professionals, and others) concerning their views

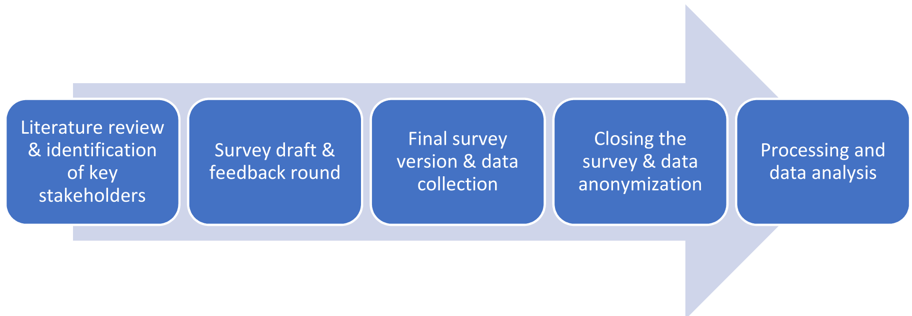

Fig. 1. The research process.

on these challenges (see Fig. 2).

The open-ended questions garnered some additional information on factors which limit the establishment of biochar production facilities. Experts highlighted the lack of clear legal and policy incentives promoting biochar production/application or carbon removal generally as key challenges. Some respondents viewed price and the availability of feedstock as challenges while some described legal barriers such as environmental permits regarding the use of certain feedstocks with official waste status, such as wastewater sludge. Some mentioned that the price of biochar especially limits widespread use in high-volume applications such as the metallurgical industry. One response suggested that offtake agreements with biochar customers would help producers secure investments.

The results (see Fig. 3) indicate that carbon credits and biochar were considered the main products of pyrolysis while heat could be described as the most important co-product. The roles of bio-oil, distillate, and gas were more controversial though half of the respondents still considered them to have at least a slightly important role. In their responses to the open-ended questions, some of the respondents highlighted REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) - a European Union regulation that affects the supply and use of substances as the main challenge in commercializing pyrolysis products such as biochar, bio-oil, and distillates.

4.3. Biochar applications

Respondents were asked how important diverse biochar applications currently are in their countries, and how important they will be in the future, in the year 2040. The results are presented in Fig. 4 below.

The most important biochar application areas could not be determined unequivocally as biochar was considered to have a role to play in all the application areas in question, especially in the future, in the year 2040. However, the following five application areas could be highlighted as being among the most important: 1) Carbon removal, 2) Water filtration and management, 3) Soil remediation, 4) Landscaping, and 5) Composting. In addition, it is noteworthy that volume-driven industries such as metallurgy were seen to have the potential to contribute to a sudden and rapid growth of the biochar market.

Respondents were asked about their views on statements related to widespread usage of biochar and the results are presented in the Fig. 5 below.

The aim of this question was to investigate whether five specific factors are impeding the market growth of biochar applications: public awareness, government subsidies, practical experience, scientific research, and the market price of biochar. The findings show that most participants at least somewhat agree with the given statements, with slight variations among them. Notably, researchers tend to more strongly agree that the market price of biochar is a significant barrier to its widespread use. Conversely, business stakeholders are more inclined to believe that limited public awareness and lack of practical experience are the primary constraints on the widespread adoption of biochar.

4.4. Drivers of biochar market development

The respondents were presented with a set of statements and asked to evaluate their importance for biochar market development and as market drivers (Fig. 6).

While all the statements were viewed as important, the environmental and climate benefits associated with biochar production and applications are considered more crucial than the economic aspects. Market actors are mainly driven by the environmental and climate advantages of biochar, and though economic factors are deemed important, they are not the primary motivators.

