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Research article

Business model innovation in food system transitions: An exploratory case study of fermentation firms

Linus Thomson [a,*], Johnn Andersson [b], Niklas Fernqvist [b]

[a] Innovation and R&D Management, Chalmers University of Technology, 41206, Gothenburg, Sweden
[b] RISE Research Institutes of Sweden, Division Built Environment, Department System Transition, Gothenburg, Sweden

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ABSTRACT

This paper explores how new technology-based firms innovate their business models in a dynamic transitions context. Through a case study of emerging biotech firms in the European biomass and precision fermentation industries, we analyze how firms adopt fit-and-conform and stretch-and-transform approaches to the malleable boundaries of a multi-dimensional business model design space. Conceptually, our study advances this analytical framework by integrating an ecological dimension, offering a broader socio-techno-ecological perspective on business model innovation. Empirically, we find that firms stretch-and-transform the ecological boundary through circular value delivery practices. We also find that firms fit-and-conform to the markets & users boundary by focusing on low-cost value propositions. In addition, we find that technological and business model innovation are deeply interconnected, challenging prior business model design space studies treating them as more distinct. The paper adds to a growing literature that integrates firm- and system-level perspectives on sustainability transitions.

1. Introduction

Biotech is a rapidly evolving field with transformative potential for advancing sustainability transitions in sectors such as agriculture, food, health, and energy (Arantes-Oliveira, 2007; Greenwood, 2014; Parker and Zilberman, 1995; Teng et al., 2021). By harnessing biological processes and organisms, biotech enables the creation of novel products and services that can address critical societal challenges, including climate change and associated resource constraints (Jahn et al., 2023; Popa et al., 2019; Tylecote, 2019). However, the path to developing and commercializing biotech innovations is complex and fraught with challenges (Autio, 1997; Pisano, 2010; Trimi and Berbegal-Mirabent, 2012), including hurdles such as lengthy and uncertain development cycles, high capital requirements, complex regulatory landscapes, and the difficulty of gaining consumer acceptance (Arantes-Oliveira, 2007; European Commission, 2024; Matei and Zirra, 2019; Popa et al., 2019). To navigate these obstacles, firms must innovate not only their technologies but also their business models (Onetti et al., 2012). This involves designing strategies that effectively create, deliver, and capture value from technological innovations, thereby translating advancements into successful business opportunities (Teece, 2010). However, existing research on business model innovation has largely overlooked the unique challenges and dynamics faced by New Technology-Based Firms (NTBFs) in high-tech industries (Lubik and Garnsey, 2016; Thomson, 2022; Trimi and Berbegal-Mirabent, 2012). In particular, much of the current literature and practice has focused on the internal dynamics of incumbent firms, often overlooking the crucial influence of the external environment (Bolton and Hannon, 2016; Boons and Lüdeke-Freund, 2013).

* Corresponding author.
E-mail addresses: linus.thomson@chalmers.se (L. Thomson), johnn.andersson@ri.se (J. Andersson), niklas.fernqvist@ri.se (N. Fernqvist).

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An external perspective on firm-level business model innovation is offered by the transitions literature, which is concerned with transformative change at the level of industries and economic sectors (Geels, 2024; Markard et al., 2012). Transitions theories position firms and consumers as parts of socio-technical systems, which also consist of elements such as policy, culture, knowledge, technology and infrastructure (Bergek et al., 2008; Geels, 2004; Smith et al., 2005). Socio-technical systems are characterized by multi-level dynamics, where established system configurations are challenged by niches that promote alternative technologies, products and/or behaviors, all under the influence of landscape factors (Geels, 2002; Rip and Kemp, 1998). NTBFs take part in these dynamics as key actors in emerging niches. As such, they are profoundly affected by their external environment, which they, in turn, help to shape (Amendola and Bruno, 1990; Autio, 1997; Geels, 2004). For example, established systems become internalized within firms through business model innovation, manifesting in both the solutions being developed and the processes chosen for their development (Amendola and Bruno, 1990). Conversely, established systems are influenced by new business models which can pave the way for transformative change (Autio, 1997; Sarasini and Linder, 2018). However, a key challenge firms face is determining how to navigate external constraints and opportunities, while anticipating the potential reactions that may arise from their actions (Amendola and Bruno, 1990). We therefore advocate for an integrated approach combining an internal and external perspective for better understanding how NTBFs innovate their business models in a dynamic transitions context.

One such approach is the business model design space (BMDS) framework, which was developed as a bridge between the firm-oriented literature on business model innovation and the systems-oriented transitions literature (Wesseling et al., 2020). The core idea behind the framework is that firms innovate their business models within more or less malleable boundaries that arise as a result of established system configurations in the external environment. However, like the transitions literature in general, the BMDS is based on a socio-technical systems perspective, which treats the natural environment as a contextual factor (e.g., as a part of the broader landscape (Andersson, Lennerfors, et al., 2024)). Previous applications of the BMDS framework by Huijben et al. (2016), Wesseling et al. (2020) and (Thomson et al., 2025) align with this socio-technical approach and do not explicitly incorporate an ecological design-space dimension. The framework thus overlooks how factors associated with firms' use of natural resources and impact on ecosystems influence business model innovation. This is particularly problematic when considering NTBFs in the biotech field, since their creation of value by harnessing biological processes and organisms gives rise to a direct interdependence with the natural environment. But also generally, scholars have called for a broader socio-techno-ecological systems perspective (Ahlborg et al., 2019; Andersson, Lennerfors, et al., 2024; Andersson, Plummer, et al., 2024) that accounts for the fact that societal production and consumption is increasingly affected by, and affecting, natural ecosystems at local and global levels (Waters et al., 2016). There thus remains a critical gap in the understanding of how biotech NTBFs innovate their business models within these dynamic transition contexts.

Addressing this gap, our study explores the following research question: *how do NTBFs innovate their business models in a dynamic transitions context?* To answer this question, we conducted an exploratory case study involving thirteen European firms developing and deploying business models focused on biomass and precision fermentation technologies. These biotech areas hold significant potential for catalyzing sustainability transitions in the agri-food sector. Biomass fermentation grows whole microorganisms that can double their weight within hours. This method is particularly suited for large-scale protein production, yielding minimally processed biomass that can be used as a primary or supplementary ingredient in food products (i.e., the microbial biomass is the product of interest) (GFI, 2023b). Precision fermentation, in contrast, uses microorganisms as tiny factories to produce specific functional ingredients such as proteins and fats. These ingredients can, for example, be used to significantly enhance plant-based foods by improving their sensory properties (GFI, 2023b). Both biomass and precision fermentation are marked by high levels of technological and market uncertainty, complex regulatory environments, and ethical and social considerations. To explore how NTBFs navigate these challenges, we depart from a socio-techno-ecological systems perspective on their transition context. In doing so, we apply a novel and enhanced version of the BMDS framework that alongside lifting the socio-technical boundaries of science & technology, culture, markets & users, industry, policy, also explicitly integrates ecology as a key dimension.

Like previous research based on the BMDS framework (Huijben et al., 2016; Thomson et al., 2025; Wesseling et al., 2020), our study reveals both fit-and-conform and stretch-and-transform approaches to business model innovation. However, the focus on NTBFs in biotech has uncovered insights distinct from those of BMDS studies of more mature industries such as electric mobility and renewable energy, where the science & technology boundary is relatively fixed. Our findings challenge this notion, suggesting that for NTBFs in emerging industries where there is a greater level of technological uncertainty, technological and business model innovation are deeply intertwined and co-evolve. For these firms, the business model often represents an evolving vision of a future technological state, or conversely, technological progress drives shifts in business model design. Our study therefore underscores the significant role of a firm's context in influencing the malleability of BMDS boundaries and the potential for boundary stretching and transformation. In addition, by introducing an ecological boundary dimension, we demonstrate a more comprehensive BMDS framework.

