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RESEARCH ARTICLE

Emerging Business Models of Nordic Biochar Producers: A Sustainable Business Model Typology

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Abstract

Biochar production is gaining momentum not only as a climate change mitigation and carbon-removal solution but also as an emerging industrial sector with growing commercial potential. Although biochar production in the Nordic countries is expanding, research on biochar business models and their sustainability characteristics remains limited. This study examines emerging biochar business models in the Nordic region and develops a typology of sustainable business models based on a value analysis framework. The study employs an exploratory, qualitative, multiple-case study approach, using semi-structured interviews with 10 biochar producers in Finland, Sweden, and Denmark, conducted between December 2024 and February 2025. The analysis identifies six sustainable biochar business model types: biochar products, waste-to-resource, partnership, carbon removal, service-based, and technology commercialization models. The findings show that producers simultaneously combine multiple sustainable business model configurations. The future development of biochar business models is influenced by policy frameworks, carbon pricing, feedstock availability, and technological maturity.

Keywords Sustainable Business Models · Sustainable Value · Biochar · Biocarbon · Multiple Case Study · Business Model Typologies · Carbon Removal · Emission Reductions

1. Introduction

While biochar production through pyrolysis is often regarded as a relatively recent innovation emerging from academic research since the 2000s (Qin et al., 2022), its roots in the Nordic countries go much further back. Historically, what is now called pyrolysis was known as dry distillation or wood carbonization. As described by Talvitie (1924), the dry distillation process involved heating wood in a sealed environment to temperatures of around 400°C or higher. In contemporary terminology, pyrolysis refers to the thermal conversion of biomass in an oxygen-limited atmosphere at temperatures of approximately 350°C or higher, producing a carbon-rich, porous material known as biochar (Lehmann & Joseph, 2015). Unlike today, biochar (formerly referred to as charcoal when produced from wood) was primarily regarded as a low-value byproduct used mainly for combustion and metallurgical purposes. In traditional charcoal production, the excess heat generated during the process was either used to sustain the carbonization or released into the atmosphere (Valmari & Wainio, 1913). The economic viability of the wood carbonization industry increasingly depended on recovering valuable pyrolysis liquids, particularly from resin-rich pine feedstocks and pine stumps (Valmari & Wainio,

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1913; Talvitie, 1924). According to Talvitie (1924), the profitability of wood carbonization was strongly linked to tree species: birch was used for producing disinfectant and preservative liquids, pine for high-quality tar, while spruce was considered unsuitable due to its low-value outputs. Still in the 1920s, the industry remained notable; for example, Finland had around 50 operating carbonization plants processing approximately 120,000 cubic meters of wood annually. However, the industry gradually declined due to the economic crisis, cheap tar imports, declining tar demand, and the emergence of cheaper synthetic and fossil-based alternatives.

Recent decades, however, have witnessed a revival of carbonization through modern pyrolysis technologies, with biochar emerging as the primary product. This revival has been driven by biochar's potential to address sustainability challenges, including carbon removal, soil fertility enhancement, waste valorization, and contributions to climate change mitigation and adaptation (Lehmann & Joseph, 2015; Woolf et al., 2010). Current biochar business models emphasize the use of locally available biomass (Mohammed et al., 2024; Nidheesh et al., 2024; Thengane et al., 2021), often integrating the co-products, for example, the heat for district heating or electricity generation, and pyrolysis liquids and syngases as secondary outputs (Salo et al., 2024; Schmidt et al., 2019). Thus, economic viability often relies on combining multiple value streams, including carbon removal, material applications, and energy co-products. Moreover, biochar in carbon-storing applications - ranging from soil amendment to cement and asphalt additives - can be certified under voluntary carbon standards, enabling the generation of tradable carbon credits (Raffeld et al., 2025). Biochar is also being explored as a renewable alternative to fossil-based carbon in industrial processes such as metallurgy (Sarker et al., 2024; Suopajärvi et al., 2017), linking historical practices to new sustainability imperatives.

Existing literature has extensively examined the technical properties and applications of biochar, focusing on factors such as feedstock, reactor design, and production parameters (Al-Rumaihi et al., 2022; Weber & Quicker, 2018). In contrast, comparatively limited attention has been paid to how these technical characteristics translate into viable commercialization pathways, market offerings, and business models in practice (Orlowski et al., 2026). Nevertheless, existing business model-oriented studies suggest that factors such as technology type, production scale, feedstock availability, and market context shape the development of biochar business models (Campion et al., 2023; Salo et al., 2024). However, biochar business models remain largely understudied from the perspective of value-creation mechanisms and commercialization pathways in the biochar sector. As a result, biochar production is often considered a relatively homogeneous activity, despite substantial variation in how companies create, deliver, and capture value, leading to a limited understanding of how the different biochar business models contribute to market development and sustainability outcomes.

Biochar business models frequently incorporate sustainable business model (SBM) characteristics, such as climate mitigation through carbon removal, resource efficiency through waste valorization, and diversified revenue streams from main and co-products. However, studies explicitly examining biochar businesses from an SBM perspective remain limited (Mohammed et al., 2024; Salo et al., 2024; Thengane et al., 2021). SBM frameworks provide a relevant lens for analyzing how environmental, economic, and social value are simultaneously created and captured. SBMs integrate environmental and social value alongside economic value to serve a wider range of stakeholders (Bocken et al., 2014; Schaltegger et al., 2016; Lüdeke-Freund et al., 2024), and differ from conventional models by aligning long-term business success with positive societal and environmental outcomes (Boons & Lüdeke-Freund, 2013; Evans et al., 2017). Applying these perspectives enables a more systematic examination of how different value-creation logics are structured and combined across biochar business models. Overall, more empirical studies analyzing practices and experiences related to the implementation of sustainable business models (SBMs) are needed.

This research gap highlights the need for an empirically grounded business model typology that captures how different value-creation logics are configured and combined, and how these models integrate with broader sustainability frameworks, including voluntary carbon markets and circular economy practices.

Based on interviews with 10 biochar producers from Finland, Sweden, and Denmark, this study examines emerging Nordic biochar business models, the barriers and opportunities influencing their development, and their potential development pathways toward 2040. The semi-structured interviews were developed based on the Sustainable Business Model Canvas (Joyce & Paquin, 2016), with particular emphasis on how companies create, deliver, and capture economic, environmental, and social value. The analysis further draws on the sustainable value analysis framework of Méndez-León et al. (2022) to examine how these value dimensions are configured and combined within emerging Nordic biochar business models.

This study addresses the following main research question:

- What types of business models are currently employed by Nordic biochar companies?

To support this main question, two subsidiary research questions are examined:

- What are the key sustainability characteristics of biochar-based business models?
- What factors influence the development of these business models toward 2040?

This study contributes to the literature by providing one of the first empirically grounded typologies of biochar business models, thereby advancing understanding of how heterogeneous sustainability-oriented value-creation logics are implemented in practice and how these configurations are influenced by sustainability objectives, market dynamics, and policy frameworks within an emerging biochar-based industry.

This article is structured as follows. Section 2 reviews the literature on SBMs and outlines the theoretical framework used in the study. Section 3 describes the research design, case selection, data collection, and analytical approach. Section 4 presents and discusses the empirical findings, including the identified sustainable business model characteristics, the typology, and the drivers, barriers, and future development directions of biochar business models. Finally, Section 5 concludes the study by summarizing the main findings, outlining the study's contributions and limitations, and discussing implications for research and practice.

2. Sustainable business models

2.1. Sustainable business model principles and archetypes

In recent years, the growing demand for natural resources, driven by economic and industrial activities, has increased pressure on companies to integrate sustainability into their business strategies. This shift calls for redesigning traditional business models (Bocken et al., 2014) and developing more dynamic models that incorporate environmental and social considerations alongside economic value creation (Joyce & Paquin, 2016), reflecting a transition toward SBMs.

SBMs are grounded in the triple bottom line approach, creating sustainable value for society, the environment, and the economy (Kristensen & Remmen, 2019; Laukkanen & Tura, 2020; Joyce & Paquin, 2016; Lozano, 2018). According to Geissdoerfer et al. (2018), SBMs are business models that proactively engage in multi-stakeholder management and aim to create both monetary and non-monetary value for a wide range of stakeholders, emphasizing long-term benefits for society and the environment. In addition to the SBM concept, an alternative term—*business model for sustainability* (BMfS)—has also been introduced in the literature. Schaltegger et al. (2016, p. 6) define BMfS as follows:

> *"A business model for sustainability helps describing, analyzing, managing, and communicating (i) a company's sustainable value proposition to its customers, and all other stakeholders, (ii) how it creates and delivers this value, (iii) and how it captures economic value while maintaining or regenerating natural, social, and economic capital beyond its organizational boundaries."*

The BMfS concept has later been refined by Lüdeke-Freund et al. (2024, p. 16), who describe it as:

> *"A business model for sustainability refers to how an organization proposes, delivers, captures, maintains, unlocks, and shares value with and for its stakeholders."*

Although the terms originate from different areas of the literature, both describe how sustainability is integrated into the core logic of business models. In recent years, several authors have developed SBM archetypes and typologies to classify how companies integrate environmental, social, and economic sustainability into their business activities (Albino & Fraccascia, 2015; Bocken et al., 2014; Lüdeke-Freund et al., 2018; Lüdeke-Freund et al., 2019). These classifications provide useful frameworks for analyzing, comparing, and developing SBMs in both theory and practice (Lambert, 2015; Lewandowski, 2016; Ritala et al., 2018).