For all groups, the key factors are related to environmental or climate benefits and achieving associated goals, indicating a positive evaluation of biochar's potential for environmental sustainability. While access to subsidies or funding and the opportunity to create new business ventures are also viewed as important, they are considered less important than environmental aspects. Although all recognize the importance of biochar in both environmental and economic terms, perspectives vary slightly among groups. Researchers prioritize environmental impacts, whereas businesses and other stakeholders have a more balanced view of the environmental and economic benefits. The moderate importance given to subsidies and funding across all groups, as well as biochar's role in supporting main business activities, suggests a consensus on the substantial role of financial and business considerations in the

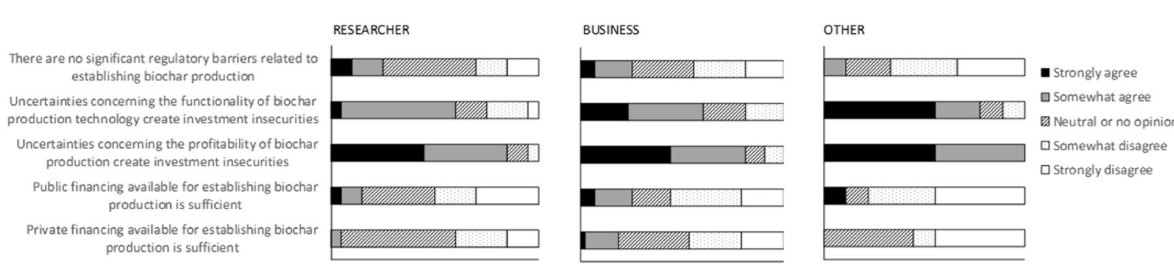

Fig. 2. Opinions of researchers (n = 20), business professionals (n = 43) and others (n = 9) on statements concerning the establishment of biochar production facilities.

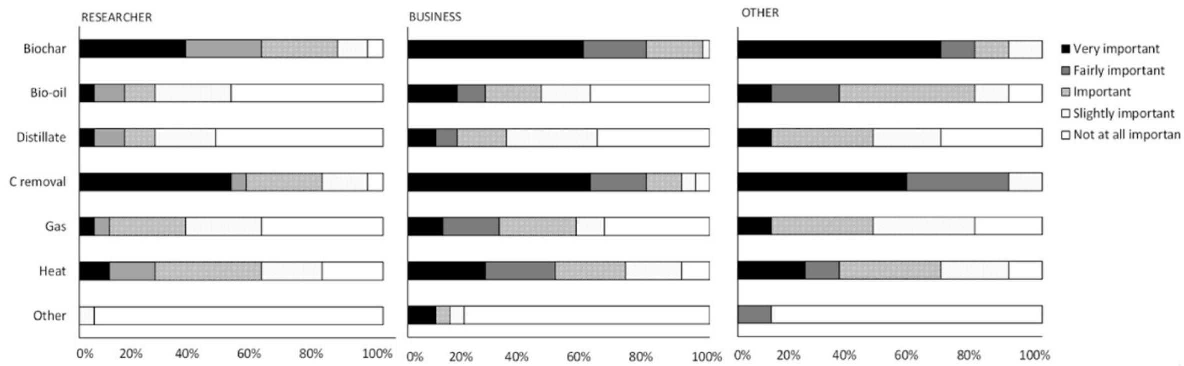

Fig. 3. Importance of various pyrolysis products to respondents' (grouped as researchers, business professionals and others) organizations' activities.

