Towards sustainable business models in the circular bioeconomy: The case of bio-based fertilizers

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Abstract. Bio-based fertilizers (BBFs) offer a sustainable solution to the environmental and economic challenges of conventional fertilizers by enhancing nutrient recycling and soil health, aligning with EU strategies. Despite the availability of frameworks like the Business Model Canvas (BMC), these models have not been comprehensively applied in the context of BBFs. This paper addresses this gap by using the BMC framework to provide a holistic overview of BBF business models, integrating economic, environmental, and social dimensions. A comprehensive literature review was conducted, focusing on studies examining specific aspects of BBF business models, including value proposition, value creation and delivery, and value capture. The analysis highlights key insights, such as BBFs' potential to recycle waste, and enhance soil health, alongside challenges like nutrient variability and market adoption barriers. These findings support strategies for advancing sustainable circular bioeconomy practices, offering valuable guidance to stakeholders in the fertilizer and agricultural sectors.

Keywords: circular bioeconomy, bio-based fertilizers, sustainable business model, Business Model Canvas

JEL codes: M10, Q13, Q57

1. INTRODUCTION

1.1. Towards sustainable agriculture: From bio-waste to bio-based fertilizers

Agricultural production growth has relied heavily on chemical fertilizers and synthetic pesticides (European Commission, 2019). However, excessive application of essential nutrients like nitrogen (N) and phosphorus (P), combined with inefficient plant absorption, has caused air, soil, and water pollution and has significantly reduced biodiversity in aquatic ecosystems (Juncal et al., 2023;

Yang et al., 2008). Similar to healthcare principles that warn against overuse, agronomy advocates for limited fertilizer application to maintain ecological balance (Pandian et al., 2024). Moreover, fertilizer production relies on finite fossil-based resources, such as natural gas, phosphate rock, and potassium salts, which are depleting (Anlauf, 2023; Cordell et al., 2009). The European agricultural sector, heavily dependent on imports of these essential raw materials, is vulnerable to supply chain disruptions, threatening food security (Smol, 2021; de Ridder et al., 2012). This dependency highlights the fertilizer industry's critical challenge: efficient nutrient recycling (Barquero et al., 2024).

Despite these issues, global chemical fertilizer use increased from 12 million tons in 1961 to over 110 million tons by 2018 (Rodríguez-Espinosa et al., 2023). The European Commission (EC) has targeted a 50% reduction in nutrient losses while maintaining soil fertility (Heyl et al., 2023; European Commission, 2020). The Common Agricultural Policy promotes precision agriculture to improve nutrient efficiency (Álvarez Salas et al., 2024). Additionally, the EU's Farm to Fork (F2F) Strategy, part of the Green Deal, aims to reduce fertilizer use by 20% by 2030, promoting a shift to circular bio-based production processes (European Commission, 2020). Supporting this goal, the 2019 EU Fertilizing Product Regulation (Regulation (EU) 2019/2009), effective since May 2022, mandates circular and sustainable fertilizer systems by integrating organic and waste-derived fertilizers into the market.

The bioeconomy, encompassing sectors reliant on biological resources (Bröring and Vanacker, 2022), along with bio-based fertilizers (BBFs) as sustainable alternatives to synthetic fertilizers, plays a crucial role in advancing a circular economy. A prominent initiative is the Circular Bio-based Europe Joint Undertaking (CBE JU), a public-private partnership between the EU and the Bio-based Europe Joint Undertaking, with a €2 billion budget for 2021-2031 (Donner and De

Vries, 2023). In addition to CBE JU, initiatives such as Horizon Europe, the European Circular Bioeconomy Fund (ECBF), the European Investment Bank (EIB), and national research and innovation programs provide critical financial and strategic support for advancing BBFs development and commercialization. BBFs offer sustainable alternatives by recycling bio-waste, improving nutrient use efficiency, and reducing environmental impacts compared to traditional fertilizers (Álvarez Salas et al., 2024). Although no standardized definition exists, efforts at European level aim to establish one. BBFs are generally described as materials or products sourced from biomaterials (such as plant, animal, or microbial sources, often including waste, residues or by-products from agriculture, industry or society) containing bioavailable nutrients fit for use as crop fertilizers (Arzeni et al., 2024). Examples of BBFs include compost-based fertilizers, manure-derived fertilizers, biochar, and nutrient-rich products from anaerobic digestion, such as digestate or struvite (Kurniawati et al., 2023; Chojnacka et al., 2020).