Existing SBM archetypes include approaches such as creating value from waste, low-carbon solutions, circular economy approaches, zero-emission initiatives, collaborative approaches, base-of-the-pyramid solutions, and licensing models (Bocken et al., 2014). As shown in Figure 1, these archetypes can be broadly grouped into environment-focused, socially oriented, and market-oriented categories (Boons & Lüdeke-Freund, 2013; Ritala et al., 2018). Together, these frameworks illustrate different pathways through which companies align business activities with sustainability objectives and therefore provide a useful basis for analyzing hybrid and multi-value business configurations, such as those observed in the biochar sector.

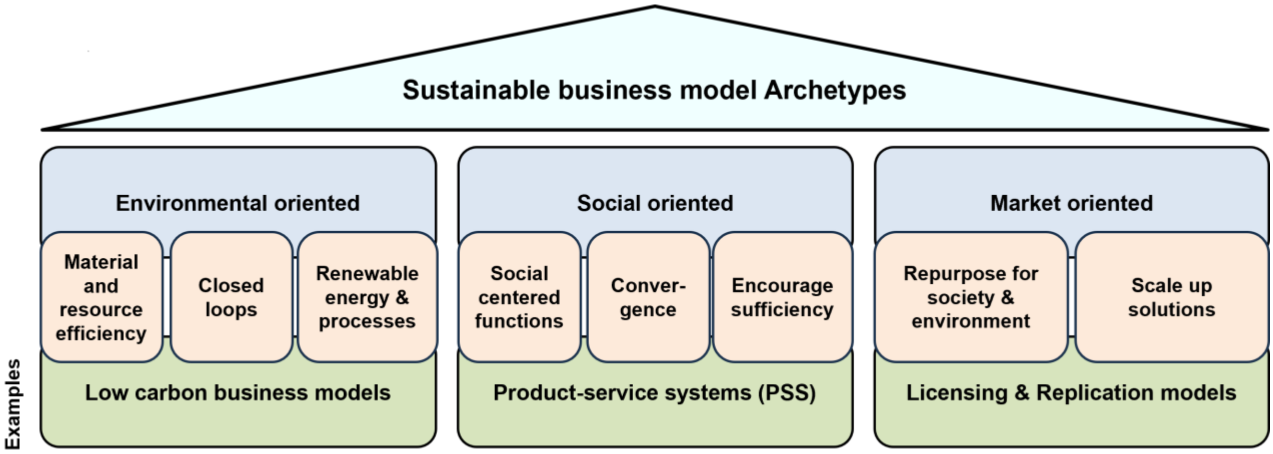

Figure 1. Sustainable business model archetypes, business models examples (based on Bocken et al., 2014 and Ritala et al., 2018)

Examples of business models emerging from these archetypes include circular business models (CBMs), which emphasize slowing, closing, and narrowing resource loops (Bocken et al., 2016; Geissdoerfer et al., 2020); low-carbon business models focused on emissions reduction and carbon removal (Sairanen & Aarikka-Stenroos, 2024); product-service systems (PSS) and servitized models that shift value creation from product sales toward long-term services (Tukker, 2015); and bioeconomy business models integrating cascading biomass use, multi-output valorization, and industrial symbiosis within biorefinery-type configurations (Bröring & Vanacker, 2022; D'Amato et al., 2020).

CBMs integrate sustainability through resource efficiency, waste minimization, and material recirculation (Ellen MacArthur Foundation, 2013; Kirchherr et al., 2017). Typical examples include the reuse of industrial residues, the upcycling of biomass side-streams into value-added products, and process designs that maximize material durability while reducing dependence on virgin resources (Geissdoerfer et al., 2017). These models contribute to sustainability by reducing environmental impacts, improving resource productivity, and decreasing waste generation across production systems (Islam et al., 2025; Zucchella & Previtali, 2019).

Low-carbon business models, in turn, focus on reducing greenhouse gas (GHG) emissions or enabling negative emissions. Their sustainability benefits arise from substituting fossil-based inputs, integrating renewable energy sources, commercializing carbon removal solutions, and participating in climate policy mechanisms such as carbon credit markets (Sairanen & Aarikka-Stenroos, 2024; Wainstein & Bumpus, 2016).

Bioeconomy and biorefinery-oriented business models emphasize integrating multiple biomass-based value streams, valorizing residues, and optimizing material and energy flows in cascading systems. Their sustainability potential emerges from replacing fossil-based resources, improving resource circularity, and strengthening industrial symbiosis through co-location and cross-sectoral collaboration (D'Amato et al., 2020; Gatto & Re, 2021; Mesa et al., 2024).

Together, these perspectives provide a useful basis for understanding how sustainable value is created, delivered, and captured within emerging biochar business models. The next section examines these processes through the lens of the sustainable value analysis framework.

2.2. Sustainable value analysis framework

Integrating value dimensions (value proposition, creation, delivery, and capture) with sustainability dimensions (economic, social, and environmental) demonstrates how companies create and deliver sustainable value (SV), which is particularly important in emerging industries driven by sustainability-oriented innovation (Bocken et al., 2014; Markard et al., 2012).

SV is not only involved in generating financial wealth but also in translating social and environmental contributions into meaningful forms of value, ensuring that business activities are resilient, responsible, and aligned with long-term sustainability goals (Cosenz et al., 2020; Laukkanen & Tura, 2020). Méndez-León et al. (2022) developed a framework for analyzing SV across various business models to improve sustainability. The framework proposes a combination of *activities* that can be merged into *elements,* which in turn can be grouped into *components* as the highest level of SV analysis. In this study, the framework is used to structure the analysis of sustainable value creation in biochar business models. Figure 2 shows the framework used in this study for the SV analysis of the biochar business model in the context of biochar production systems.

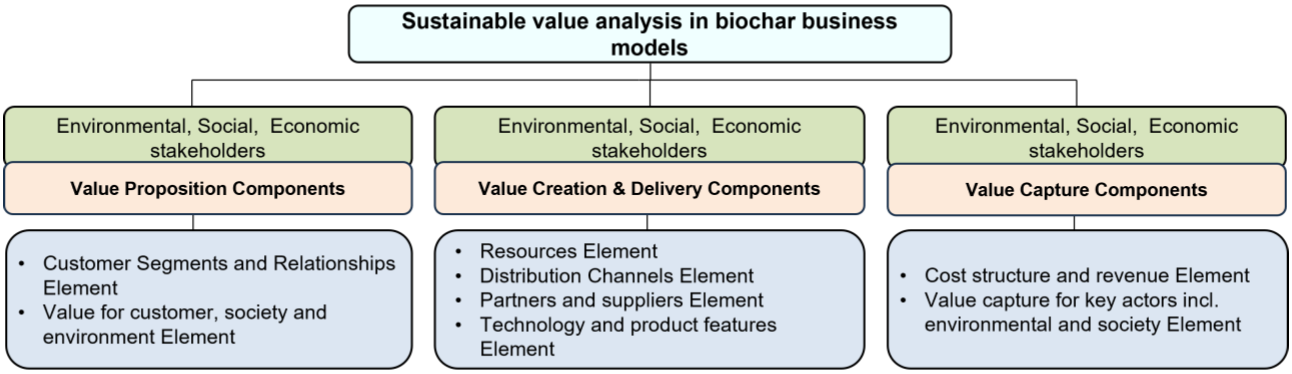

Figure 2. Structuring model of sustainable value analysis (adapted from Méndez-León et al. (2022))

2.2.1. *Value proposition*

As Lüdeke-Freund et al. (2024) show, what distinguishes SBMs from conventional BMs is not individual activities alone, but the extent to which activities, design themes, and value functions occur simultaneously and interdependently. In this extended view, SBMs complement conventional business model logics by adding sustainability-specific design themes and value functions—maintaining, unlocking, and sharing value—to the traditional mechanisms of proposing, delivering, and capturing value (Lüdeke-Freund et al., 2024; Ritala et al., 2018; Svensson et al., 2016). Together, these interconnected elements shape how organizations contribute to sustainable value creation and influence how they formulate their sustainable value propositions. According to Laukkanen and Tura (2022), a sustainable value proposition is the core of all SBM. An effective sustainable value proposition represents a company's commitment to delivering both short-term and long-term value to multiple stakeholders by integrating economic, environmental, and social benefits (Patala et al., 2016; Bocken, 2014; Laukkanen & Tura, 2020).

Examples of sustainable value propositions include reduced emissions, enhanced resource efficiency, and improved ecological well-being (Bocken et al., 2014; Joyce & Paquin, 2016). Sustainable value propositions thus shift attention from traditional product-centric approaches toward solution-oriented offerings that align with stakeholder expectations for responsibility and long-term sustainability (Boons & Lüdeke-Freund, 2013; Lüdeke-Freund et al., 2018; Baldassarre et al., 2017). In the context of biochar, the value proposition can relate to how production meets market demand while contributing to environmental and socio-economic outcomes, including employment and value creation across the biochar value chain (Mohammed et al., 2024).