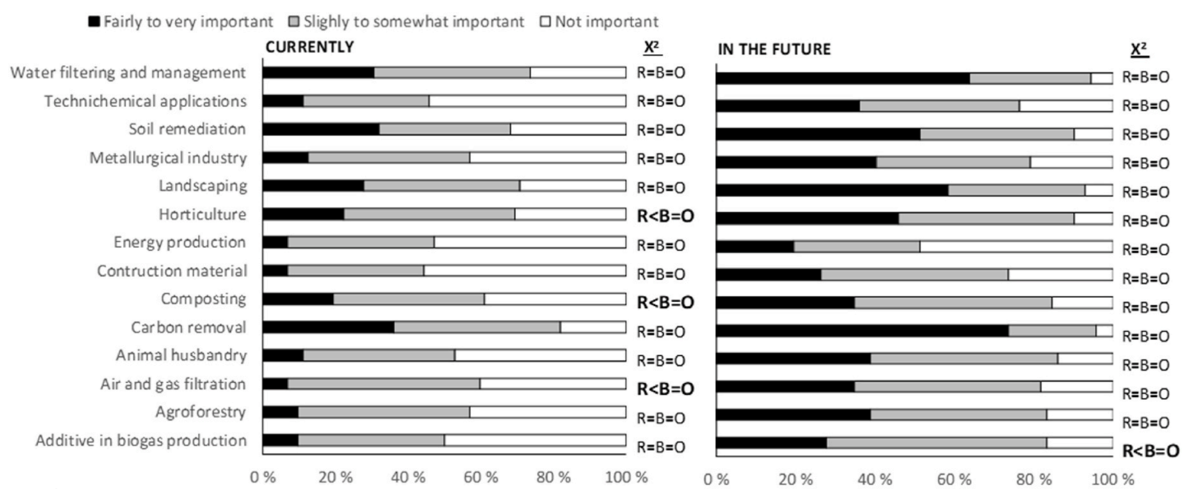

Fig. 4. Current and future biochar application areas. All responses (n = 72) concerning current and future (in the year 2040) biochar markets, are grouped into three classes: 1) Not important (white bars), 2) slightly to somewhat important (grey bars) and 3) fairly to very important (black bars). Results of the Pearson Chi Square test of statistical significance ($p < 0.05$) of differences among the groups (R = researcher, B = business, O = others) are shown with signs: no difference between the groups (=), group viewed this as less important/critical than other groups (<).

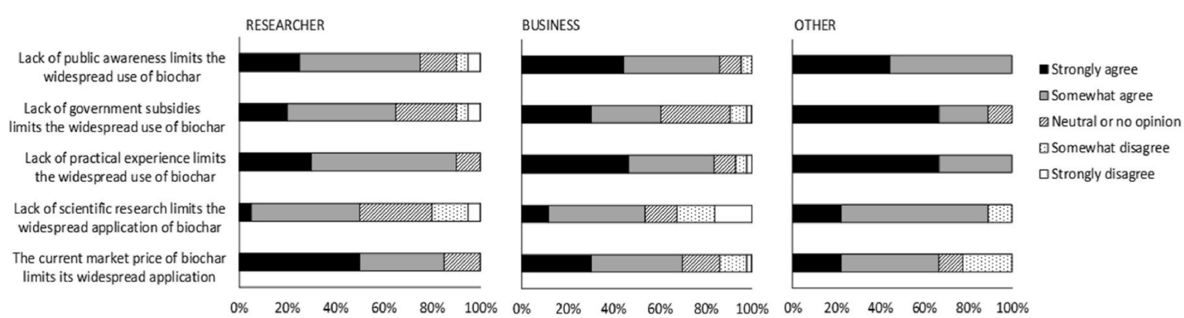

Fig. 5. Responses of researchers (n = 20), business professionals (n = 43) and others (n = 9) on factors limiting the widespread usage of biochar.

development and usage of biochar.

4.5. Future directions to enable biochar market development

This section summarizes the responses to the open-ended survey questions related to future directions in research, industry, policies and the role of biochar associations and networks in enabling the development of the biochar industry by 2040.

4.5.1. Research

The survey data suggest that the biochar sector could benefit from extended research across the natural sciences, engineering/technical disciplines, and social sciences. In the natural sciences, the focus should be on investigating biochar's role in agriculture, soil fertility, wastewater management, soil restoration, and its interactions with soil microbiota, and consider diverse soil types, climatic conditions, and practical settings, including urban landscapes.

In engineering and technical disciplines, efforts should be directed towards enhancing biochar production and application processes. This includes conducting Life Cycle Assessments (LCAs), upscaling biochar production, advancing production technologies, and exploring novel applications like converting biochar into activated carbon or other forms of carbon material. Moreover, evaluating how feedstock selection and pre-treatment influence the production process and the characteristics