The remainder of this paper is structured as follows. In Section 2, we provide a theoretical background on business model innovation in biotech NTBFs, introduce the concept of the BMDS and expand it to include the ecological dimension. In Section 3, we describe our research design and methodology, including the case selection, data collection, and data analysis procedures. In Section 4, we present our findings on how the NTBFs in our sample innovate their business models in a socio-techno-ecological BMDS. Section 5 discusses the theoretical and practical implications of these findings, offers policy recommendations, and suggests directions for future research. Finally, Section 6 concludes the paper.

2. Theoretical background

2.1. Business model innovation in biotech NTBFs

New business ventures emerge from the identification of market opportunities or through technological innovations. However, their success depends not just on these initial foundations, but on the ability to transform them into sustainable economic outcomes, necessitating the development and execution of an effective business model (Chesbrough and Rosenbloom, 2002; Onetti et al., 2012; Teece, 2010). Although technological innovation and business model innovation are distinct processes, they are closely intertwined (Baden-Fuller and Haefliger, 2013). This interconnection is especially evident in NTBFs, that is, new firms in high-tech industries such as bio-tech (Bollinger et al., 1983; Rydehell, 2020), which lead the way in developing both novel technologies and innovative business models (Holzmann et al., 2020). For instance, where technologies are still in development, the business model acts as a cognitive framework that not only guides the trajectory of technological innovation but is also continuously influenced by it (Baden-Fuller and Haefliger, 2013). Despite the relevance of business model innovation for NTBFs, prior research has primarily focused on incumbent firms (Del Giudice et al., 2021), providing limited insights into the dynamic interplay and co-evolution of technological and business model innovation in emerging ventures. Moreover, the limited studies that do explore the business model innovation of new ventures have predominantly focused on digital-only businesses (Loon and Chik, 2019; Rosin et al., 2020). In contrast, relatively little attention has been devoted to exploring the business model innovation of NTBFs also developing physical technologies, such as those in biomass and precision fermentation (Lubik and Garnsey, 2016) for an exception see Thomson (2022).

NTBFs in the biotech industry face significant hurdles as they navigate the path from innovation to commercialization. Operating at the forefront of both emerging markets and emerging technologies, NTBFs strive to bridge the gap between research and development (R&D) and commercialization with technologies that are often not fully developed at the time of their founding (Lubik and Garnsey, 2016). The risky and unpredictable scale-up phase, where early-stage technologies must be refined and tested at larger scales, often without a clear timeline for success, represents one of the primary hurdles for NTBFs (Aldrich and Fiol, 1994). This phase is fraught with uncertainties, as firms work to transition from lab-based success to market-ready products. As such, NTBFs not only need to navigate typical liabilities of newness but also contend with a unique set of additional challenges from establishing a business in a context where few precedents exist (Aldrich and Fiol, 1994). Moreover, NTBFs often face challenges such as long development lead times and the need for substantial capital and resource investments, making their journey more arduous than that of more mature firms (Lubik and Garnsey, 2016; Trimi and Berbegal-Mirabent, 2012). Developing new technologies typically requires significant resource commitments to bring innovations to full fruition (Shane and Stuart, 2002). Securing these resources presents a formidable challenge, given the inherent uncertainty and ambiguity surrounding technological and market development (Aldrich and Fiol, 1994; Tushman and Rosenkopf, 1992). This challenge is particularly pronounced for biotech NTBFs, which often require support from universities, larger firms, and financiers to cover R&D costs, but also need considerable resources to achieve scaled production in an immature market and to establish a robust resource base for successful operation (Dosi, 1982). The complexity of this context, with continual and rapid changes to technologies and markets, results in substantial ambiguity and uncertainty which challenges NTBF survival.

Research indicates that business model adaptation is crucial for firm survival in nascent, capital-intensive, and high-velocity industries such as biomass and precision fermentation (Andries and Debackere, 2007; Lubik and Garnsey, 2016; Onetti et al., 2012). In these contexts, NTBFs must navigate significant uncertainty and ambiguity, necessitating the concurrent engagement with technological and business model innovation (Onetti et al., 2012). The case of Metalysis (Lubik and Garnsey, 2016) illustrates this co-evolution. To commercialize its molten salt electrolysis process, the company had to refine the technology while simultaneously shaping a viable business model. Initially, Metalysis focused on licensing the technology (crucially requiring further development to reach this step), but as the process matured and industry interest grew, the company included upstream collaborations that supported complementary innovations, as well as a joint venture with an industry incumbent. This dynamic interplay required continuous adjustments, including further technological innovation, attainment of intellectual property rights and aligning the process with market needs. For instance, an early focus on tantalum switched to titanium based on commercial opportunities.

The case of Metalysis highlights the dynamic role of business model innovation in NTBFs, and how technologies shape, and are shaped by it. Unlike mature firms, which often operate in more stable and clearly defined market conditions, NTBFs face the dual challenge of technological and business model innovation, all while targeting a future market that has yet to be fully realized (Aldrich and Fiol, 1994; Andries and Debackere, 2007; Autio, 1997; Baden-Fuller and Haefliger, 2013). In this environment, firms face the choice of either accepting existing conditions and shaping their innovations accordingly or attempting to modify and transform these conditions into something new and more favorable (Amendola and Bruno, 1990). Yet we lack insights into the ways in which NTBFs engage with business model innovation in response to their external environment.

This discussion underscores that high-tech NTBFs in biotech operate within a complex socio-technical context that significantly influences their success. The dynamic and uncertain nature of emerging technologies and markets necessitates continuous adaptation of business models in response to external conditions (Trimi and Berbegal-Mirabent, 2012). Navigating this complex business environment requires NTBFs to adopt a holistic approach that considers both the organization and its broader context (Onetti et al., 2012). Effective business model innovation, therefore, requires strategic alignment with external structures and processes, an aspect often overlooked in both business model innovation research and practice. Much of the existing literature and practice tend to focus primarily on dynamics within the firm, often neglecting the critical influence of factors associated with the production and consumption systems in which it is embedded (Bolton and Hannon, 2016; Boons and Lüdeke-Freund, 2013). This highlights the need for an approach that integrates both the internal dynamics of innovation and the external environment shaping the firm's trajectory. Addressing this gap is essential for understanding how firms can better position themselves within the complex and interconnected systems in which they operate (Onetti et al., 2012).

2.2. The business model design space associated with an established socio-technical regime

In contrast to the firm-oriented literature on business model innovation, sustainability transitions research focuses on the dynamics of transformative processes at the level of industries and economic sectors (Geels, 2024; Köhler et al., 2019). A key observation is that production and consumption in society is governed by socio-technical systems that involve not only firms and consumers, but also elements such as policy, culture, knowledge, technology and infrastructure (Bergek et al., 2008; Geels, 2004; Smith et al., 2005). Interdependencies in socio-technical systems result in negative feedback that favors stable system configurations and path dependent innovation processes, as well as positive feedback that rather propels learning and institutional adaptation around alternative configurations (Geels, 2002; Rip and Kemp, 1998). This is captured by the multi-level perspective (MLP) framework, which distinguishes socio-technical regimes, niches, and landscapes as different but interrelated analytical levels. Regimes refer to established system configurations at the meso-level, which have evolved and stabilized over long periods of time (Geels, 2002). They thus constitute sources of inertia that hinder the emergence of more sustainable production and consumption systems. In contrast, niches refer to alternative system configurations that are yet to diffuse at scale to influence established regimes, while landscapes capture macro-level developments such as geopolitical shifts and climate change.

Research has shown that transitions to more sustainable regimes unfold along pathways characterized by different dynamic patterns (Geels et al., 2016; Geels and Schot, 2007). The traditional conception is that (successful) niches gradually gain momentum and eventually replace existing regimes (Kemp, 1994; Kemp et al., 1998), but scholars increasingly emphasize that pressure from emerging innovations often results in the endogenous renewal or reconfiguration of established structures (Geels et al., 2016; Geels and Schot, 2007). Within niches, innovations may be developed to fit-and-conform to institutions associated with existing regimes or challenge these structures through a stretch-and-transform logic (Smith and Raven, 2012).