2.2.2. *Value creation and delivery*

Another core dimension of SBMs concerns value creation and delivery mechanisms, which determine how sustainability outcomes are achieved. These mechanisms increasingly rely on circular processes, the use of renewable or secondary materials, and collaboration within and across supply chains, municipalities, and research institutions (Bowman & Ambrosini, 2000; Freudenreich et al., 2020). Collaboration and networks are particularly central to sustainability because companies often depend on shared resources, complementary capabilities, and cross-sectoral knowledge exchange (Evans et al., 2017; Ritala et al., 2021). In biochar production, value creation often involves cascading biomass use, multi-output valorization, and integration within industrial symbiosis or biorefinery-type configurations (Bröring & Vanacker, 2022; D'Amato et al., 2020).

2.2.3. Value capture Furthermore, SBMs can link value-capture mechanisms, such as financial performance, to environmental and social outcomes, including waste valorization, cost savings, service-based circular offerings, and climate-related outcomes, such as emission reductions or carbon removals (Bocken et al., 2014; Sairanen & Aarikka-Stenroos, 2024). Moreover, external factors, including regulatory instruments such as environmental regulations and emissions trading schemes, as well as voluntary initiatives such as corporate climate targets, can support the development of new SBMs (Boons & Lüdeke-Freund, 2013; Hakovirta et al., 2023). These approaches illustrate that value capture can incorporate the broader societal and ecological benefits created by the company. By internalizing part of this sustainable value, companies enhance the scalability and viability of SBMs and strengthen incentives for continued sustainability-oriented innovation (Schaltegger et al., 2016). In biochar business models, value capture is typically achieved through multiple revenue streams that combine physical products and environmental services, such as carbon removal credits (Salo et al., 2024).

2.3. Biochar business model research

Existing studies on biochar commercialization have primarily focused on techno-economic feasibility, market and policy conditions, and environmental or system-level impacts (Shackley et al., 2011; Haeldermans et al., 2020). While these studies provide valuable insights into the feasibility and impacts of biochar deployment, their analytical focus remains fragmented. Although some studies acknowledge elements such as revenue streams, stakeholder involvement, or emerging business configurations, relatively limited attention has been paid to how companies systematically combine mechanisms for sustainable value creation, delivery, and capture within biochar business models.

More recently, studies have begun to examine biochar- and pyrolysis-related business model configurations and archetypes (e.g., Orlowski et al., 2026). However, existing research remains limited in its examination of how biochar producers configure and combine multiple sustainability-oriented value-creation logics in practice, particularly with respect to circularity, carbon removal, industrial partnerships, and multi-output valorization. In addition, empirical research grounded in firm-level experiences within the Nordic biochar sector remains scarce.

Table 1 summarizes key studies on biochar commercialization and business-related aspects, highlighting their research focus, methodological approaches, key findings, and limitations for business model analysis. The table includes representative studies on techno-economic performance, market development, system-level assessments, and emerging business-model perspectives.

Table 1. Overview of key studies on biochar commercialization and their relevance to business model research

Study	Research focus	Methodology	Key findings	Identified limitations and relevance to this study
Shackley et al. (2011)	Feasibility of biochar deployment	Techno-economic assessment	Identifies biochar, energy, and co-products as key revenue streams	Focuses on techno-economic feasibility
Crombie & Mašek (2015)	Biochar systems and value trade-offs	System analysis	Highlights trade-offs between energy production and carbon sequestration	Focuses on system-level trade-offs
Haeldermans et al. (2020)	Techno-economic performance of biochar production	Comparative techno-economic analysis	Demonstrates variability in profitability depending on feedstock, technology, and biochar price; identifies price as a key driver of economic viability	Focuses on techno-economic performance and price sensitivity
Thengane et al. (2021)	Regional biochar market prospects, applications, and barriers (California)	Market analysis + surveys/interviews + market sizing	Identifies key application markets, major barriers (capital, demand), and the importance of carbon credits and ecosystem development	Region-specific focus on market conditions

Table 1 (cont.). Overview of key studies on biochar commercialization and their relevance to business model research

Study	Research focus	Methodology	Key findings	Identified limitations and relevance to this study
Torres-Morales et al. (2023)	Biochar as a net-negative emissions strategy (Colombia)	Mixed-method (literature + interviews + techno-economic + modelling)	Identifies mitigation potential, key cost drivers, and the importance of carbon credits and local production	Country-specific focus on system-level sustainability and techno-economics
Campion et al. (2023)	Costs, benefits, and economic viability of biochar	Systematic review	Synthesizes evidence on profitability, externalities, and key economic drivers	Focuses on system-level economic assessment
Lefebvre et al. (2023)	Environmental factors influencing biochar climate mitigation potential	Spatial + soil carbon modeling	Demonstrates significant mitigation potential and variability depending on environmental conditions	Focuses on environmental performance
Salo et al. (2024)	Emerging biochar business in Nordic countries	Qualitative study	Identifies multiple revenue streams and early business configurations	Provides early empirical insights into Nordic biochar business models
Mohammed et al. (2024)	Co-designing sustainable biochar business models in Sub-Saharan Africa	Co-creation workshops + TLBMC + Value Proposition Canvas	Develops context-specific business models integrating economic, environmental, and social value	Focuses on co-designed and context-specific business models
Senadheera et al. (2025)	Biochar commercialization, policy frameworks, and ESG relevance	Literature review	Identifies key commercialization drivers, barriers, and links to sustainability goals	Focuses on commercialization drivers, policy, and ESG perspectives
Kivijakola et al. (2025)	Biochar business ecosystem and value chain development	Qualitative case study (interviews + ecosystem analysis)	Highlights the importance of ecosystem actors, interdependencies, and multiple revenue streams	Focuses on ecosystem-level interdependencies
Morim et al. (2025)	Comparative business scenarios for biochar production	Techno-economic + scenario modeling + sensitivity analysis	Shows that integrated multi-revenue models are economically viable, while standalone biochar is not	Based on modeled scenarios rather than real firms
Haq et al. (2020)	Techno-economic assessment of CHP-based biochar co-production and district heating integration	LCC and NPV analysis of a proposed CHP-biochar system	Illustrates regional value creation through integration of renewable energy production, biomass utilization, and biochar co-products	A techno-economic energy systems study based on a conceptual system design.
Uotila et al. (2025)	Economic and environmental performance of biochar in mine closure applications	Case-based techno-economic + LCA analysis	Shows biochar reduces emissions but increases costs; viability depends on carbon pricing and technology development	Focuses on application-level cost and benefit trade-offs
Orlowski et al. (2026)	Pyrolysis business model archetypes in the DACH region	Taxonomy development + workshops/backcasting	Identifies four pyrolysis business archetypes linked to energy-system transitions and carbon neutrality pathways	Focuses primarily on pyrolysis systems and energy-transition archetypes

Overall, existing studies provide important insights into techno-economic feasibility, commercialization conditions, ecosystem development, and emerging business model archetypes. However, relatively limited attention has been paid to how biochar producers combine multiple sustainability-oriented value-creation logics within firm-level business model configurations. This limitation is particularly relevant in the biochar sector, where business models often integrate circularity, carbon removal, industrial partnerships, and multi-output valorization simultaneously. Responding to this gap, this study develops an empirically grounded typology of Nordic biochar business models. It examines how sustainable value is configured across value proposition, value creation and delivery, and value capture within an emerging sustainability-oriented industry.