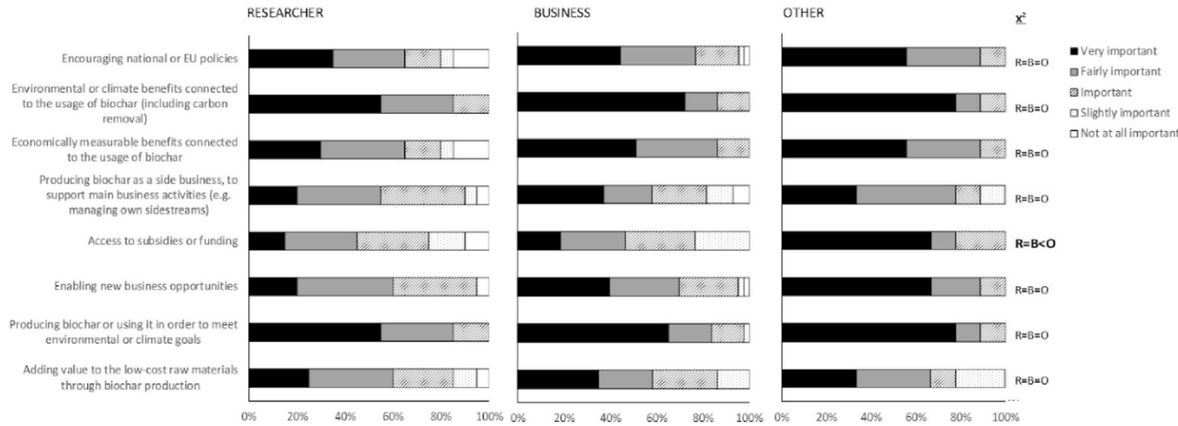

Fig. 6. Responses of researchers (n=20), business professionals (n=43) and others (n=9) on propositions concerning the drivers of biochar market development. Results of the Pearson Chi Square test of statistical significance ($p < 0.05$) of differences among the groups (R = researcher, B = business professionals, O = others) are shown on the right side with signs: no difference between the groups (=), group viewed this as less important/critical than other groups (<).

of biochar across different reactor types is critical. One proposed suggestion is the development of an AI-driven biochar modeling tool, designed to model biochar properties based on feedstock information. Furthermore, advancing research into the commercial potential of biochar co-products, such as wood vinegar and bio-oil, was identified as an essential area for further development.

Research within the social sciences should focus on economic modeling, understanding market dynamics, and the societal implications of biochar-based businesses. This includes examining biochar's contribution to circular economies and its social acceptance, devising effective communication strategies, and assessing the sustainability of biochar production at scale, including biomass availability for biochar production. The establishment or improvement of standards for the quality of biochar and its applications is also deemed a crucial area of focus. Ultimately, adopting a comprehensive and interdisciplinary research approach will deepen understanding and broaden the application of biochar across different sectors.

4.5.2. Industries

The survey results underscore that agriculture is a key industry for the development of biochar applications by 2040, a view widely shared across the various respondent groups. In addition to agriculture, the metallurgy industry was also considered a sector with significant potential, as mentioned by eight respondents. The electro-chemical industry, encompassing sectors like battery carbons and activated carbon, was mentioned by six respondents, primarily from the business sector. Similarly, uses in the construction industry, such as applying biochar as an additive to cement, were mentioned six times, mostly by respondents from the business sector. Moreover, six respondents mentioned the waste and water treatment sector as having potential for the adoption of biochar. Other industries, though mentioned less, contribute to the diverse potential of biochar. These include energy production (integrated energy and biochar production), farm-scale or local production in small biochar plants, fertilizer companies, and sectors such as landscaping and urban green building. This array of industries, from high-tech to traditional sectors, illustrates the wide opportunities for usage of biochar across various fields by 2040.

4.5.3. Policies

The survey findings represent a unanimous call for relevant climate policies at regional, national, EU, and international levels. These policies should aim to reduce emissions and boost technical carbon removal. Respondents advocated for legally binding carbon removal targets, emission reduction schemes, establishing a definitive CO_2 price, formally recognizing biochar as a tool to achieve climate targets, and shifting from voluntary towards compliance carbon markets. This includes adding biochar to greenhouse gas (GHG) inventories under frameworks such as the EU's regulations on land, land use change and forestry (LULUCF) and the Paris Agreement.

Policies around waste and side stream management were also deemed essential. Proposed measures include discouraging the direct combustion of potential biochar feedstocks and banning landfilling of feedstocks suitable for biochar production. Financial instruments similar to feed-in tariffs for biochar were suggested to foster early development of biochar production processes and applications.

Other key policy recommendations focused on promoting nutrient cycling, incentivizing carbon farming, developing pyrolysis-based industrial symbiosis, and financial policies related to the replacement of fossil-based carbon with biochar in various applications. The necessity for policies to enable the production and use of biochar co-products such as pyrolysis liquids and establishment of standards for biochar quality and end-uses was also highlighted.

The overarching themes were the integration of biochar into broader climate and environmental policies, supporting its production and application through financial incentives, and regulating its quality. This approach is geared towards ensuring biochar makes an effective contribution to sustainable development by 2040.