To bridge the gap between firm-level business model innovation and the broader transitions context outlined by the MLP, Huijben et al. (2016) introduced the BMDS framework, which offers a tool for understanding how firms navigate the complex interplay of factors that influence their business models. Conceptually, the BMDS outlines a set of dimensions in which firms face selection pressures and perceive constraints that influence how they can create, deliver and capture value (Wesseling et al., 2020). Whereas regimes associated with established systems exist in firms' external context, the BMDS thus appears and evolves as firms navigate and negotiate this context when innovating their business models. This makes the BMDS framework a valuable tool for analyzing how business model innovation both shapes and is shaped by opportunities and constraints associated with different aspects of established regimes, offering a nuanced perspective on the dynamic interdependencies between firms and their external environments (Huijben et al., 2016; Thomson et al., 2025; Wesseling et al., 2020).

Inspired by the MLP framework, the BMDS is organized around dimensions of socio-technical regimes (i.e., science & technology, culture, markets & users, industry, and policy), each playing a crucial role in shaping the business landscape (Wesseling et al., 2020). In each dimension, firms encounter boundaries and constraints that must be strategically navigated to design and implement effective business models. This may involve a fit-and-conform approach where firms engage with business model innovation within established regime structures, thus striving to integrate into established industry practices, cultural norms, and regulatory frameworks (Huijben et al., 2016; Smith and Raven, 2012). Although this strategy is often less risky, it may also limit the firm's ability to drive significant change within the industry (Wesseling et al., 2020). Conversely, firms may adopt stretch-and-transform approaches that aims to challenge regime structures (Huijben et al., 2016; Smith and Raven, 2012). These firms are typically pioneers in their fields, introducing disruptive innovations that necessitate shifts in market norms, regulatory changes, or new industry standards. While this approach carries higher risks, it also offers the potential for greater rewards if successful (Smith and Raven, 2012).

Previous studies have utilized the BMDS framework to explore how policies affect business model innovation in industries like solar photovoltaics and electric vehicles (Huijben et al., 2016; Wesseling et al., 2020), where technologies are relatively mature and supported by well-established markets and policy frameworks. More recent work has extended the framework to emerging niches such as insects as food and feed (Thomson et al., 2025), which –like biomass and precision fermentation –face greater technological uncertainty, limited legitimacy, and policy support. In these contexts, technological and business model innovation tend to occur concurrently (Baden-Fuller and Haefliger, 2013; Lubik and Garnsey, 2016). This highlights the need to consider both technological innovation and business model innovation (Baden-Fuller and Haefliger, 2013) when applying the BMDS framework.

2.3. Expanding the business model design space to account for socio-techno-ecological interactions

When Hujiben et al. (2016) introduced the first version of the BMDS framework, they had a narrow focus on the policy boundary as part of the regulatory regime. Wesseling et al. (2020) then extended the concept to include four additional boundaries –science & technology, culture, markets & users, and industry –derived from the literature on socio-technical regimes (Geels, 2002; Geels and Kemp, 2007; Rip and Kemp, 1998). This put the BMDS in a socio-technical systems context and arguably made for a more comprehensive framework. As put by Wesseling et al. (2020), it is "not only the policy dimension that enables and restricts the options for new business model design, but all dimensions of the [socio-technical] system" (p.3).

Despite these advancements, however, the ecological dimension remains a critical gap in the current conceptualization of the BMDS. Socio-technical systems are deeply intertwined with structures and processes in their natural environment (Berkes et al., 2003; Berkes and Folke, 2000), particularly as we are entering the Anthropocene where human activities (of production and consumption) are the main drivers of planetary change (Waters et al., 2016). Adopting a broader socio-techno-ecological perspective (Andersson, Lennerfors, et al., 2024; Andersson, Plummer, et al., 2024), which incorporates attention to the ecological dimension into the BMDS framework, would thus provide a more holistic understanding of the external factors that shape firms' efforts to innovate their technologies and business models. As noted in the introduction, this is particularly important when considering NTBFs in the biotech field, which is based on the harnessing of biological processes and organisms.

Therefore, this paper views *ecology* as an additional dimension of the BMDS, supplementing the commonly used dimensions derived from the literature on socio-technical regimes (Table 1). The ecological dimension highlights opportunities and constraints associated with firms' use of natural resources and impact on local and global ecosystems. Interactions between firms and the natural environment not only enable value creation through technological processes, but also shape the sustainability and legitimacy of value propositions and delivery mechanisms, thus exerting an important influence on firms' engagement with business model innovation (and general competitiveness) (Hart, 1995). Established configurations in the ecological dimension give rise to a more or less malleable boundary, in relation to which firms may adopt a fit-and-conform strategy, seeking to align business model innovation with the prevailing relationships between socio-technical and ecological systems, or a stretch-and-transform strategy, rather challenging and attempting to redefine these relationships (Huijben et al., 2016; Smith and Raven, 2012).

A fit-and-conform strategy in the ecological dimension thus aligns business model innovation with prevailing regime-level practices based on linear material flows. Established value chains are ultimately dependent on natural resources and ecosystem services for raw materials, energy and waste management (Arthur, 2009; Grübler, 1998). In relation to these ecological inputs, regulations and subsidies, as well as attitudes and norms among customers and other stakeholders, give rise to a legal and moral boundary that (most) firms respect to stay legitimate and maintain their social license to operate (Hurst et al., 2020; Prno and Scott Slocombe, 2012). However, in the current techno-economic paradigm (Schot and Kanger, 2018), this boundary allows extractive practices with high environmental impacts, which means that firms with fit-and-conform strategies can develop business models based on unsustainable practices. While such strategies may offer firms short-term gains, they also challenge their legitimacy and profitability in the long-term, since the ecological boundary will tighten with increasing scarcity of natural resources, shrinking capacity of ecosystem services and growing awareness about the consequences of environmental degradation.

In contrast, firms with stretch-and-transform strategies in the ecological dimension challenge regime-level practices by developing business models that strive to follow different standards. Although such firms are still a part of value chains that depend on natural resources and ecosystem services, which inevitably brings an environmental footprint (Arthur, 2009), they strive to reduce the dependence on virgin raw materials, fossil energy and land through business models based on circular principles. These may involve using renewable and recyclable materials, capturing value from waste, extending product life (i.e., repair, remanufacture and refurbish), increasing product utilization (e.g., through sharing platforms), offering products as services, and designing products for disassembly and component reuse (Bocken et al., 2016). This can be seen as an effort to stay within a tighter ecological boundary,[1] by complying with self-imposed guidelines and constraints that shift resource dependencies from the ecological to the socio-technical domain. However, stretch-and-transform strategies based on circular principles are often contingent on the emergence of new value chain configurations that, for example, enable firms to obtain recycled materials (Molden et al., 2025). These transcend the boundaries of individual firms, particularly for NTBFs that normally aim to occupy a specialized position in a network of firms that together deliver new products to end-customers, rather than integrating a large part of their value chain. Consequently, stretch-and-transform strategies often require new types of partnerships and collaborations as well as complementary innovation by other firms. While this makes the approach more costly and uncertain in the short-term, setting higher standards in the ecological dimension is clearly a way to differentiate value propositions and align with sustainability transitions.

3. Methods

3.1. Research design

Given the paucity of empirical research examining the interactions between firm-level and system-level dynamics in the business model innovation of NTBFs, particularly when considering the novel exploration of ecological dimensions in this context, we conduct an exploratory qualitative case study. This approach is well-suited for collecting and interpreting rich, nuanced data, thereby advancing both theoretical and empirical understanding of emerging phenomena (Eisenhardt and Graebner, 2007). Methodologically, we thus prioritize analytical over statistical generalization, aiming to develop new insights rather than to confirm existing theories.