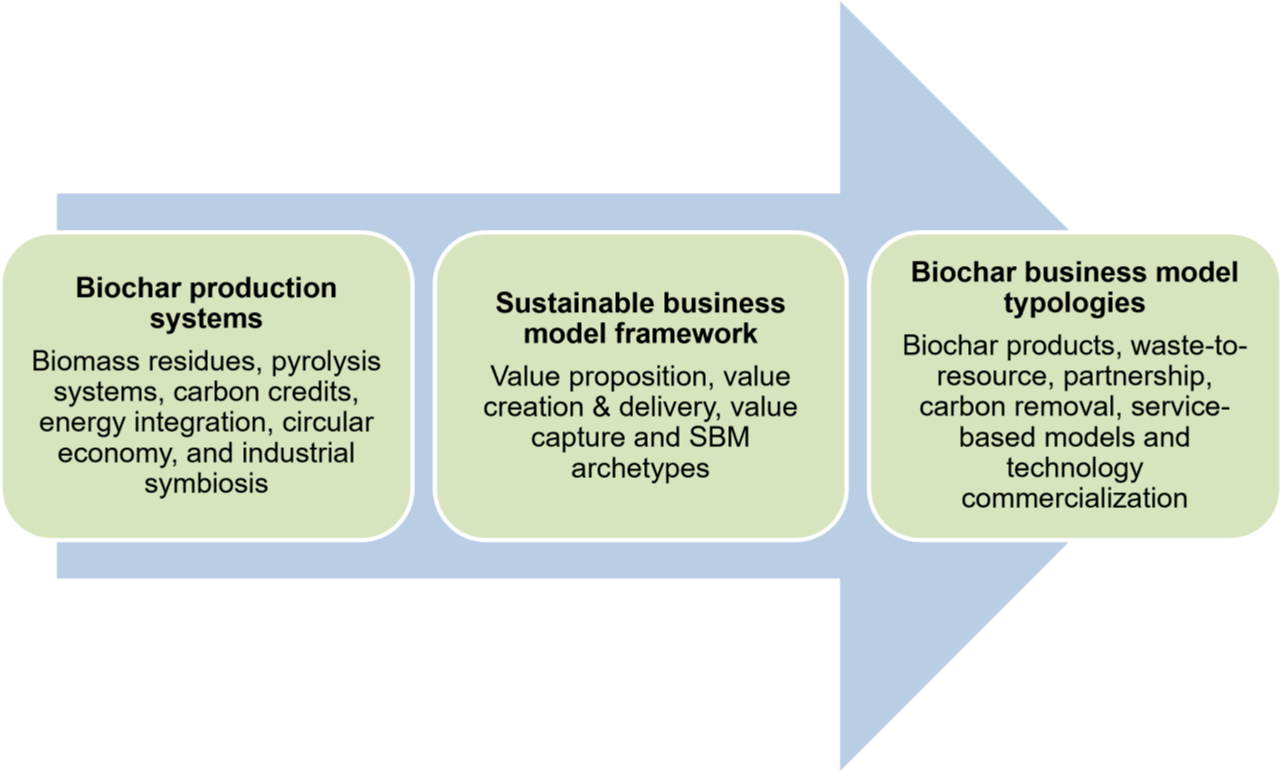

Figure 3. Analytical framework for developing biochar business model typologies

Figure 3 illustrates the analytical framework of this study. The framework links practical biochar production systems with SBM theory to develop empirically grounded biochar business model typologies. On the left, the figure presents the practical and industrial context of biochar production, including biomass residues, pyrolysis technologies, value streams, circular economy practices, and industrial symbiosis. In the center, these empirical characteristics are interpreted through the lens of the sustainable business model framework, particularly the dimensions of value proposition, value creation and delivery, value capture, sustainable value, and SBM archetypes. On the right, the figure presents the resulting typologies of Nordic biochar business models identified in this study. The framework, therefore, illustrates how the study connects empirical observations with the sustainability-oriented business model literature to analyze and classify emerging biochar business configurations.

3. Materials and methods

3.1. Research design and case selection

This study applies a qualitative multiple-case study design to examine emerging business models among Nordic biochar producers through a sustainability lens. A qualitative approach was considered appropriate for exploring how companies operating in an emerging and heterogeneous sector configure their business models, sustainability characteristics, and future development pathways in practice (Lim, 2025; Maxwell, 2021). Given the still-emerging nature of the sustainable biochar sector, a multiple-case study design was considered particularly suitable for generating empirically grounded insights into real-world business model configurations and sustainability practices. Furthermore, multiple-case study research enables both within-case and cross-case analysis, facilitating the identification of similarities, differences, and recurring patterns across heterogeneous cases (Yin, 2018).

Across the Nordic region, 28 companies involved in biochar production and development were initially identified through systematic online searches using keywords such as biochar AND producer, biokul AND producent, biohiili AND valmistaja, biokull, biohiili, and biokol. To ensure broad sectoral coverage, publicly available member lists from biochar-related associations and networks -including Norsk Biokullnettverk, Bioenergia ry, Innovationsklustret Biokol Sverige, and Biochar Europe - were reviewed. In addition, members of the Nordic Biochar Network board were consulted to verify that all relevant companies had been identified.

To be included in the study, companies had to:

1. Be actively engaged in biochar production and development, with demonstrated practical experience in biochar production;
2. Possess operational and technical expertise related to feedstocks, production processes, and applications; and
3. Conduct business activities in which biochar production constituted a central or strategically important component.

The study included companies currently operating biochar production facilities or companies that had operated such facilities within the previous five years, technology developers operating pilot or demonstration plants, and firms involved in procuring and commissioning biochar production systems. Companies at early planning stages without operational experience, as well as small-scale hobby or farm-level producers, were excluded.

Based on these criteria, 14 companies were invited to participate, resulting in 10 semi-structured interviews with representatives from companies operating in Finland, Sweden, and Denmark (Table 2). In Norway, three relevant companies were identified; however, despite several contact attempts, participation could not be secured. Nevertheless, the study covered most of the significant companies engaged in biochar production and development within the Nordic region. To maintain anonymity, specific organizational roles are not reported; however, all interviewees held senior managerial or strategically oriented positions related to business development, operations, product development, or executive management.

Table 2. List of interview participants

Interviewee	Country
R1	Denmark
R2	Denmark
R3	Finland
R4	Finland
R5	Finland
R6	Finland
R7	Sweden
R8	Sweden
R9	Sweden
R10	Sweden

3.2. Data collection and analysis

A semi-structured interview guide was developed based on prior literature on SBMs, particularly the SBM Canvas (Joyce & Paquin, 2016), and related value dimensions, including value proposition, value creation and delivery, and value capture. Initial analytical categories included value proposition, value creation and delivery, value capture, customer segments, key partners, and key resources. To capture broader contextual and future-oriented dynamics, these categories were supplemented with themes related to sustainability aspects, drivers and barriers, policy and market context, and future perspectives.

The interview guide was developed collaboratively by the co-authors and refined to ensure that the questions were clear and practically relevant for industry respondents. The aim was to balance consistency across interviews with sufficient flexibility for respondents to elaborate on company-specific practices, strategic priorities, and future expectations. The full interview guide is presented in the Appendix. Semi-structured interviews were selected because they provide a flexible yet sufficiently consistent approach to data collection, enabling participants to elaborate on context-specific experiences, practices, and future expectations while maintaining comparability across interviews (Kvale & Brinkmann, 2009). The interviews were conducted online via Microsoft Teams between December 2024 and February 2025. Each interview lasted approximately 45-70 minutes and was conducted in English. All interviews were audio-recorded with participants' informed consent, transcribed verbatim, and pseudonymized prior to analysis.

To complement the analysis of current business models, the study also incorporated a prospective perspective examining how companies envision the development of their business models toward 2040. This part of the analysis focused particularly on drivers and barriers, policy and market conditions, and future development pathways. Including both present and future perspectives helps address the still-emerging understanding of how business models evolve and transform over time, which has been identified as an important gap in research on business model innovation and sustainable business model transformation (Brunner et al., 2025; Foss & Saebi, 2017).

The interview material was analyzed using theory-informed coding and systematic cross-case comparison, drawing particularly on the sustainable value analysis framework proposed by Méndez-León et al. (2022). First, each interview was analyzed individually to construct a case-level understanding of the company's business model and sustainability characteristics. The transcripts were coded using a structured analytical matrix based on the study's analytical categories, including value proposition, value creation and delivery, value capture, customer segments, key partners, key resources, sustainability aspects, drivers and barriers, policy and market context, and future perspectives.

Second, the coded data were systematically compared across cases to identify similarities and differences in business model configurations, particularly regarding revenue streams, feedstock strategies, partnerships, and sustainability characteristics. Rather than focusing on isolated variables, the analysis emphasized recurring combinations of business model elements.

Third, the typology of sustainable biochar business models was developed iteratively by grouping recurring patterns observed across cases into higher-level configurations. The typology was thus derived inductively through repeated comparison between the empirical material and emerging analytical groupings. Because individual companies often combine several business model logics simultaneously, the resulting typology should be understood as an analytical classification of dominant and recurring configurations rather than as mutually exclusive categories.

Several measures were taken to enhance the trustworthiness of the analysis. All interviews were conducted using the same semi-structured interview guide, recorded, and transcribed to ensure consistency and transparency. The pseudonymized transcripts were organized into a structured analytical matrix to support systematic cross-case comparison. In addition to the main author, one co-author cross-checked the transcripts and recordings to ensure consistency of interpretation. The use of multiple cases across three Nordic countries further strengthened the robustness of the findings. The study does not aim for statistical generalization but for analytical transferability by developing an empirically grounded typology of sustainable biochar business models.

4. Results and discussion

This chapter presents the findings from interviews with 10 Nordic biochar producers and examines how sustainable business models (SBMs) are emerging within the Nordic biochar sector. The analysis first explores the key characteristics of these business models, including value propositions, revenue streams, partnerships, location factors, and critical resources. It then develops a typology of six biochar-based SBMs identified across the cases. Finally, the chapter discusses how policy frameworks, market conditions, institutional uncertainty, and future development pathways influence the evolution of these business models.

4.1. Sustainable business model characteristics in Nordic biochar production

Nordic biochar producers create, deliver, and capture value through multiple and often overlapping value streams. Although biochar was consistently described as the core product, the interviews showed that economic viability rarely depends on biochar sales alone. Instead, producers combine biochar sales with carbon credits, excess heat or electricity, feedstock gate fees, consulting and R&D activities, technology sales, and emerging opportunities related to pyrolysis liquids and other side streams. These findings align with previous research suggesting that biochar production systems increasingly operate according to integrated biorefinery and multi-product valorization logics, where economic value is generated through combinations of biochar, energy, gases, liquids, and other co-products rather than through a single-product business model (Ravenni et al., 2024; Soni & Karmee, 2020). Earlier studies primarily emphasized biochar, energy, and pyrolysis liquids as key revenue streams (Crombie & Mašek, 2015; Shackley et al., 2011), whereas more recent research has highlighted the growing importance of carbon credits and feedstock-related revenues in improving economic viability (Haeldermans et al., 2020; Salo et al., 2024; Torres-Morales et al., 2023; Orlowski et al., 2026).