4.5.4. Biochar associations and networks

The primary focus of biochar associations and networks was on increasing public awareness of biochar. This involves disseminating both scientific and practical knowledge about biochar's uses and its significance as a climate solution. The creation of biochar guidebooks, active participation in policy development, engagement with biochar businesses, and establishing an online information platform for biochar were considered key.

Another critical strategy involves facilitating collaboration among various stakeholders. This includes businesses, researchers, and policymakers, with the aim of enhancing the synergy between existing biochar associations and networks. Alongside this, there was a significant emphasis on developing industry standards for biochar and its end-uses. Monitoring the quality and consistency of various standards and certificates is deemed essential.

The survey also highlights the importance of promoting an industrial perspective on biochar, encouraging both its production and application. Additionally, increasing awareness of innovative approaches, especially lesser-known biochar end-uses and the commercialization of pyrolysis co-products, is seen as crucial for market development. Lastly, developing financial mechanisms to support small and medium-sized biochar projects was suggested.

Overall, these strategies underscore the need for a comprehensive effort from biochar associations and networks. The focus should be on enhancing public understanding, fostering collaborations within industry, standardizing practices, and supporting innovative and financially viable biochar applications. The ultimate goal is to leverage the environmental and climate benefits offered by different parts of the biochar value chain.

5. Concluding discussion

5.1. Current state of the biochar market in the nordics

Over the last decade, interest in biochar has been largely driven by academia. The number of biochar research publications has been rapidly increasing, with over 23,800 publications currently available, more than half of which were published after 2019 (Kumar et al., 2023). To encourage business development, various national, regional, and international biochar associations and networks have been established to advocate for the production and application of biochar as well as to disseminate science-based practices (IBI, 2023). Currently, the biochar market in the Nordics is primarily driven by small companies with under 50 employees, focusing on biochar production mainly as a side business. According to the European Biochar Industry (2024) market report, the annual biochar production in the Nordic countries is 21,000 tons, which constitutes approximately 28% of the total European production. The feedstock for biochar production in the Nordics includes mostly woody biomass but also wheat straw, manure, and wastewater sludge. However, legal constraints related to specific waste feedstocks pose challenges.

The research findings reveal a significant interest in advancing biochar production, with 49% of the survey respondents expressing intentions to establish a biochar production facility in the future, indicating potential market growth. However, should this enthusiasm not translate into actual market development, it might imply that stakeholders are cautious, possibly delaying investments and entry into the biochar market due to perceived obstacles and uncertainties. To further explore these dynamics, we recommend that a detailed study of entities currently planning biochar operations, as well as of biochar-based business models, be carried out in order to acquire a more comprehensive understanding of the factors influencing the establishment of biochar production facilities. Moreover, the survey results indicated that biochar could especially benefit from more practice-oriented research in order to improve understanding of its application-specific and economically measurable co-benefits. Previous research by Gerstlberger and Urbaniec (2011) has also highlighted the crucial role of active cooperation among stakeholders, including research organizations, businesses, and initiatives related to education and information, in enabling the development of the eco-innovation market, given that it is a long-term process.

The findings suggest that due to the variety of perspectives on biochar application and the main and co-products of pyrolysis, biochar producers are currently applying various technological and business approaches to biochar production which result in varying efficiency levels, costs, and biochar product qualities. Similar findings have also been reported by Campion et al. (2023) who found the profitability of biochar production to be highly case-specific and to depend on the biochar price, feedstock, production technology/conditions, scale of production and internalization of externalities. Similar to previous studies (Bydén and Fridlund, 2020; Campbell et al., 2018; Shrestha et al., 2023; Tian et al., 2020), the findings from this study suggest a wide price range for biochar (€400 – €1950 per ton). While some degree of price variation can be attributed to differences in biochar quality and properties, other factors influence price fluctuations such as the varying levels of understanding of biochar and its added value from the perspective of the demand side. For instance, some innovators and early adopters might be willing to pay a premium for innovative products due to perceived benefits and environmental consciousness (Cantono and Silverberg, 2009).