1.2. The sustainable business model for bio-based fertilizers

Academic research on business models, stemming from foundational theories like Drucker's (1985), defines a business model as a structure detailing how a company creates, delivers, and captures value (Teece, 2018; Osterwalder et al., 2005). The Business Model Canvas (BMC), developed by Osterwalder and Pigneur (2010), remains the most widely adopted template, comprising nine elements. Central to this model is the value proposition, which captures the unique benefits a company offers to its customers. The market component (customer segments, channels, and customer relationships) addresses external elements critical for reaching customers and determining product desirability. The infrastructure component, which includes key activities, resources, and partnerships, defines operational feasibility, while the financial component (cost structure and revenue streams) ensures economic viability.

The concept of "bioeconomy," introduced by Christian Patermann, emphasizes using renewable biological resources to meet societal needs with reduced environmental impact (Lange, 2022). Transitioning to a bioeconomy requires substantial changes to existing business models (Reim et al., 2019). Although the literature on bioeconomy business models often overlaps with circular economy discussions, there are distinctions (Donner and De Vries, 2023). The bioeconomy emphasizes replacing fossil resources with renewables, while the circular economy focuses on cascading resource use (Bröring and Vanacker, 2022; Venkatesh, 2022).

Sustainable business models communicate value propositions that capture economic value while maintaining or regenerating environmental, social, and economic capital (Schaltegger et al., 2016), as outlined in the Triple Layered Business Model Canvas (TLBMC) by Joyce and Paquin (2016). The TLBMC extends Osterwalder and Pigneur's BMC by adding social and environmental layers, providing a holistic view of value creation. While bioeconomy models have sustainability potential, they are not inherently sustainable (De Keyser and Mathijs, 2023). Challenges such as resource use, environmental impact, and social equity must be addressed for these models to realize their sustainability potential. When sustainability is embedded in bioeconomy goals, it can foster positive social and environmental impacts and stimulate economic growth through innovation, particularly in agriculture and food production sectors (Pfau et al., 2014).

Research on sustainable business models, particularly within the agrifood sector, is still sparse (Mili and Loukil, 2023; Bröring and Vanacker, 2022; Donner and de Vries, 2021; Salvador et al., 2023; Reim et al., 2019). While interest in the BMC has been growing, its application within the agrifood sector is still limited. Only a few studies (e.g., Mili and Loukil, 2023; Basile, 2021; Partalidou et al., 2018) have applied this model within this specific context, and none directly focus on BBFs. The existing literature does touch upon various aspects of BBF business models (e.g., Álvarez Salas et al., 2024; Garmendia-Lemus et al., 2024; Kvakkestad et al., 2023; Moshkin et al., 2023; Cazador et al., 2022; Chojnacka et al., 2020; Egan et al., 2022; Smol, 2021; Tur-Cardona et al., 2018). However, to the best of the authors' knowledge, no study offers a comprehensive BMC incorporating sustainability-oriented value propositions specific to BBFs. This study contributes to the existing literature by applying the BMC framework to BBFs, offering a comprehensive analysis of their commercialization pathways. Although not all elements of the BMC for BBFs are addressed in current literature, broader bioeconomy studies and research on diverse business model components provide valuable insights to guide the development of sustainable BBF business models. Customer-related components, however, remain relatively underexplored (Hatvani et al., 2022). Conventional business model frameworks often underemphasize sustainability (França et al., 2017). This paper seeks to address this by examining key elements for sustainable BBF business models.