The study explores how NTBFs innovate their business models in a dynamic transitions context. We focus on biotech NTBFs in biomass and precision fermentation, hereafter referred to as microbial[2] firms, and employ a modified version of the BMDS framework that incorporates an ecological dimension (Section 2). The empirical scope is pertinent for exploring firm- and system-level dynamics in high-tech business model innovation and highlights a context where ecological considerations are integral.

[1] Notably, a stretch-and-transform strategy can in principle be oriented towards the opposite objective, i.e., to loosen rather than tighten the ecological boundary.

[2] We adopt the term microbial to refer to biotech firms in biomass and precision fermentation.

Table 1
The six BMDS dimensions used in this paper. Based on Hujiben et al. (2016) and Wesseling et al. (2020), with additions to account for the ecological dimension.

BMDS dimension	Description
Science & technology	The technical components, systems and infrastructures, as well as related knowledge and competence, which are essential for delivering and capturing value.
Culture	The societal values, beliefs and norms, which govern the legitimation of value propositions among consumers and other stakeholders.
Markets & users	The preferences of customers and end-users, which must align with value propositions for market viability and commercial success.
Industry	The presence and characteristics of industry actors, which are essential for delivering shared value through collaborative innovation or offer competing value propositions.
Policy	The public laws, regulations, subsidies and support that determine what is permissible while favoring certain ways to deliver and capture value.
Ecology	The natural resources and ecosystem services, which shape the legitimacy and long-term sustainability of value propositions while enabling their delivery.

3.2. Data collection

Microbial firms were identified through a comprehensive search of companies listed in two databases: the Good Food Institute[3] and the Protein Directory.[4] We selected firms through purposive sampling to align as closely as possible with the study (Bell et al., 2022; Eisenhardt and Graebner, 2007), using the following criteria: (1) the firm is a NTBF; (2) the firm operates in the biomass or precision fermentation fields; (3) the firm is based in Europe, providing a consistent geographical and institutional context for defining the boundaries of the BMDS; and (4), the firm has achieved at least a proof-of-concept stage for its technology.

In total, data was gathered from thirteen microbial firms (Table 2) using semi-structured interviews.[5] This is an effective format for eliciting detailed insights through open-ended questions while allowing flexibility to adjust the conversation based on the participants' responses (Yin, 2018). For instance, interviewees were prompted to expand on noteworthy deviations from the pre-planned questions when doing so could enhance the study's understanding. Note also that interviewees were granted anonymity, which is why the names of firms and informants are not disclosed.

Each interview involved a single key informant, selected on the basis of their seniority and direct involvement in the firm's strategic and operational decision-making. Most held roles such as founder, CEO, CTO or equivalent (see Table 2) and had been with the firm since its inception. These individuals were uniquely positioned to discuss both internal business model innovation and external engagement with broader BMDS elements. While we acknowledge the limitation of relying on a single informant per firm, our sample consists of small enterprises and our research design prioritized depth of insight from highly knowledgeable participants over breadth of coverage.

The interviews were conducted online through video calls. Each session was recorded and subsequently transcribed to facilitate detailed analysis. The interviews had an average duration of 42 min and were carried out between May and September 2024. Questions were designed to explore several key areas: the business model and its core components, the broader context in which the firm operates, specifically in relation to the BMDS dimensions, and how this context influences business model innovation. Additionally, the interviews delved into the ecological dimensions of business model innovation and included a forward-looking perspective. A sample interview guide is included in Appendix A. To enhance our understanding of the firms and mitigate potential biases from relying on single informant data, we supplemented the interviews with a variety of secondary data sources to enable data triangulation (Miles et al., 2020). These sources included company websites, social media posts, news articles, reports and insights from an EU level workshop focused on industrial applications of fermentation technologies, which provided additional context and validation for the interview findings. For instance, reports from the Good Food Institute offered detailed insights into industry trends, including technological advancements and market developments which were critical for helping to define and contextualize the BMDS dimensions. Additionally, expert perspectives and policy discussions from the EU-level workshop helped frame the study within a broader sectoral context. Company specific information, such as social media posts and website content, further supported our research by informing interview preparation, allowing us to ask more targeted and relevant questions. By integrating these sources, we ensured a more comprehensive and reliable understanding of the topic, reducing reliance on self-reported data from interviews and enhancing the robustness of our findings (Miles et al., 2020).

3.3. Data analysis

Our data analysis followed a reflexive thematic analysis approach (Braun and Clarke, 2006), guided by an iterative process of coding, theme development, and collaborative sense-making. The analysis proceeded with the two lead authors independently reading and re-reading the interview transcripts to gain familiarity with the data. During this process, notes were made to capture themes relevant to the study's focus, particularly related to characterizations made of the BMDS boundaries, as well as the firms business

[3] See www.gfi.org
[4] See www.proteindirectory.com
[5] One of the firms declared bankruptcy shortly after the interview was conducted.

Table 2
List of interviews with microbial firms.

Organization	Type of fermentation	No. of employees	Role of interviewee(s)	Date of interview	Recorded duration (min)
Firm 1	Biomass	2–10	Chief Product Officer	May 2024	55
Firm 2	Biomass	51–100	Founder	May 2024	46
Firm 3	Biomass	11–50	Chairman	June 2024	42
Firm 4	Biomass	11–50	Business Manager & Founders Associate	June 2024	51
Firm 5	Biomass	11–50	CEO & Co-Founder	June 2024	59
Firm 6	Biomass	2–10	Chief Scientific Officer	May 2024	37
Firm 7	Biomass	11–50	CEO & Founder	June 2024	35
Firm 8	Precision	2–10	Founder	August 2024	32
Firm 9	Precision	11–50	CTO & Co-Founder	August 2024	38
Firm 10	Biomass	2–10	Director	September 2024	54
Firm 11	Biomass	11–50	Founder & CEO	September 2024	23
Firm 12	Precision	2–10	Business Developer	September 2024	50
Firm 13	Biomass	11–50	CTO & Co-founder	September 2024	25

model innovation with respect to these. For instance, in the Firm 6 transcript, the statement "…what are the challenges? Yeah, I guess the novel food is definitely one…" was coded as *novel food regulation,* and the associated comment "trying to stay as close to the approved ingredients as possible" as *fit-and-conform*. Code generation was therefore both inductively informed by the data (e.g., *novel food regulation)* and deductively informed by theory (e.g., *fit-and-conform)*; akin to the approach of systematic combining that moves iteratively between data and theory (Dubois and Gadde, 2002). NVivo software was used to streamline the coding and organization of data. To facilitate both written and verbal discussion and enhance our sense-making process, both authors collaboratively developed shared firm narratives (Miles et al., 2020). These narratives condensed the lengthy, unstructured transcripts into more concise summaries based on our interpretation of the data. The analysis progressed as a joint and iterative endeavor to converge on an understanding that best aligned the data with the theoretical framework (Dubois and Gadde, 2002). In the final analysis, which was validated by all authors, we paid close attention to both commonalities and distinctions within the data, ensuring that it provided an accurate and nuanced reflection of empirical reality. For instance, while all microbial firms introduce new methods for sustainably meeting protein demand, we distinguished between more linear and circular business models, an important distinction for understanding the relationship with the ecological boundary (see Section 4.6). Finally, each interviewee received a copy of the manuscript for validation and were invited to review the document in its entirety, with particular attention to sections of relevance to their firm and contributions. This process provided an opportunity for interviewees to validate the manuscript and report on any misrepresentation or misunderstandings. Any clarifications or amendments suggested by the interviewees were carefully reviewed for incorporation into the final manuscript.