From a sustainability perspective, producers emphasized carbon removal and emission reductions, but also highlighted co-benefits, including improved soil fertility, stormwater management, enhanced material performance in construction, and fossil-carbon substitution in industrial applications. Some companies also produce or aim to produce biochar-derived carbon materials, such as activated carbon, hard carbon, or other upgraded materials for filtration, purification or energy storage applications. These findings support earlier observations that biochar systems create value through multiple environmental and industrial pathways rather than through carbon sequestration alone (Campion et al., 2023; Crombie & Mašek, 2015).

Carbon credits were highlighted as particularly important for improving the feasibility of durable biochar carbon removal applications, such as soil amendment, cement, and asphalt. Producers estimated that carbon credit income may cover approximately 20-50% of production costs. However, it was not viewed as a sufficient income stream on its own, but rather as one component of broader multi-revenue business models. Similarly, excess heat was widely regarded as an important value stream, particularly when production facilities are located near district heating networks or industrial heat users. Pyrolysis liquids were also identified as potential future revenue streams despite immature markets and regulatory barriers. These findings align with earlier techno-economic studies that emphasize the importance of integrating multiple value streams for profitability (Crombie & Mašek, 2015; Haeldermans et al., 2020; Morim et al., 2025).

Feedstock-related value creation was another important feature. Some producers receive, or aim to receive, gate fees or economic benefits from avoided disposal costs when processing waste or residue streams, such as wastewater sludge and other organic residues. In these cases, value is created not only through the sale of biochar or its co-products but also through waste treatment, emission avoidance, nutrient recycling, and pollution mitigation. This highlights the circular economy logic embedded in several Nordic biochar business models and aligns with previous research on waste valorization and industrial symbiosis in biochar systems (Geissdoerfer et al., 2017; Haq et al., 2020).

Table 3 below summarizes the main revenue streams identified among Nordic biochar producers, along with examples of applications, sustainable value propositions, and key business considerations.

Table 3. Summary of revenue streams and value propositions, based on interviews (n=10)

Revenue Stream	Application examples	Sustainable value proposition	Other considerations	Reported by (n=10)
Feedstock (gate fees)	Wastewater sludge and other organic sludges, certain agro/wood-based waste	Valorization of waste streams; emission avoidance by preventing methane and CO_2 from unmanaged biomass	Requires a reliable feedstock supply chain; depends on waste regulation	2
Biochar for carbon removal applications	Soil amendment, asphalt, cement	Carbon removal combined with co-benefits (soil fertility, improved material performance)	Requires quality certification, reliable end markets	8

Table 3 (cont.). Summary of revenue streams and value propositions, based on interviews (n=10)

Revenue Stream	Application examples	Sustainable value proposition	Other considerations	Reported by (n=10)
Carbon credits	Biochar Carbon Removal (BCR) can be certified into carbon credits and commercialized for offsetting purposes	Climate mitigation through permanent storage of biogenic carbon	Covers only part of production costs (~20-50%)	6
Biochar for temporary applications	Animal bedding, compost, and short-lived products	Short-/medium-term carbon storage with additional benefits (e.g., animal welfare, nutrient cycling)	Cascading use can extend carbon storage (e.g., bedding → soil amendment);	3
Biochar for fossil carbon substitution or upgrading	Metallurgy, water/air purification and treatment, energy storage	Fossil carbon substitution in industrial processes; emission reductions	Certain carbon materials require activation or other high-temperature post-treatment	2
Pyrolysis liquids (bio-oil, vinegar, tar, distillates)	Fertilizers, pesticides, growth stimulants, chemicals, energy	Substitution of fossil-based inputs; contribution to emission reductions	Not yet commercialized due to immature markets and regulatory barriers; potential to improve profitability	3
Excess energy (heat/electricity)	District heating, power generation, and on-site drying	Renewable energy substitution for fossil fuels; enhanced system efficiency	Requires a production location where energy can be utilized	9
Services, R&D	Consultancy, commissions, facility support, research collaborations, and pyrolysis piloting services	Indirect value creation through testing/piloting feedstocks and applications, enabling market access for others	Project-based; complements core revenues; builds networks and markets	4
Technology sales or licensing	Developing, selling, or licensing biochar production technology	Indirectly, by enabling others to produce biochar and utilize know-how	Requires high market maturity (stable demand for tech)	3

The interviews further showed that revenue generation is closely connected to feedstock availability, production location, pyrolysis technology, and industrial integration opportunities. Producers emphasized that location decisions are primarily driven by access to reliable and low-cost feedstock, opportunities for energy integration, and logistics. Proximity to biochar customers, a supportive regulatory and permitting environment, and opportunities for research collaboration were also considered relevant, although generally less decisive than feedstock and energy-related considerations. Similar patterns have been identified in previous studies examining industrial integration and regional biochar ecosystems (Kivijakola et al., 2025; Thengane et al., 2021).

Table 4 below summarizes the main factors influencing the location of biochar production facilities identified in the interviews.

Table 4. Factors influencing location choice for biochar production, based on interviews (n=10)

Factor	Description	Priority
Feedstock availability	Proximity to reliable, low-cost biomass residues (sludge, demolition wood, agro/forest by-products).	High
Energy integration	Access to district heating grids or industrial processes to utilize excess heat/electricity.	High
Logistics & transport	Minimizing transport costs, especially for feedstock sourcing	High
Biochar customer	Being close to biochar end-users (farmers, municipalities, industry)	Medium
Regulatory/permit environment	Local acceptance and permitting for waste feedstocks (e.g., sludge, demolition wood).	Medium
Visibility & demonstration value	Locations that enable showcasing technology (reference plants, pilots).	Low
Research & partnerships	Proximity to universities, research labs, or clusters to enable R&D and collaboration.	Low

The interviews further demonstrated that partnerships play an essential role in the value creation and delivery processes of Nordic biochar business models. Biochar producers operate within broader industrial and institutional ecosystems where collaboration is often necessary to secure feedstock supply, commercialize co-products, develop applications, and scale operations. Key partners (Table 5) included feedstock suppliers such as waste management facilities, wastewater treatment plants, biogas producers, and industries that generate forest or agricultural residues. Industrial partners, particularly district heating companies, steel manufacturers, and growing media producers, were important for the utilization of biochar, excess heat, and other co-products. Co-location with such partners was frequently described as a strategic way to secure feedstock, reduce logistics costs, commercialize excess energy, and improve the credibility of biochar production. These findings support earlier research emphasizing the importance of industrial symbiosis and ecosystem-level collaboration in biochar commercialization (Haq et al., 2020; Kivijakola et al., 2025).

Research organizations, universities, networks, and associations were also important partners. Research partners supported feedstock testing, product development, application development, and certification processes. Industry associations and networks contributed to advocacy, public awareness, legitimacy-building, practice harmonization, and policy influence. Several companies also emphasized that collaboration with large industrial actors improves credibility and market acceptance. Technology partners supported plant construction, scaling, and internationalization, while financial partners provided funding and legitimacy for further development.

The findings further demonstrate that Nordic biochar business models depend heavily on ecosystem-level collaboration involving industrial actors, municipalities, research organizations, and technology providers. Key partners recognized in this study are presented in the Table 5 below.

Table 5. Key partnership categories in biochar business models, based on interviews (n=10)

Category	Examples	Role or contribution	Reported by (n=10)
Feedstock partners	Waste management facilities, wastewater treatment plants, biogas plants, and actors supplying wood or agricultural residues	Secure feedstock supply, reduce waste, lower logistics costs	10
Industrial partners	District heating plants, steel manufacturers, growing media producers, and established large companies	Commercialization of excess heat, enabling volume biochar end-use, improving credibility and market acceptance, and other collaborations	7
R&D partners	Universities and other research organizations	Feedstock testing and developing new applications for biochar, innovation support	9
Networks & associations	Associations, international/national/local networks, and standardization bodies	Advocacy, public awareness, legitimacy, harmonizing practices, development of standards, policy influence	10
Technology partners	Technology vendors, including pyrolysis plant manufacturers and co-equipment suppliers	Plant construction, scaling, and internationalization	6
Financial partners	Strategic investors, funding agencies, and public programs	Funding, legitimacy, credibility	5
Consultancy partners	Certification and sustainability consultants, market-entry advisors	Certification expertise, regulatory navigation, and market entry support	3

In addition to partnerships and revenue streams, the interviews highlighted several critical resources required for scaling biochar production and commercialization (Table 6). The key resources identified across the cases were technological, human, feedstock-related, and infrastructural. Technological resources included proprietary pyrolysis and gasification systems, as well as pilot and demonstration facilities, which supported production, technical validation, and scale-up. Feedstock access was another critical resource, as a secure and low-cost biomass supply reduces operational risk and improves competitiveness. In-house feedstock processing capabilities, such as drying, crushing, and pelletizing, further improved operational flexibility.