The so-called chicken and egg dilemma can be recognized in the relationship between the demand for and supply of biochar. Industries such as green building, agriculture, and metallurgy are keen on adopting biochar but require it to be available at a certain price and in large, steady volumes. Achieving this, however, would necessitate significant investment in the supply side to achieve technological advancements and economies of scale. This leads to a scenario where demand-side uncertainties also hinder supply development. Similar findings have also been reported by Zilberman et al. (2023), who suggest that low demand for biochar translates into insufficient investment in improving production technology.

Additionally, potential demand-side adopters of biochar, such as soil producers and fertilizer companies, could boost biochar demand among their customers through marketing efforts and by increasing awareness. However, uncertainties about how this growing demand can be met may dampen initiatives intended to foster a growth in demand in the first place. This chicken and egg dilemma means there is a risk of market stagnation and the seemingly limited demand for biochar further discourages market entry. To mitigate these issues, policy instruments such as investment subsidies and grants could support the supply side, while off-take agreements could bolster the demand side. The chicken and egg dilemma is an obstacle commonly recognized in previous studies that have examined the impact of widespread adoption of environmentally friendly technologies (Brozynski and Leibowicz, 2022; Cantono and Silverberg, 2009; Mäkitie et al., 2021). In the case of biochar, a temporary subsidy policy could be sufficient to support the industry through its early development stages, overcome initial barriers, and offset high upfront costs, ultimately enabling self-sustainable and widespread adoption. In addition, it is essential to recognize that the overall climate and environmental benefits of biochar production and its applications are highly dependent on the feedstocks and production technologies employed. Ensuring that biochar feedstocks do not contribute to sustainability issues, such as deforestation, and that emissions (e.g., methane and particulates) from the production process are controlled is crucial. Although biochar production is often energy self-sufficient and can even produce excess energy, this is not always the case. Some biochar production processes rely on external energy sources, such as electricity or natural gas. Therefore, policies supporting biochar production as an environmental material must also establish requirements for feedstock sustainability and production processes.

It could be said that biochar is undergoing a transformation; while once it was merely a subject of scientific research, relevant actors are now working on practical implementations and market development. The findings of this study suggest that the biochar market is currently driven by innovators and is in its early stages of development, taking its first steps towards widespread adoption. This aligns with the findings of Hockerts and Wüstenhagen (2010), who noted that sustainable business efforts in the early stages of industry are typically driven by small companies and new entrants, while larger corporations tend to join after early market success has been demonstrated.

5.2. Current and future biochar market segments and role of the co-products of biochar

This study identified the five most important biochar application areas in the Nordics as: 1) carbon removal, 2) water filtration and management, 3) soil remediation, 4) landscaping, and 5) composting. Similar findings have also been reported by Thengane et al. (2021) in a California biochar market study, where the most relevant biochar market areas were considered to be soil-based applications followed by filtration, livestock feed, and manure management. Indeed, the Nordic biochar market is currently especially driven by applications in which biochar acts as carbon storage and contributes towards carbon removal. During biochar production originally atmospheric CO_2 transformed via photosynthesis into organic biomasses is processed into stable carbon (Lehmann and Joseph, 2015). When applied in soil or non-soil applications such as construction materials biochar can act as long-term carbon sink (Deng et al., 2024; Kung and Mu, 2019). Thus, biochar has critical function as a negative emission technology (Werner et al., 2022) to be used in achieving current climate goals and has been mentioned also in newest IPCC (2023) report as a way on carbon sequestering.

This study suggests several other sectors with significant growth potential by 2040, beyond the most important current biochar applications. These include metallurgy, which has the potential for rapid expansion due to its high-volume usage of biochar; the electro-chemical industry, where biochar can be applied in battery carbons and activated carbon; the construction sector, where biochar can serve as an additive to cement and other building materials; and waste and water treatment, where biochar can be utilized in waste management and water purification processes. Among these applications, the metallurgical industry stands out as a large-scale market that can significantly boost biochar production. Unlike the soil sector, which involves various stakeholders, metallurgy is a highly concentrated and volume-driven industry. If even one metallurgy company adopted biochar, it would represent a substantial increase in demand. In metallurgy, biochar has significant potential to enhance emission reductions by replacing fossil coal (Gul et al., 2021).