4. Findings

4.1. Science & technology

Due to their status as NTBFs and the nascent stage of the fermentation industry, microbial firms are extensively engaged in R&D that generates new knowledge, competence and technologies, with "innovation in this field largely driven by private-sector research and development" (GFI, 2023b). Europe plays a leading role in this innovation landscape, with high levels of patent activity (GFI, 2023b), and is considered to be "ahead of the game [with] almost half of all fermentation companies worldwide based in Europe" (EU Commission Workshop, 2024). The core focus of these firms is on advancing microbial production strains, optimizing fermentation processes, enhancing product performance, and scaling technologies for commercial applications. Public research institutions and universities are key enablers of this progress, contributing through open-access research. Many microbial firms originate as university spin-offs, rooted in academic research. A key area of interest is selecting sustainable feedstocks for fermentation processes. Today, processed sugars from crops like maize and sugar cane serve as primary carbon sources (GFI, 2023b). However, as the bioeconomy grows, the rising demand for these sugars underscores the need for alternatives. Options such as woody biomass, agricultural residues, food waste, alcohols, and gaseous carbon, present viable options but further R&D is necessary (GFI, 2023b).

Our findings align with prior research indicating that business model innovation can indirectly stretch-and-transform the science & technology boundary (Wesseling et al., 2020). This influence manifests in several ways. First, many microbial firms, originating as university spinouts with strong R&D involvement, embody a shift from academic research to commercial use where the customer perspective gains focus. For instance, reflecting on their R&D process, Firm 9 commented that "you start the technology with unit economics in mind…not for the sake of science, always for the sake of the consumer price". Their market-orientated business models both shape and are shaped by ongoing research, serving as platforms that channel scientific advancements into commercial opportunities. For instance, Firm 4, founded whilst its creators were still at university, iterated through cycles of product testing and refinement to develop a "minimum viable product with the first functioning few grams of protein", which provided a foundation for securing additional funding and becoming independent. This market focus can steer scientific inquiry toward commercially promising areas, thus indirectly stretching-and-transforming the science & technology boundary. Reflecting on the R&D focus of their business model, the CEO at Firm 7 commented that "you need to start figuring out, making decisions in terms of where you add most value as a company. And for us, that was in researching, discovering, optimizing, scaling, fungi-based solutions to solve animal-based ingredients in the food industry". Second, several firms' business models are designed around technologies or processing methods that are not yet fully developed. By anticipating future technological developments, these firms structure their business models to align with an expanded science & technology boundary. For instance, Firm 5, despite a clear vision of its future business model, noted it was still "in the process of cracking that code and coming up with technologies and approaches to be able to do this, to be able to use a range of side streams in our process". In other words, engaged in R&D to support novel side-stream process inputs. Firm 2 has similarly engaged in R&D for the development of a viable business model: "we've worked with more than 20 different types of side-streams…from paper industry and other industrial segments". While business models can indirectly shape science & technology boundaries by establishing commercial pathways and guiding research priorities, their success is also contingent on broader societal acceptance. In the food sector, this acceptance is deeply intertwined with cultural norms and values, which influence how new technologies and products are perceived.

4.2. Culture

Food production and consumption are deeply embedded in cultural norms and values, reflecting food's essential role in human wellbeing and survival as well as the unique fact that food is ingested and becomes part of the consumer. Consequently, food choices are influenced not only by price and performance but also by deeply rooted normative values and cognitive beliefs about what is acceptable and desirable. In Europe and other regions, food is strongly linked to cultural identity, with longstanding preferences for animal-based proteins. While concerns about animal welfare have sustained a niche market favoring plant-based alternatives for decades, this niche has recently expanded, driven by rising concerns over climate change and biodiversity loss. However, despite growing awareness of values related to health, taste, origin and sustainability across diverse cultural contexts, the agri-food system remains predominantly oriented towards affordability, prioritizing speed, efficiency, and productivity within an industrial paradigm. This globalized, industrial logic produced a large-scale, complex food system that prioritizes predictable, controllable supply chains and operational efficiency. Consequently, a significant spatial and conceptual separation has emerged between food production and consumption, reinforcing a disconnection between humans, nature, and the food they consume. This disconnection is evident in the shift from raw ingredients to functional ingredients valued for their performance rather than their natural qualities. Consumers, are increasingly purchasing processed, branded products instead of fresh, unprocessed food, underscoring a cultural dissonance between traditional views of food and the realities of its modern production and consumption.

Our research finds that microbial firms navigate these cultural boundaries by innovating business models that largely fit-and-conform to existing norms. The most prominent strategy is a focus on creating products that replicate established foods, particularly meat, in taste, texture, and appearance, rather than introducing new sensory experiences. For instance, Firm 11 is using a "technology based on fungal fermentation…to recreate the mouthfeel and the overall experience that comes with whole cuts, muscle tissue". Some firms supply ingredients for hybrid products, combining fermented fungal protein with meat, thereby appealing to mainstream perceptions regarding the nutritional importance of animal proteins. Firm 2 perceived this to be a more realistic strategy to gain consumer acceptance, emphasizing that "we need slow transitions…especially when it comes to food". Moreover, firms have avoided labels like 'vegan', opting instead for 'plant-based', due to the cultural connotation that may deter mainstream consumers, particularly those who identify as 'meat eaters'. As Firm 4 reflected "the more you tell someone that this is vegan, the more opposed they are". Firm 3 recognized this challenge, and similarly commented that: "to convert like these people that just eat meat, that is not our job, if you put it that way, it is going to happen slowly, automatically" - reflecting a fit-and-conform approach to cultural norms.

However, fermentation-based products also challenge cultural norms by redefining food production beyond conventional agriculture. In particular, their use of specialized fermentation processes, rather than traditional agricultural methods, redefines how and where food can be produced. As a result, the firms in our sample thus balance fit-and-conform strategies with efforts to stretch-and-transform this part of the cultural boundary, reshaping aspects of food production that have traditionally been tied to agriculture. For instance, as Firm 6 emphasizes, "agricultural land has its limits", whereas fermentation technologies enable "local food production all around the world, if you have electricity and some water". This perspective reframes food production as a decentralized, technology-driven process rather than one tied to farmland and livestock. However, despite these innovations, the spatial and conceptual divide between food production and consumption limits the extent to which novel fermentation-based methods reshape cultural perceptions of food with consumers.

While microbial firms must carefully navigate societal values, beliefs, and norms within the cultural dimension, they must also ensure that their products or technologies meet the technical, performance, and quality requirements of customers and end-users. While these market expectations are shaped to some extent by cultural factors, they are separately considered in the next section.

4.3. Markets & users

Microbial firms primarily operate within business-to-business markets, supplying ingredients to food manufacturers who incorporate them into products sold through established retail channels. Food manufacturers prioritize cost-competitive ingredients that meet specific technical and quality requirements, such as solubility and texture, and are available in large volumes to support commercial scalability. While sustainability attributes are valued, price remains the predominant factor in purchasing decisions. Although microbial firms focus on business-to-business transactions, consumer preferences indirectly shape these markets as food processors and retailers respond to shifting consumer demands. However, consumer awareness of fermentation-derived products remains limited and is mainly associated with traditional fermented foods like misoand sauerkraut (GFI, 2023b). Therefore, a core aspect of marketing strategies for fermentation-derived products involves reaching out with "mainstream benefits that truly resonate with consumers –like taste, price and convenience" (GFI, 2023b).

Our findings reveal that all of the microbial business models are structured to fit-and-conform to the market boundary, employing several approaches to achieve this fit. The microbial firms' value propositions are tailored to meet business-to-business customer expectations, prioritizing like-for-like product performance that can seamlessly integrate into existing production systems and end-product applications. For instance, Firm 1 emphasized the importance of delivering to customer expectations "so if they say that there are certain functionalities they wants to see…then we can try and increase it or implement it through fermentation". A key aspect of this approach is a cost-orientated strategy, where microbial alternatives aim to either match or undercut the price of conventional ingredients. Aware of food manufacturers' sensitivity to price, especially amidst global market volatility, many microbial firms have adopted cost-focused business models. As Firm 9 noted, if "price is not checked, then zero [considerations] are given about sustainability", emphasizing that cost is a primary focus. Firm 13 echoed this sentiment, stating, "we cannot change the rules of the game, so we have to play with it," underscoring their commitment to fitting within the existing market framework.