Human and intellectual resources were especially important. Producers emphasized the role of multidisciplinary teams, including engineers, chemists, operators, logistics specialists, policy experts, and finance professionals. Research expertise was considered important for application development, certification, regulatory engagement, and scientific credibility. These findings suggest that competitiveness in the Nordic biochar sector depends not only on production assets but also on knowledge, credibility, partnerships, and the ability to integrate technical, regulatory, and commercial expertise. This observation is consistent with broader research on sustainable business models, which emphasizes the importance of knowledge-intensive and network-based capabilities in emerging sustainability-oriented industries (Evans et al., 2017; Schaltegger et al., 2016).

Table 6. Key resources of Nordic biochar producers (based on interview data, n=10)

Category	Examples	Role / Contribution	Reported by (n=10)
Technological	Proprietary pyrolysis/gasification systems; pilot & demo plants	Production capacity, intellectual property, commercialization via sales/licensing, enabling scale-up	10
Human	Multidisciplinary teams; PhD-level researchers	Innovation, certification compliance, regulatory engagement, and application development	9
Feedstock access	Municipal sludge, garden waste, industrial side-streams; in-house processing	Secure and low-cost supply, reduced risks, efficiency, and operational flexibility	10
Infrastructure	Integration with municipal/industrial systems; public ownership/funding	Stable frameworks for investment, long-term strategies beyond short-term profitability	6

Overall, the findings indicate that sustainable value in Nordic biochar production emerges from the combination of multiple value streams, resources, partnerships, and end-use applications. Sustainability is therefore not inherent to biochar production itself, but depends on how feedstocks, technologies, partners, revenue models, and applications are configured in practice. This supports the SBM perspective that sustainable value emerges from interconnected value-creation mechanisms rather than isolated technological solutions (Bocken et al., 2014; Lüdeke-Freund et al., 2024).

4.2. Typology of biochar-based sustainable business models

Based on the interview data, six biochar-based sustainable business model types were developed: biochar products, waste-to-resource, partnership, carbon removal, service-based, and technology commercialization. These models are not mutually exclusive. Instead, producers often combine several models simultaneously, typically emphasizing one dominant model while using others as complementary mechanisms. The relative importance of each model may also change over time as markets, technologies, regulations, and customer demand evolve. This aligns with broader observations in sustainable business model (SBM) and emerging industry literature, in which firms experiment with multiple value-creation logics under conditions of technological and institutional uncertainty (Boons & Lüdeke-Freund, 2013; Lüdeke-Freund et al., 2024; Schaltegger et al., 2016).

The biochar products model represents the baseline configuration, in which biomass feedstocks are processed into biochar or upgraded carbon materials for environmental, industrial, or construction-related applications. Its value proposition is based on application-specific environmental and functional benefits. The model depends on reliable feedstock sourcing, process control, certification, and market development. It resembles product-oriented SBMs and material-efficiency archetypes, where sustainability value is created through the commercialization of environmentally beneficial products and materials (Bocken et al., 2014; Boons & Lüdeke-Freund, 2013).

The waste-to-resource model focuses on converting biomass residues, waste streams, or other organic feedstocks into marketable products. Revenue may derive from gate fees or avoided disposal costs, while sustainability value is created through waste valorization, emission avoidance, nutrient recycling, and pollution mitigation. The model is particularly relevant for feedstocks such as wastewater sludge, garden waste, demolition wood, and other residual biomass streams. Its viability depends on regulation, feedstock quality, and the ability to demonstrate product safety and usefulness. It aligns with the circular economy and "creating value from waste" archetypes, in which problematic waste streams are transformed into economically and environmentally valuable resources (Bocken et al., 2014; Geissdoerfer et al., 2017; Lüdeke-Freund et al., 2019).

The partnership model integrates biochar production into broader industrial or municipal systems through joint ventures, co-location, or collaboration with actors such as sawmills, biogas plants, district heating operators, waste management companies, or industrial end-users. Feedstocks may originate from partners' residues, while heat, biochar, or other co-products may be used internally or commercialized externally. The model creates value through resource efficiency, industrial symbiosis, energy integration, and shared infrastructure. It resembles cross-sector partnership and industrial symbiosis models discussed in sustainability transition literature (Dentoni et al., 2021; Pedersen et al., 2021). The findings also support earlier biochar studies emphasizing the importance of ecosystem collaboration and co-location for commercialization and scaling (Haq et al., 2020; Kivijakola et al., 2025).

The carbon removal model prioritizes long-term carbon storage and the generation of certified biochar carbon removal credits. Producers follow carbon standard methodologies and ensure that biochar is used in durable applications, such as soil amendment, cement, or asphalt. Revenue is generated through carbon credit sales, but the model depends on credible monitoring, reporting, and verification systems, recognized certification frameworks, and reliable carbon markets. The findings suggest that the model is important but risky if producers become overly dependent on uncertain voluntary or compliance carbon markets. It reflects emerging low-carbon and carbon-removal-oriented business models that monetize environmental externalities through carbon markets and certification systems (Fuss et al., 2018; Sairanen & Aarikka-Stenroos, 2024). Its viability is also closely linked to broader climate policy frameworks and measurement, reporting, and verification (MRV) requirements (IPCC, 2022; Schneider & La Hoz Theuer, 2019).

The service-based model focuses on enabling other actors to produce or use biochar through consultancy, feasibility studies, R&D, training, project development, mobile pyrolysis units, or equipment-related services. Revenue is generated from knowledge, expertise, and service provision rather than solely from biochar production. Its sustainability impact is indirect, reducing entry barriers and supporting the diffusion of biochar technologies and applications across sectors. The model resembles servitization-oriented SBMs, where value creation shifts from products toward services, knowledge transfer, and customer support (Bocken et al., 2014; Tukker, 2015).

The technology commercialization model is based on the development, sale, or licensing of pyrolysis technologies. Companies use proprietary technologies, pilot plants, demonstration projects, and intellectual property to commercialize production systems. The model enables scaling through technology transfer rather than direct ownership of production facilities, while reducing exposure to feedstock or end-market risks and supporting the diffusion of biochar production technologies. Similar technology licensing and innovation commercialization strategies are widely discussed in the literature on innovation and emerging technologies (Chesbrough, 2010; Teece, 2018).

Table 7 below summarizes the six biochar-based sustainable business model typologies identified in this study.

Table 7. Summary of biochar-based SBM typologies

Business model	Value proposition	Key activities	Revenue streams	Sustainability characteristics
Biochar products	Producing biochar and/or biochar-derived value-added carbon materials from sustainably sourced biomass for diverse applications (e.g., soil, metallurgy, energy storage, purification)	Sourcing biomass, producing and packaging biochar, R&D and quality control, certification, and supply chain management	Sales of standardized biochar and/or advanced carbon products	Providing application-specific environmental and climate benefits. Promoting sustainable biomass use and substituting fossil-based carbon materials (e.g., activated carbon)
Waste-to-Resource	Utilizing biomass residues, waste, or other organic feedstock (e.g., wastewater sludge)	Securing feedstock supply, developing the supply chain, ensuring compliance with regulations, and R&D for feedstock suitability	Gate fees and avoided feedstock disposal costs	Circular economy: turning negative-cost/problematic waste into resources; emission avoidance & pollution mitigation

Table 7 (cont.). Summary of biochar-based SBM typologies

Business model	Value proposition	Key activities	Revenue streams	Sustainability characteristics
Partnership	Improving the sustainability of core operations by integrating biochar as a side business; commercializing excess energy and co-products	Heat recovery, integration with district heating/industry; joint ventures and partnerships; co-location/integration of pyrolysis into core processes; use of biomass residues as feedstock.	Heat/electricity sales; cost savings via cooperation and integration, while improving the profitability of the main business	Resource efficiency & fossil replacement: maximizing renewable energy recovery while producing biochar; improving the main business's resource efficiency, circularity, and climate performance by valorizing residues and utilizing biochar or its co-products
Carbon removal	Certifying and commercializing Biochar Carbon Removal (BCR) based carbon credits	Compliance with international carbon removal standards and related certification schemes and MRV systems. Ensuring that biochar is applied in permanent carbon storage applications (e.g., soil amendment, cement, or asphalt)	Carbon credit sales	Enabling industries to offset residual or hard-to-abate emissions and align their operations with net-zero strategies
Service-based	Enable others to produce or use biochar via consulting	Consulting, commercialization of know-how, R&D support	Consulting and equipment rental fees	Scaling adoption: knowledge dissemination, lowering entry barriers
Technology commercialization	Proprietary pyrolysis technologies for global roll-out	IP protection, demonstration, licensing agreements, and technical support	Tech sales and licensing	Commercializing sustainable technology for others

As shown in Table 7, the identified business models differ in their value propositions, activities, and revenue structures. However, several sustainability characteristics recur across the typologies, particularly circularity, emission reductions, industrial integration, and resource valorization. While analytically distinct, the models often overlap in practice, as producers may simultaneously combine biochar products, carbon credits, waste feedstocks, the utilization of excess heat, and consultancy or technology services. This reflects both the multi-output nature of pyrolysis systems and the evolving character of SBMs in emerging industries. The findings therefore support views of SBMs as hybrid and dynamic rather than isolated or static configurations (Lüdeke-Freund et al., 2024; Schaltegger et al., 2016), while complementing recent work on pyrolysis business model archetypes (Orlowski et al., 2026) through an empirically grounded typology focused on Nordic biochar producers.