In addition to biochar, most producers considered carbon removal (commercialized as carbon credits) as the main product of pyrolysis while heat could be described as the most important co-product. The role of bio-oil and distillate was more controversial, though half of the respondents still considered them to have at least a slightly important role. The commercialization of biochar co-products, such as excess energy, wood vinegar, and tars (or bio-oil), into value-added products to be used in applications such as pesticides, biostimulants, and biofertilizers (Hagner, 2013; Hagner et al., 2020; Salami et al., 2021) could enhance the economic feasibility of biochar production and contribute to overall sustainability. Moreover, the commercialization of co-products can make biochar production economically viable when it might otherwise not be feasible.

5.3. Enabling and limiting factors for biochar market development

The main drivers of biochar production and applications are closely connected with benefits that contribute to environmental and climate goals as well as encouraging national and EU policies to support it. The findings of this study suggest that the environmental and climate aspects connected to biochar are considered to be even more important than the financial factors. This could indicate that businesses are willing to compromise direct profitability aspects to gain indirect benefits for their main business and other environmental and climate-related co-benefits.

Moreover, this study identified various market, policy/regulatory, social and technology specific factors that influence the diffusion of biochar production processes and applications that were also identified as important factors impacting eco-innovation diffusion by Kemp et al. (2019). For instance, scientific understanding and official recognition of biochar as a carbon removal solution has significantly increased, and carbon methodologies have already been deployed which enables pricing and the commercialization of biochar-based carbon removal, thereby supporting the economic feasibility of biochar production. There are also various indications that the biochar market is further expanding and moving towards widespread adoption. For instance, biochar is being actively discussed as part of various climate and environmental related policy initiatives. The production, application, and co-benefits of biochar are also gaining an increasing amount of official recognition and its legal status, e.g., as a soil amendment, is improving (European Comission, 2023). It is also part of the European Carbon Removal Certification Framework (EUCOM, 2022).

In addition, standardization of biochar is rapidly evolving on different levels. For instance, the International Organization for Standardization (ISO) has an active task group working on biocarbon and biochar standard development (Douek et al., 2023) and the German Institute for Standardization (DIN, 2021) has a committee working on pyrogenic carbonaceous materials. In addition, voluntary biochar standards such as the European Biochar Certificate (EBC, 2012) and the World Biochar Certificate (WBC, 2023) have already been established. The important role of voluntary standards in enabling (or hindering) the development of eco-innovations has also been recognized by Kemp et al. (2019), who suggest that voluntary standards can enable market expansion and improve the scalability of eco-innovations while an absence of standards can contribute to fragmented market development as well as increased consumer and production costs. It could be said that even though biochar is in its early market stages, it has already overcome various market barriers.

On the other hand, when it comes to establishing biochar production facilities, the most limiting factors identified by this study are the uncertainties regarding the profitability of biochar production and technological obstacles. Unlike the biochar market study of Californian biochar producers by Thengane et al. (2021), which identified a lack of capital investment as the most significant obstacle, this was not considered an important obstacle in the Nordics. Regarding biochar applications, this study identified the current market price of biochar as well as the lack of practical experience, lack of public awareness and lack of governmental subsidies as the most important limiting factors. In the study by Campion et al. (2023), the profitability and desirability of biochar production and applications were considered to be highly uncertain and case-specific, and dependent on factors such as feedstock, scale, location, production conditions, the price of biochar and internalization of externalities.

The findings of this study indicate that the biochar market would benefit from business models that are based on joint ventures and cooperation, under which the responsibilities, risks and benefits related to biochar production and its co-products are distributed. For instance, biochar production could be approached as a multi-output production process, as suggested by Wenger et al. (2022), and an allocation approach similar to that employed in biorefineries could be used in order to improve understanding of the economic and environmental performance of the biochar production process as a whole. In addition, approaching biochar production as multi-output production would encourage the development of local industrial symbioses and improve the overall sustainability of biochar (and its co-products) production.

The biochar market could also be further developed through more ambitious climate policies and the inclusion of biochar (for emissions reduction and carbon removal) as part of legally binding carbon removal targets and emissions schemes that would set clear pricing for carbon removal. Another area worthy of exploration is recognizing biochar as a means for achieving national and international climate targets e.g., under the regulations on land, land use change and forestry (LULUCF), the EU Emissions Trading System (EU ETS), and the Paris Agreement (counting biochar in the GHG inventories). This was also considered important in previous research, for instance the study by Fridahl et al. (2023) highlighted the importance of novel carbon dioxide removal techniques such as biochar being integrated into the European Union's climate policies such as EU ETS and LULUCF.