Beyond price considerations, microbial firms align with market expectations by positioning their products as direct substitutes for conventional ingredients. Many firms market their offerings in terms of equivalency, positioning them as functional replacements for items like meat, fish, cheese, or other protein sources. For instance, one firm producing a cheese-like product from fermented vegetables seeks to replicate critical attributes of traditional cheese, such as melting properties and flavor, collaborating with clients to customize the product to meet specific production requirements –commenting "consumers are actually very reluctant to change their behaviour…they want to recreate something that is as close to a real dairy cheese as possible". In addition, some microbial firms diversify their business models to target not only food, but also animal feed with their value propositions. As Firm 5 put it, this offers "an easier journey that we can construct to the market", even though the long-term vision is to produce food since this unlocks a larger sustainability potential.

None of the microbial firms adopt a stretch-and-transform approach to the market boundary; instead, all prioritize product attributes that align with existing market demands. Their business models emphasize cost-competitiveness, reliability, and familiarity, reflecting the established characteristics of the current market boundary. While microbial firms align their value propositions with existing market demands, scaling and delivering their solutions requires more than just meeting customer expectations. To achieve commercial viability, these firms must also leverage the capabilities and resources of actors within the fermentation industry, or adjacent industries, principally to overcome scale-up challenges and support production.

4.4. Industry

The fermentation industry, while rapidly evolving, remains relatively nascent with fewer than 200 companies worldwide (GFI, 2023b). Although limited in number, the industry can be traced back to a single large-scale biomass fermentation company in the 1980′s (GFI, 2023b). Precision fermentation for food applications began in the 1990s with the production of rennet, an enzyme used in cheese making (GFI, 2023b). A central challenge facing the industry is developing the technical capabilities and manufacturing infrastructure needed to scale fermentation-derived products effectively. Microbial firms have three principal approaches to securing production within the industry: partnering with contract manufacturing organizations (CMOs), constructing their own facilities, or retrofitting used equipment (GFI, 2023c). Partnering with CMOs is a cost-effective option, allowing firms to bypass high capital expenditures associated with building infrastructure while accessing existing production expertise. As collectively recognized, fermentation is a "CAPEX-heavy business…[where] private capital is impossible to come by for food grade facilities at industrial size" (EU Commission Workshop, 2024). However, the CMO landscape also presents challenges. Nearly half of the facilities are based in Europe (47 %), and limited global capacity often results in production bottlenecks (GFI, 2023c). Additionally, much of the existing fermentation infrastructure was not originally designed for food-grade applications and lacks the advanced control systems necessary for modern food production (GFI, 2023c). Retrofitting older facilities requires specialized skills and lacks standardized blueprints, adding further complexity for microbial firms wanting to scale (GFI, 2023c).

Our findings indicate that most microbial firms adopt a fit-and-conform approach relative to the industry boundary. Many firms are in the pre-scale-up phase, exploring scalable production pathways. As Firm 5 described, they face a "classic valley of death scenario", needing to achieve a scale sufficient to meet investor price-point expectations, yet struggling to secure the investment required to reach that scale. Firm 7 similarly echoed these scaling challenges, rhetorically questioning "am I going to scale the technology before I run out of money?". Staged scaling, as exemplified by Firm 1, seeks to overcome this challenge, going from in-house lab production and successively expanding from a "20 L scale today…to [a] one hundred and one thousand liter fermenter" with CMO support, ultimately aiming to invest in proprietary facilities or partner with established industry players capable of supporting large-scale production. Such collaborations can offer additional benefits, including production expertise, advanced product development capabilities, and access to the established brands of large food processors.

However, we also identified two distinct value delivery approaches characterized by a stretch-and-transform orientation, challenging the industry boundary. First, two firms have pursued alternative production routes by repurposing underutilized facilities from adjacent sectors. For instance, Firm 13 noted that "we are converting shut down breweries into protein production plants", while Firm 4 explained "we are actually at a facility of [a global pharmaceutical company], so [they] had their headquarters [here] way back and then they moved 90 % of this…they have a lot of the capacities there open…still have the infrastructure". These strategies enable firms to bypass traditional food industry collaborations. This approach not only introduces new actors from other sectors, but also leverages existing infrastructure to, as Firm 13 described, "reach a production level with a fraction of CAPEX that other competitors would need". In contrast, another firm secured funding for the development of an in-house production facility capable of producing mycoprotein biomass at scale. However, this effort was ultimately unsuccessful, resulting in the company's move into administration.

Irrespective of how microbial firms chose to navigate the industry boundary, compliance with public laws and regulations set a minimum requirement for market participation, and a potential opportunity to innovate. The legal bounds of business model innovation for microbial firms are examined in the next section.

4.5. Policy

In the EU, firms introducing new ingredients derived from fermentation processes must secure pre-market authorization under the Novel Foods Regulation (GFI, 2023a). Novel food is defined as "food that had not been consumed to a significant degree by humans in the EU before 15 May 1997″ (EU Commission, 2024). This encompasses foods produced through new processes as well as new extracts from existing food sources. Once approved by the European Commission and EU member state representatives, a novel food product can be marketed across all 27 member countries (GFI, 2023a). Authorization under the Novel Foods Regulation is significant as it enables market access across the EU, creating opportunities for large-scale commercialization in the single market. However, the long lead times for securing approval can represent a significant challenge to NTBFs who tend to operate with shorter time horizons than established industry players. This was a recurrent theme during an EU commision workshop on fermentation, where it was recognized that the "novel foods proceedure in the EU can be complicated, lengthy, and costly for SMEs –other regions as the US and Singapore, are much faster" (EU Commission Workshop, 2024). The lengthy approval process, especially within the EU, can therefore challenge the viability of NTBFs innovating products classified as novel foods by delaying market entry. Firm 13 commented on this regulatory landscape more generally, stating that "when you want to start a business in Europe it is like playing soccer with one of your feet tied to your back…there's more regulatory constraints".

Our findings indicate that the regulatory boundary, especially as manifested in the Novel Foods Act, has significantly influenced the business model innovation strategies of microbial firms. Most firms in our sample adopt a fit-and-conform strategy, ensuring that their value propositions comply with extant regulatory approvals through the avoidance of fermentation-derived products classified as novel foods. For instance, Firm 12 highlighted this approach, noting that by focusing on an already approved product for human consumption "it is really just the process that needs approval…which is much easier than approval for a totally new product". Firm 6 showed a similar avoidance for novel foods "I don't want to go into novel food so easily because it makes you farther way from the market…so this is definitely something I'm taking into account…trying to stay as close to the approved ingredients as possible". While this fit-and-conform approach allows firms to advance their fermentation-based products without incurring delays from lengthy regulatory approval processes, it primarily serves as a short-term compliance strategy that enables firms to bring products to market more quickly. However, this approach may also have a limiting effect on innovation by restricting the exploration of a broader range of value propositions. Firm 3 reflected on this, commenting that "we maybe have one thousand different types of mycelia in our lab, that can provide better product functionalities, like taste, how it grows and its texture. It can be color, smell and such things…but many of [the strains] require approval, so we chose to begin with already approved strains…we didn't want to take the risk in the beginning, it [regulatory approval] takes time"

Beyond these more immediate compliance strategies, some firms aim at influencing the regulatory landscape. Several firms combine short-term fit-and-conform strategies with attempts to indirectly stretch-and-transform the policy boundary, viewing potential regulatory change as a long-term business opportunity. These firms actively explore new fungal strains and production processes and align their business models with these new technologies, positioning themselves to benefit from anticipated regulatory changes. For instance, Firm 10 reflected that one of their "innovation routes…is looking out-of-the-box like I said with different strains and the novel food". This suggests that while business model innovation does not directly shape policy, it may serve as a precursor, creating indirect pressures for regulatory change. Another key avenue through which microbial firms influence the policy boundary is through their engagement with associations which lobby for reforms favoring microbial firms. These industry-wide efforts represent a more strategic, long-term approach to shaping the policy boundary to better accommodate fermentation-derived products. For instance, the European Commission Directorate-General Grow Food Team workshop, which brought together over 250 participants with a focus on the microbial industry perspective, captured the need for "more public funding in R&I and in infrastructure" and suggested that "less money should be spent on low TRL research and more money should be aimed at industrial impact". Organizations such as these push for clearer guidelines, streamlined approval processes, and increased recognition of the benefits of fermentation-derived products, amounting to a more direct attempt to stretch-and-transform the policy boundary over time.