4.3. Biochar business models within sustainable business model literature

The findings show that Nordic biochar producers do not converge toward a single dominant business model. Instead, they develop hybrid configurations that combine several sustainability-oriented value-creation logics. These include circularity, carbon removal, fossil-carbon substitution, industrial symbiosis, service provision, and technology commercialization. This partly reflects the multi-output nature of pyrolysis systems, which enables flexible combinations of value streams depending on local conditions and strategic priorities (Crombie & Mašek, 2015; Ravenni et al., 2024). The findings also align with SBM literature, suggesting that firms in emerging industries experiment with multiple value-creation logics under technological and institutional uncertainty (Boons & Lüdeke-Freund, 2013; Lüdeke-Freund et al., 2024; Schaltegger et al., 2016).

This finding contributes to SBM literature by showing that sustainable value emerges from the configuration of interdependent business model elements rather than isolated activities. In the biochar sector, feedstock choices, production processes, partnerships, and end-use applications jointly shape both economic and sustainability outcomes, including carbon removal, emission reductions, soil improvement, waste treatment, and fossil substitution. This supports the view that sustainable value creation depends on the interaction between technological, organizational, and institutional factors (Bocken et al., 2014; Boons & Lüdeke-Freund, 2013).

The typology developed in this study both aligns with and extends existing SBM archetypes. The biochar products model relates to product-oriented SBMs and material-efficiency logics (Bocken et al., 2014; Boons & Lüdeke-Freund, 2013). The waste-to-resource model aligns with circular economy and "creating value from waste" archetypes (Bocken et al., 2014; Geissdoerfer et al., 2017; Lüdeke-Freund et al., 2019). The partnership model reflects industrial symbiosis and cross-sector collaboration (Dentoni et al., 2021; Pedersen et al., 2021). The carbon removal model is connected to low-carbon business models and the commercialization of environmental externalities through carbon markets (Fuss et al., 2018; Sairanen & Aarikka-Stenroos, 2024). The service-based model reflects servitization logics (Tukker, 2015), while the technology commercialization model aligns with innovation diffusion and licensing-based business models (Chesbrough, 2010; Teece, 2018).

However, the findings suggest that these archetypes rarely operate independently in practice. Biochar producers often combine several archetypes within one business model configuration. This supports recent critiques arguing that SBM research should pay greater attention to hybrid, multi-value, and evolving business model configurations, especially in emerging sustainability-oriented industries (Lüdeke-Freund et al., 2024; Schaltegger et al., 2016).

The Nordic context further impacts these configurations. Abundant forest biomass, established district heating infrastructure, strong climate policy ambitions, and circular economy priorities create favorable conditions for integrating biochar production with energy systems and industrial processes. At the same time, strict waste regulation, evolving product standards, and emerging carbon market mechanisms create both opportunities and constraints. Similar enabling conditions have been identified in earlier Nordic and European biochar studies emphasizing the importance of industrial integration, ecosystem collaboration, and supportive policy frameworks for commercialization (Haeldermans et al., 2020; Salo et al., 2024; Senadheera et al., 2025). Rather than producing one dominant business model, these conditions enable multiple viable configurations.

The findings also show that many current business models are transitional. Several producers described their current operations as pilot, demonstration, or early-stage configurations that do not fully reflect their long-term strategic objectives. Future business models are expected to shift toward larger production units, standardized plant concepts, more diverse feedstocks, higher-value applications, stronger integration with the carbon market, and broader industrial partnerships. Similar development trajectories have been discussed in previous biochar commercialization and pyrolysis studies, where scaling, technology maturation, and diversification of value streams are viewed as essential for long-term competitiveness and market growth (Crombie & Mašek, 2015; Morim et al., 2025; Shackley et al., 2011).

4.4. Drivers, barriers, and future directions

The interviews indicate that policy frameworks, regulations, market development, carbon pricing, certification systems, feedstock availability, technology maturity, and customer awareness influence the future development of Nordic biochar business models. Producers identified significant growth potential, but also several structural barriers limiting large-scale commercialization. These findings align with previous research emphasizing that biochar commercialization depends not only on technological feasibility but also on supportive institutional conditions, stable demand, and the ability to combine multiple value streams (Haeldermans et al., 2020; Senadheera et al., 2025; Thengane et al., 2021; Torres-Morales et al., 2023).

Policy frameworks and carbon pricing were considered particularly important. At the time of the interviews, EU ETS carbon prices of around €65/t were viewed as insufficient to support large-scale biochar deployment; one interviewee suggested that prices above €150/t would be required for broader adoption. Producers emphasized the importance of stable, long-term carbon pricing mechanisms, credible certification procedures, and explicit recognition of biochar in carbon removal policy frameworks, such as the EU Carbon Removal Certification Framework (CRCF). Several interviewees also noted that biochar currently receives less policy attention than BECCS or DAC, despite being viewed as more technically mature and scalable in the near term. Similar observations regarding the importance of policy incentives, carbon markets, and MRV systems for biochar commercialization have been identified in earlier studies (Fuss et al., 2018; Haeldermans et al., 2020; IPCC, 2022; Schneider & La Hoz Theuer, 2019).

Regulation was viewed simultaneously as a driver and a constraint. Tightening PFAS and sludge-related regulations were considered likely to increase demand for biochar-based waste treatment and contaminant removal solutions. At the same time, several producers regarded feedstock-based restrictions as unnecessarily limiting, arguing that regulation should focus primarily on the quality, stability, and safety of the final product rather than feedstock origin alone. Finland was frequently cited as an example in which sludge-derived biochar has been integrated into fertilizer legislation, enabling commercialization, whereas similar applications remain restricted in several other European countries. These findings reflect broader tensions identified in previous biochar studies concerning waste regulation, product acceptance, and commercialization opportunities (Senadheera et al., 2025; Thengane et al., 2021).

The interviews further highlighted several market drivers supporting future growth. Climate targets, decarbonization strategies, and circular economy policies were seen as increasing demand for low-carbon materials, residue valorization, and carbon removal solutions among industries, municipalities, and corporate buyers. Municipalities were considered particularly important actors because of their dual role as regulators and potential early adopters in areas such as sludge treatment, stormwater management, landscaping, and soil improvement. Emerging applications, including PFAS adsorption, peat substitution, construction materials, filtration, and industrial fossil-carbon substitution, were also viewed as promising future markets. Similar drivers related to circular economy policies, carbon removal demand, and industrial applications have been discussed in earlier biochar commercialization studies (Campion et al., 2023; Senadheera et al., 2025; Torres-Morales et al., 2023).

Despite these opportunities, producers identified several barriers to scaling. Market immaturity and price sensitivity remain major challenges, particularly in agriculture and soil amendment markets. High capital costs, financing difficulties, uncertain payback periods, and limited availability of long-term offtake agreements were also frequently mentioned. In addition, competition for biomass feedstocks, seasonal variability, contamination risks, and regulatory restrictions create uncertainty regarding long-term feedstock availability. Technical challenges related to plant reliability, heat integration, scaling from pilot to commercial capacity, logistics, and access to skilled personnel were likewise emphasized. Limited customer awareness, especially in agriculture, further slows adoption and increases the need for demonstration projects and market-building activities. These findings are broadly consistent with earlier techno-economic and market-focused biochar research emphasizing market immaturity, economic uncertainty, feedstock constraints, and scaling-related challenges in biochar commercialization (Campion et al., 2023; Haeldermans et al., 2020; Kivijakola et al., 2025; Morim et al., 2025; Thengane et al., 2021; Trapero et al., 2025).

Looking toward 2040, three broad development pathways can be identified. First, a policy-driven carbon removal pathway would strengthen carbon removal business models through higher carbon prices, stronger integration into compliance carbon markets, and expanded use of certified carbon credits. Second, a circular economy and waste valorization pathway would support waste-to-resource and partnership models by tightening waste regulations and raising disposal costs, thereby embedding biochar production more strongly within municipal and industrial ecosystems. Third, a market-driven industrial pathway would increase the importance of higher-value applications in metallurgy, construction materials, filtration, energy storage, and fossil-carbon substitution. Similar pathways emphasizing carbon removal, industrial integration, and advanced carbon-material applications have also been discussed in recent studies on pyrolysis and biochar commercialization (Morim et al., 2025; Orlowski et al., 2026; Senadheera et al., 2025).

Economically viable biochar systems are likely to depend on diversified, integrated revenue structures rather than on standalone biochar sales alone. Carbon credits, energy sales, product markets, gate fees, and technology or service revenues may all contribute to profitability, although each is associated with specific uncertainties. This supports earlier arguments that resilient biochar business models rely on combining multiple complementary value streams and adapting to evolving policy, market, and feedstock conditions (Crombie & Mašek, 2015; Haeldermans et al., 2020; Morim et al., 2025).

4.5. Implications for theory and practice

The findings have several implications for sustainable business model (SBM) research. First, they show that multiple sustainability-oriented value-creation logics can coexist within a single business model configuration. Nordic biochar producers simultaneously combine circularity, carbon removal, fossil substitution, industrial symbiosis, service provision, and technology commercialization. This extends SBM and circular economy literature, which has often examined these value logics separately (Bocken et al., 2014; Geissdoerfer et al., 2017; Lüdeke-Freund et al., 2019). The findings therefore support recent views of SBMs as hybrid, multi-value, and evolving configurations rather than discrete archetypes (Lüdeke-Freund et al., 2024; Schaltegger et al., 2016).