2. METHODOLOGY

This study employs a qualitative approach, using a literature review as the foundation for analyzing sustainable business models within the circular bioeconomy. The BMC framework was applied as a conceptual framework for this study to evaluate and categorize key components of sustainable business models, with a literature review serving as the primary method to populate and elaborate on its components. While the TLBMC provides a framework to deepen insights into sustainability-specific dimensions, this study uses the BMC for its clear structure and broad applicability, serving as a practical starting point for analyzing BBF commercialization.

The literature review was conducted using three primary academic databases: Scopus, Web of Science, and Google Scholar. To ensure a comprehensive search, relevant keywords were used, including "circular bioeconomy," "bio-based fertilizers," "sustainable business model," "Business Model Canvas," "recycling-derived fertilizers (RDFs)," "waste-based fertilizers," and "bio-based fertilizer products (BFPs)." Boolean operators such as *AND* and *OR* were applied to refine and expand the search results. The search primarily targeted peer-reviewed articles, book chapters, and reports published in English, with the majority dating from 2013 to 2024 to reflect recent advancements and industry developments. Earlier studies were included when particularly relevant to the research objectives. The selection process followed a systematic three-step approach. First, titles and abstracts were screened to assess relevance to BBF business models and the BMC framework. Next, studies passing the initial screening underwent a full-text review to ensure alignment with the research objectives. Finally, studies providing insights into at least one of the BMC components—value proposition, value creation and delivery, or value capture—were included for analysis. Only high-quality sources, such as peer-reviewed journals and academic publications, were considered to ensure reliability and rigor. To enhance the reliability and robustness of the concepts presented, this study incorporates insights from real-world business models drawn from the B-FERST project, which focuses on integrating bio-waste valorization into fertilizer production, offering practical examples of sustainable business models in the bioeconomy. Data extraction was performed manually, with insights mapped to the nine building blocks of the BMC framework: value proposition, customer segments, channels, customer relationships, key activities, key resources, key partners, revenue streams, and cost structure. These elements were further grouped into three main BMC segments: value proposition, value creation and delivery (market and infrastructure), and value capture (financial aspects) (Vehmas et al., 2024; Schaltegger et al., 2016; Richardson, 2008). The extracted data were synthesized systematically to identify common themes, opportunities, and challenges associated with BBF commercialization. To guarantee the quality of the included studies, criteria such as source credibility, methodological rigor, and relevance to BBF business models were applied during the review process. Studies contributing to BBF commercialization, circular bioeconomy frameworks, and sustainability were prioritized, while those lacking sufficient methodological detail or academic rigor were excluded.

3. RESULTS AND DISCUSSION

The key components of the BMC applied to BBFs are summarized in Table 1, providing a structured framework for analyzing their commercialization pathways. This table serves as a foundation for the following discussion, outlining the critical aspects of value proposition, value creation and delivery, and value capture.

Table 1. Business Model Canvas for Bio-Based Fertilizers: Key components and insights