Efforts to influence policy and streamline regulatory pathways are closely linked to the broader goal of creating a more sustainable and resource-efficient food system. Policy has a big impact on innovation trajectories by supporting the commercialization of fermentation-derived products. In turn, these innovations can have significant impacts in the ecological dimension, with fermentation technologies offering the potential to move away from linear to more circular and regenerative food production.

4.6. Ecology

When compared with animal-based products, fermentation-derived proteins "reduce emissions, feed more people with fewer resources, reduce pandemic and antibiotic resistance risks, and free up lands and waters around the world for restoration and recovery" (GFI, 2023b). This has the potential to disrupt agricultural value chains by advancing circularity and aligns with a regenerative model of food production, aiming to create closed-loop systems that work in balance with ecological processes. However, microbial firms operate in an agri-food system that is deeply rooted in a linear and extractive relationship between socio-technical and ecological domains. Conventional agriculture relies heavily on extracting resources from the environment, drawing on a range of ecosystem services such as water, land, and nutrients, to produce food. This often leads to significant waste and emissions that are released back into nature without being effectively reused or recycled, thereby burdening natural ecosystems (Baroni et al., 2007). Moreover, animal-based food products, which make up a substantial part of food consumption in many countries, are generally associated with more resource use, waste and emissions than plant-based alternatives. As noted above, the cultural and policy landscapes reflect and reinforce the linear and extractive approach by externalizing the ecological costs associated with food production. While there is growing engagement among actors in the agri-food system to move toward more sustainable modes of production and significant consumer demand for products with lower environmental footprints, these efforts generally focus on incremental improvements within the existing linear framework. They seldom embrace the more radical changes that can result in new business models that can fundamentally alter the ecological impact of the food system.

In contrast, the value propositions of microbial firms go beyond incremental changes, representing entirely new ways to meet the demand for proteins, functional ingredients and complete food products. While all the firms thus stretch-and-transform the ecological boundary, notable variations exist in how this is achieved. Although in the minority, we find that two of the firms rely on a more linear extraction of resources as input substrate for the fermentation process. Firm 1 uses "the edible part of a vegetable crop" as feedstock for its biomass fermentation process, primarily because "the regulatory status makes it easier as it's consumed already in Europe". Firm 6 feeds their lab demonstration with sugar but are "looking into side streams" moving forwards. Despite opting for pragmatic choices at the outset, both firms expressed a strong desire to move towards feedstocks based on circular flows for improved sustainability performance.

Most of the firms in our sample already embrace a more circular production model by valorizing industrial side-streams as input substrates for their fermentation processes. Examples include brewer's yeast, spent grains and vegetable production by-products. Interestingly, several of the firms reflected on the importance of ensuring that variabilities in the side-stream do not impact product quality and consistency. Firm 10, for example, emphasized the importance of maintaining product uniformity, "on Monday the same like on Friday…so consistency and the quality is important". Further, as Firm 9 described, and as was echoed by others, their stretch-and-transform approach aligns with their vision to "decouple food production from limited resources, limited resources being land use…(with) deforestation being a major driver for land use change". Building on this, several of the firms highlighted the appeal of valorizing what are today classified as industrial waste streams, as well as their own production side streams to further improve sustainability performance. For instance, Firm 4 explained that achieving their goal of becoming "fully circular", requires addressing their own side streams, "as you can imagine…these still flow back into the feed industry, so for animal feed…we have side streams as well, and in the future we want to reduce this by basically 100 %". Unsurprisingly, all the firms in our sample emphasize sustainability as a key driver. Some have even reshaped their value propositions and production technologies to enhance sustainability. For instance, Firm 5 acknowledged that their original business model "wasn't going to have both the financial or the environmental impact of why [we] got into this in the first place right?". Similarly, Firm 1 transitioned from B2C plant-based niche-products to B2B fermentation-based ingredients supply, stating that "we think that the impact of [the company] on the industry will be bigger", also targeting a larger positive impact on the environment.

5. Discussion

Our study set out to investigate how NTBFs innovate their business models in a dynamic transitions context. Through an exploratory qualitative case study, drawing on interviews with thirteen microbial firms, we revealed the underlying approaches for business model innovation by relating fit-and-conform and stretch-and-transform strategies to the more or less malleable boundaries of a multi-dimensional BMDS. The result is an elucidating empirical narrative that yields several contributions to the literature.

Incorporating an ecological dimension into the BMDS framework, defined as "the natural resources and ecosystem services, which shape the legitimacy and long-term sustainability of value propositions while enabling their delivery", has led to interesting insights. Most microbial firms not only develop technologies to reduce the environmental impact of food production (e.g., biomass fermentation), but also engage in business model innovation to stretch-and-transform the ecological boundary (e.g., sourcing sustainable inputs for fermentation). However, this innovation is largely limited to capturing and delivering value from waste streams. The focus on food products constrains broader circular economy strategies such as offering products as services or designing for reuse (Bocken et al., 2016). Nevertheless, it is notable that the use of renewable and recyclable materials when setting up production processes, as well as efforts to minimize downstream waste, does not feature more prominently in our findings. This suggests that while firms do adopt stretch-and-transform strategies, they often do so in relatively narrow ways that do not fully embrace circular principles, likely reflecting the resource constraints of NTBFs. However, this must be understood in the broader context of the radical transformation these firms' business models represent. Producing fermentation-derived products from waste streams represents a significant departure from conventional food systems and offers a more resource-efficient and environmentally sustainable approach to food production.

Applying the BMDS framework to NTBFs also showed that the science & technology boundary is more fluid than previously assumed. Earlier applications of the framework have primarily focused on established industries, such as solar photovoltaics and electric vehicles, where this boundary is seen as relatively fixed, or 'hard', in relation to business model innovation (Huijben et al., 2016; Wesseling et al., 2020). More recent work in other emerging niches, such as insects as food and feed (Thomson et al., 2025), has begun to challenge this assumption by showing how business models and technological innovation evolve in tandem. Our findings reinforce and extend this by demonstrating that in the context of biotech NTBFs, the science & technology boundary is more malleable. In some cases, the business model anticipates a future technological state, while in others, technological development drives business model innovation (Baden-Fuller and Haefliger, 2013). As a result, the business model becomes closely intertwined with the technology it seeks to commercialize, suggesting a more fluid science & technology boundary than in more established sectors.