Moreover, half of the respondents at least somewhat agree that there are still research gaps that limit the widespread application of biochar. Before discussing research gaps, it is important to highlight that there is already an extensive amount of research results available on biochar and that ensuring that these results are utilized in practice is crucial to enable further market development. The research gaps and future directions for enabling biochar commercialization span the natural sciences, engineering/technical disciplines, and social sciences. In the natural sciences, further research is needed into biochar's role in agriculture, soil fertility, wastewater management, soil restoration, and interactions with soil microbiota. This research should consider local conditions such as diverse soil types, specific climatic conditions, and urban landscapes. For example, in urban green buildings, the established practices can vary significantly between countries.

Engineering and technical research should focus on conducting Life Cycle Assessments (LCAs), upscaling biochar production, advancing production technologies, and exploring new applications such as upgrading biochar into activated carbon. Currently, the majority of biochar research is conducted using batch-type laboratory reactors; continuous reactor types are more relevant for the industry. Conducting research using continuous-type reactors and comparing them in order to gain an understanding of the scalability, benefits, and challenges of each reactor type could support the industry in choosing the right reactor type for each business case and feedstock. Moreover, safety aspects related to biochar production, processing, transportation and usage, such as dusting, dust explosion, self-heating, and spontaneous ignition risks connected with biochar would be crucial in supporting safe widespread usage and production of biochar. In the social sciences, economic modeling, cost-benefit analysis, understanding market dynamics, and studying the societal implications of biochar-based businesses are key areas of focus. This includes examining biochar's contribution to circular economies, its social acceptance, effective communication strategies, and the sustainability of biochar production at scale, including biomass availability. Establishing or improving standards for biochar quality and applications is also crucial.

This study has limitations that have to be acknowledged. It primarily focuses on actors that are engaged with slow or intermediate pyrolysis technologies in the biochar field, and does not include actors working with fast pyrolysis aimed at bio-oil production. The study's quantitative approach and the diverse stages of biochar applications and market maturity also imposed constraints. Notably, respondents with experience in soil amendment and carbon removal through biochar were overrepresented compared to those from other backgrounds. Therefore, a potential area for future research could involve examining each biochar market segment individually and then integrating these findings into a comprehensive overview. However, such an approach would be more feasible if the biochar market were more mature and there were enough participants in each market segment.

5.4. Summary

This study on the Nordic biochar market revealed that while biochar production is at an early stage, it holds substantial growth potential driven by its environmental and climate benefits. The market is currently characterized by small-scale operations and a wide range of applications, notably carbon removal, water management, soil remediation, landscaping, and composting. However, significant challenges hinder market expansion, including inadequate legal and policy frameworks, variability in biochar pricing and quality, technological inefficiencies, and investment insecurities.

The Nordic biochar market demonstrates considerable potential for growth, with many stakeholders expressing intentions to expand operations. Biochar has diverse applications, with significant current and future market segments identified in carbon removal, water filtration, soil remediation, landscaping, and composting. The potential for rapid growth is particularly high in volume-driven industries like metallurgy.

Despite this potential, the primary barriers to market development include legal and policy-related obstacles, technological uncertainties, and market-related challenges. Specifically, the lack of supportive regulatory frameworks and public awareness, coupled with uncertainties about profitability, pose significant hurdles. The economic viability of biochar production can be enhanced by utilizing co-products such as energy-dense gases and bio-oil, which present additional market opportunities and can improve the overall sustainability of biochar operations.

Enhanced collaboration among stakeholders, including biochar networks and associations, is crucial for market development. Focused, practice-driven research on biochar applications and comprehensive evaluations of their environmental, economic, and social impacts are essential to address knowledge gaps and drive industry growth. To facilitate market development, more ambitious climate policies and the inclusion of biochar in legally binding carbon removal targets are necessary. Establishing standards for biochar quality and integrating biochar into broader environmental and climate policies will support its adoption and scalability.

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Esko Salo: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kathrin Weber:** Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Marleena Hagner:** Writing – review & editing, Visualization, Validation, Software, Data curation. **Annukka Näyhä:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT-4 in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

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