Second, the study highlights the importance of policy-constructed markets in sustainable business model development. Carbon removal business models depend partly on carbon markets, certification systems, and climate policy frameworks, but the findings also show that the sector is not dependent on carbon markets alone. Biochar business models are embedded within broader institutional environments involving waste regulation, energy policy, product standards, permitting processes, and industrial demand. This reinforces earlier observations that sustainability-oriented business models are strongly shaped by institutional and policy conditions, particularly in emerging sectors characterized by technological uncertainty and evolving market structures (Boons & Lüdeke-Freund, 2013; Fuss et al., 2018; Sairanen & Aarikka-Stenroos, 2024).

Third, the findings emphasize the systemic and multi-actor nature of SBMs. Biochar business models rely heavily on cooperation between municipalities, industrial actors, feedstock suppliers, research organizations, certification bodies, investors, and customers. Sustainable value is therefore created not only within individual firms, but through broader industrial and institutional ecosystems. This supports previous research highlighting the importance of partnerships, ecosystem collaboration, and industrial symbiosis in sustainability transitions and the development of the circular economy (Dentoni et al., 2021; Kivijakola et al., 2025; Pedersen et al., 2021).

The study also contributes to the empirical SBM literature by providing one of the first empirically grounded typologies of biochar-based SBMs. Earlier SBM research has often been criticized for conceptual abstraction and limited empirical grounding (Lüdeke-Freund et al., 2024; Schaltegger et al., 2016). By linking observed biochar business model configurations to established SBM archetypes, the study helps bridge the gap between conceptual SBM frameworks and their implementation within an emerging sustainability-oriented industry.

From a practical perspective, the findings suggest that resilient biochar business models depend on combining multiple revenue streams and partnerships rather than relying on a single product or market. Producers need to secure reliable feedstock supply, develop long-term offtake agreements, build credible partnerships, and invest in certification, product quality, and market development. These findings align with earlier techno-economic and commercialization studies emphasizing the importance of diversified and integrated value creation for long-term viability (Crombie & Mašek, 2015; Haeldermans et al., 2020; Morim et al., 2025).

For policymakers, the findings indicate that biochar commercialization requires coherent policy mixes rather than isolated support mechanisms. Stable carbon pricing, credible certification and MRV systems, product-quality-based regulation, and alignment between waste, energy, and carbon removal policies were all identified as important enabling conditions. Policies recognizing the multifunctional value of biochar—including carbon removal, waste valorization, renewable energy integration, and fossil-carbon substitution—would likely better support the development of viable and scalable biochar business models. Similar policy needs have also been identified in previous biochar commercialization and circular economy studies (IPCC, 2022; Senadheera et al., 2025; Thengane et al., 2021; Torres-Morales et al., 2023).

Overall, the results show that Nordic biochar producers are developing diverse, hybrid, and evolving SBMs in response to changing technological, institutional, and market conditions. Rather than representing a single industry logic, the sector is characterized by experimentation across multiple value-creation pathways, highlighting the importance of flexibility and integration in the development of emerging sustainability-oriented industries.

5. Conclusions

This study examined the SBMs employed by Nordic biochar producers, the sustainability characteristics associated with these models, and the factors influencing their future development toward 2040. The findings show that the Nordic biochar sector is characterized by diverse, hybrid, and evolving business model configurations rather than a single dominant business logic. Based on the empirical analysis, six biochar-based sustainable business model types were identified: biochar products, waste-to-resource, partnership, carbon removal, service-based, and technology commercialization.

The results demonstrate that the viability of biochar production depends on integrating multiple value streams within multi-output pyrolysis systems rather than relying on a single product or market. Producers combine revenues from biochar sales, carbon credits, excess energy, gate fees, services, and technology commercialization while simultaneously pursuing sustainability objectives related to carbon removal, circularity, industrial symbiosis, renewable energy integration, and fossil-carbon substitution. Sustainable value, therefore, emerges not from biochar itself but from how feedstocks, technologies, partnerships, revenue streams, and end-use applications are configured in practice.

The findings further show that contextual and institutional conditions, including biomass availability, district heating infrastructure, climate policy, waste regulation, certification systems, and the development of carbon markets, strongly influence biochar business models. In the Nordic context, these conditions create favorable opportunities to integrate biochar production into broader industrial and energy systems. At the same time, regulatory uncertainty and evolving carbon markets continue to shape commercialization pathways and scaling opportunities. The results also indicate that many current business models remain transitional, with companies continuously adapting their configurations in response to technological development, market maturation, and changing institutional conditions.

From a theoretical perspective, the study contributes to sustainable business models and circular economy literature by providing one of the first empirically grounded typologies of biochar-based SBMs. The findings extend existing SBM literature by demonstrating how multiple sustainability-oriented value-creation logics, such as circularity, carbon removal, industrial symbiosis, servitization, and technology commercialization, can coexist within hybrid business model configurations. The study also highlights the importance of policy-constructed markets, institutional conditions, and ecosystem-level collaboration in the development of sustainable business models within emerging sustainability-oriented industries.

From a practical perspective, the findings emphasize the importance of diversified revenue structures, reliable access to feedstock, long-term offtake agreements, strategic partnerships, and integration with industrial and energy systems. Business model resilience appears to depend on the ability to combine complementary value streams while adapting to evolving market and regulatory conditions. For policymakers, the results underline the need for coherent policy mixes that align carbon pricing, waste regulation, certification systems, MRV frameworks, and product-quality standards to support long-term market development and industrial scaling. Policies recognizing the multifunctional role of biochar, such as carbon removal, waste valorization, renewable energy integration, and fossil-carbon substitution, would likely better support the development of viable and scalable biochar business models.

This study has limitations. The findings are based on a qualitative multiple-case study of ten Nordic biochar producers and therefore reflect a specific regional and sectoral context. In addition, the biochar sector is rapidly evolving, meaning that business models, markets, and policy frameworks may continue to change significantly over time. While the findings reflect a specific regional and sectoral context, they provide analytically transferable insights into the development of SBMs in emerging bioeconomy industries.

Future research could extend the analysis to other geographical contexts and stakeholder groups, including investors, customers, policymakers, and industrial partners. Longitudinal studies would be particularly valuable for examining how biochar business models evolve in response to changing regulation, carbon markets, technological development, and industrial demand. Further research could also explore financing mechanisms, ecosystem-level collaboration, industrial symbiosis, and the role of advanced carbon materials and pyrolysis co-products in future commercialization pathways.

Overall, the study shows that Nordic biochar producers are developing diverse and adaptive SBMs that integrate climate mitigation, carbon removal, industrial integration, and resource valorization. Rather than converging toward a single dominant business model, the sector is characterized by experimentation across multiple value-creation pathways. Understanding this diversity is important for explaining how biochar may evolve from a niche sustainability innovation into a scalable, systemically integrated component of future circular and low-carbon economies.

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Declarations

Competing Interests The authors declare no competing interests.

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Appendix: Interview questions

Part 1: General information on current business operations

1. What does your company do / how does your company make business? (**Business model**)
2. What products do you currently produce, and in what quantities?
    a. Biochar
    b. Energy
    c. Carbon Credits
    d. Other
3. What type of feedstock and how much do you use?
4. What business targets have you set for your biochar operations?
5. What key resources, both physical (like equipment) and non-physical (like expertise or partnerships), do you require to enable your business?
6. Which feedstocks do you consider among the most promising for biochar production, and which feedstocks would you like to expand in the future?
7. What factors influenced the choice of your current feedstocks, and how do you ensure their availability and sustainability?
8. What are the most important factors to consider when choosing the location for biochar production (and priority)?
9. What competitive advantages do you believe your company has compared to others in the industry? And to what other processes or industries do you compare your biochar operations
10. How important is carbon credit income to your current biochar operations, and what impact does it have?

Part 2: Networks

11. Which industry sectors do your key partners and customers represent? Could you describe your supply chain, from feedstock sourcing to the end user?
12. Is your company a member of any biochar-related ecosystems, such as associations or networks? If so, what key topics or initiatives are you actively promoting or involved in within these ecosystems?
13. Does your company conduct research or collaborate with research organizations, and what are the research topics?

Part 3: Social and environmental sustainability

14. What social, environmental, and climate targets have you set for your feedstocks, processes, and products?
15. What approaches do you use to measure or validate the environmental or climate performance of your feedstock, processes, and products?
16. Do your partners and customers expect your business to contribute to social, environmental, and climate benefits?
17. How do you communicate environmental performance to your stakeholders (what is the main message)?

Part 4: Business directions by 2040

18. What key political or legal factors impact/support your business, and enable you to scale?

19. What key economic and technological factors are influencing your biochar operations, and what would enable you to scale?
20. What key social or environmental factors are affecting your development, and what changes would enable you to scale?
21. What key challenges, threats, or barriers do you foresee that could hinder the growth or development of your biochar operations?
22. How does the state of carbon markets (voluntary/regulated) impact your business operations? What changes would enable you to scale?
23. Biochar and carbon credits are typically commercialized separately; do you expect this to change?
24. Do you expect changes or adjustments in your business model as the biochar market matures?