Another key finding concerns the challenges associated with scaling. Scaling is particularly demanding for non-digital, physical enterprises that require production infrastructure (Lubik and Garnsey, 2016; Trimi and Berbegal-Mirabent, 2012), such as the microbial firms investigated in this paper. Yet, rather than emphasizing trade-offs between in-house, contract or partnered-based production, our data highlight the importance of developing value propositions that achieve price parity, or advantage, over conventional alternatives. In our sample, firms adopting a cost-first approach to create price-competitive value propositions appear more capable of forming industry partnerships and achieving scale. Connectedly, a recurring theme in our findings is the irrelevance of a sustainability focus if product costs are prohibitive. Despite a strong commitment to environmental goals, microbial firms' business models prioritize cost efficiency. This reflects a fit-and-conform approach to market expectations, where cost-effectiveness is central to scaling. However, while this approach may improve individual firms' viability, it may limit broader transition outcomes. While scaling is essential to realize the sustainability potential of microbial foods, a narrow focus on cost-efficiency risks overlooking alternative products and processes that, while less aligned with a cost focused market, could offer more substantial long-term benefits. However, niche markets for premium sustainable products, such as organic or locally sourced foods, offer alternative business models. These markets, although smaller, could allow microbial firms to differentiate themselves based on environmental and ethical attributes rather than price alone. By appealing to consumers who prioritize sustainability, these firms can potentially play an important role in shaping consumer preferences and driving broader systemic change.

Our findings also carry implications for policy. Public interventions can help enable the scaling of sustainable microbial innovations as well as encouraging broader experimentation within diverse alternative niches (Kanger et al., 2020). Streamlining regulatory processes for novel foods can lower entry barriers for NTBFs and provide a more realistic and survivable path to commercialization for newly started firms. Further, targeted financial incentives, such as subsidies, tax breaks, and grants, can help to bridge cost gaps and improve price competitiveness, while public investment in fermentation infrastructure can ease the capital burden of scaling. In addition, policies that boost consumer awareness can improve the demand for fermentation-derived products in both niche and mainstream markets.

Looking forward, our study presents several avenues for further research. While the BMDS framework offers a useful lens for analyzing business model innovation in dynamic transitions contexts, its dimensions are not entirely distinct. For instance, the market and cultural dimensions overlap, with societal values, beliefs and norms often aligning closely with user preferences. Clarifying such overlaps could make the framework easier to apply and better support comparative studies. There is also a need to better understand the different boundaries firms face within each BMDS dimension. Our findings suggest that firms in fact face multiple boundaries associated with socio-technical structures at the level of other emerging niches, established regimes and broader landscapes (Geels, 2002; Rip and Kemp, 1998), which also influences whether a fit-and-conform or stretch-and-transform pattern is observed. While establishing sufficient clarity is ultimately the researcher's responsibility, we believe that stronger links between the BMDS framework and the boundaries of the production and consumption systems in focus could prove beneficial. Moreover, given the inherent uncertainties faced by NTBFs operating at the intersection of emerging markets and technologies (Lubik and Garnsey, 2016), often without clear timelines for success (Aldrich and Fiol, 1994), adopting a longitudinal perspective could provide valuable insights into how business models evolve over time. A temporal analysis could reveal how firms navigate the BMDS framework over different stages of development, shedding light on the interactions between firm-level innovation and system-level dynamics. Additionally, comparative case studies in adjacent industries, such as plant-based proteins, could offer further insights into how business models evolve under different technological and market conditions, effectively operating within a different BMDS. Addressing these considerations would help refine and strengthen the framework for future use.

6. Conclusions

The study contributes to sustainability transitions research by extending the BMDS framework to include an ecological dimension and applying it to NTBFs in the microbial food sector. This conceptual extension enables a more holistic view of business model innovation that accounts for a firm's interactions with both socio-technical systems and natural ecosystems, thus aligning with recent efforts to develop a socio-techno-ecological approach to transitions (Ahlborg et al., 2019; Andersson, Lennerfors, et al., 2024; Andersson, Plummer, et al., 2024). While the ecological dimension was not the sole focus of our analysis, its integration highlights the role of circular value delivery practices in expanding firms' ecological boundaries and suggests new directions for analyzing how ecological constraints and opportunities shape business model choices. This perspective is critical when examining innovation in industries and technology fields based on land use and natural resources (Andersen and Wicken, 2021), but it arguably carries general relevance since all forms of production and consumption ultimately depend on the natural environment (Arthur, 2009). Furthermore, our findings show that firms fit-and-conform to market expectations by prioritizing low-cost value propositions. This suggests possible tensions between viable firm-level strategies and systemic transition goals. In addition, the study highlights that technological and business model innovation are deeply interconnected, challenging prior business model design space studies treating them as more distinct. These findings add to a growing literature that integrates firm- and system-level perspectives on sustainability transitions, while opening several promising avenues for future research.

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

During the preparation of this manuscript, the authors used Chat GPT 4o to assist with language refinement and to enhance clarity. All content generated with the help of this tool was reviewed and edited by the authors, who take full responsibility for the final version of this manuscript.

CRediT authorship contribution statement

Linus Thomson: Writing – original draft, Methodology, Conceptualization, Validation, Investigation, Writing – review & editing, Project administration, Formal analysis. **Johnn Andersson:** Writing – review & editing, Project administration, Formal analysis, Writing – original draft, Methodology, Conceptualization, Validation, Investigation. **Niklas Fernqvist:** Writing – review & editing, Validation, Investigation.

Declaration of competing interest

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

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Appendix A: Sample Interview Guide

The interview guide is developed to understand:

- The firm and its business model
- The context which the firm, and its business model, are a part of (the BMDS)
- If, and how, the ecological dimension has impacted the business model (a not yet developed dimension of the BMDS)
- A future perspective of their business model

Introduction by Interviewer/s (5 minutes)

- Personal introduction/s
- Explain the research focus, including intent to publish findings in an academic journal
- Confirm interviewee and firm anonymity - explain that the default is that we keep the names of the interviewees and firms anonymous.
- Explain that prior to publication, we will reach out to the interviewees to validate what is written, ensuring fair and accurate representation of the interviewees and their firms.

Introduction of the interviewee (5 minutes)

1) Please could you tell us about yourself and your role in the firm.
   - *Seek further clarification as points are raised (e.g. start-up/branch experience)*

Understanding the firm and its business model (20 minutes)

2) Could you please give us an overview of the firm, how it started, by whom and how you arrived at where you are today?
   - Explore the business model:
     - Which products and services are being offered, or are planned to be offered?
     - What is it that the firm does/specializes in, to be able to offer these products and services? *E.g., brand management, product development, ingredient manufacture*
     - Do you collaborate with any other actors to make this possible? Do you have any key suppliers?
     - How do you get paid/plan to get paid for the delivery of your products and services? *E.g. subscription model, one off sales*
     - Who are the key customers / types of customers? How do you reach your customers? B2C or B2B? *E.g. sales channels - on line, retailers*
   - Have there been any changes to how you planned your business, and your business model, as the firm developed?

Understanding the BMDS and its impact on the BM (15 minutes)

3) How would you describe the microbial food space that you are operating within?
   - For example, who are the key actors and technologies, how mature is this industry?
4) What are the key challenges and opportunities of operating within this microbial food space?
   - Do you have any examples?
   - *Explore the following points in conversation in response to Q3-Q4:*

- *Policy*
  - e.g., Impact of current and future regulations
  - e.g., Availability of public and private R&D funding
- *Science & Technology*
  - e.g., Availability of knowledge, infrastructure and technologies
- *Industry*
  - e.g., Structure of food/feed/microbial industry and its impact on the design of the business model
- *Culture*
  - e.g., Cultural values and expectations of customers, investors, public authorities and how they have shaped the development of the business model
- *Markets*
  - e.g., Has the value proposition been readily accepted into the market? Is it a product/service that the market is familiar with or is it new? Size or scope of market?
- *Ecological*
  - e.g., How have, if at all, ecological considerations shaped the development of your business model?

A future perspective on the BMDS and their business model (10 minutes)

5) How do you see your firm and its business model developing in the future?
   - Please explain. Do you have any examples?
6) What do you see as the biggest barriers and opportunities for future success in the microbial food space?
   - Please explain. Do you have any examples?

Final check (5 minutes)

7) Is there something which you would like to add as part of the interview?
8) Is there someone else that you think we should talk to as part of our study?

Data availability

The authors do not have permission to share data.

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