<table>
<tr>
<td rowspan="2">Key Partners
Suppliers: Farmers, waste management companies, and recycling firms that provide essential feedstocks for BBF production.
Collaborators: Researchers, agricultural extension services, policymakers, NGOs, and media organizations driving innovation, knowledge dissemination, and regulatory support.
Logistics Partners: Transport and distribution partners ensuring efficient supply chain operations and seamless delivery of raw materials and finished products.</td>
<td>Key Activities
Production: Nutrient recovery and fertilizer production.
Logistics: Biomass collection, transport, storage, and quality control.
R&D: Process optimization, scaling technologies, ensuring compatibility with existing infrastructure, and driving innovation in sustainable production.</td>
<td rowspan="2">Value Proposition
Economic Value: Comparable or superior plant growth and yields using recovered nutrients; Product-Service Systems.
Environmental Value: Reduce reliance on fossil-based resources, recycle biowaste, cut GHG emissions and nutrient leaching, enhance soil health, and promote sustainable nutrient cycling.
Social Value: Support local job creation, stimulate rural economies, foster community engagement, ensure fair competition, and improve health and safety through hygienized BBFs.</td>
<td>Customer Relationships
Co-Creation: Collaborate with farmers and researchers to improve products through shared expertise and feedback.
Peer Influence: Leverage farmer networks to share knowledge and promote sustainable practices.
Engagement: Build trust via education, and online communities.</td>
<td rowspan="2">Customer Segments
Primary Users: Farmers and nurserymen seeking sustainable alternatives to conventional fertilizers.
Target Segments: Environmentally conscious and premium customers willing to pay for certified, eco-friendly products that align with their values.
Adoption Opportunities: Eco-labelling, certification and branding strategies to build trust and market appeal. Address knowledge gaps and build confidence through education, technical support and demonstration trials to showcase BBFs effectiveness.</td>
</tr>
<tr>
<td>Key Resources
Tangible Resources: Biomass, biostimulants, biodegradable coatings.
Intangible Resources: Research facilities, advanced technologies, and expertise.
Human Resources: Skilled workforce and collaborative teams.</td>
<td>Channels
Traditional: Print media, agricultural fairs, posters, and field demonstrations.
Digital: Social media, webinars, agricultural apps, and video content.
Support: Efficient logistics, proper product handling, and after-sales technical assistance.</td>
</tr>
<tr>
<td colspan="2">Cost Structure
Major Costs: Biomass sourcing, logistics, quality control, regulatory compliance, and navigating lengthy approval processes.
Key Investments: Technology development, advanced nutrient recovery methods, strategic marketing, and premium packaging to differentiate BBFs.
Cost Optimization: Leverage economies of scale, high-quality concentrated biobased materials, and innovative recovery technologies to streamline production and reduce costs.</td>
<td colspan="3">Revenue Streams
Primary Revenue Streams: Fertilizer sales, soil testing, consulting, distribution, specialty products, and licensing.
Pricing Strategies: Competitive pricing to drive market adoption and maximize share, or premium pricing to reflect quality, environmental benefits, and customization.
Additional Revenue Streams: Value-added services (e.g., customer support and loyalty programs), subsidies, and EU funding to support R&D and commercialization efforts.</td>
</tr>
</table>

3.1. Value proposition in sustainable business models for BBFs

A value proposition encompasses the benefits a company offers its customers, including not only product/service features that drive sales but also environmental and social values (Hatvani et al., 2022). Studies indicate that plant growth and yield potentials achieved with recovered nutrients are comparable to or even surpass those of conventional fertilizers (Barquero et al., 2024). Integrating services into business models is vital for the bioeconomy, enhancing value creation and promoting bio-based solutions. Product-Service Systems (PSS) combine products with complementary services, tailored to meet customer needs (Bröring and Vanacker, 2022). In BBF context, service offerings could include nutrient management consulting, application services, monitoring and analysis, product customization, and logistics solutions.

The environmental value of BBFs lies in their ability to address the ecological challenges posed by conventional fertilizers. This value can be assessed using the Life Cycle Assessment (LCA) approach, which evaluates a product's environmental impact through indicators such as CO_2 emissions, energy use, resource depletion, and water consumption. By recycling bio-waste, BBFs contribute to nutrient recovery, reduce dependence on finite fossil-based resources, and promote circularity in agriculture. Furthermore, BBFs help minimize greenhouse gas (GHG) emissions, reduce nutrient leaching, and enhance soil health and quality. However, BBFs also present environmental challenges that must be addressed to maximize their potential. Nutrient variability in BBFs can impact their agronomic performance, often leading farmers to favor synthetic fertilizers due to their predictability and immediate results (Bonnichsen et al., 2020). BBFs also require mineralization for nutrients to become available to plants (Leytem et al., 2024). This process may not always match crop growth cycles, leading to inefficient uptake, nitrate leaching, eutrophication, and potential acidification. Additionally, BBFs derived from waste (e.g., manure or sewage sludge) may contain pathogens or heavy metals, posing health and ecological risks if not properly treated (Kurniawati et al., 2023). Effective mitigation strategies are essential to manage these risks (Álvarez Salas et al., 2024).

BBFs also create significant social values related to stakeholder management approach, focusing on indicators such as community engagement, labor conditions, health and safety, and fair competition (Vidaurre et al., 2020; Rafiaani et al., 2018; Joyce and Paquin, 2016). By utilizing local bio-waste as feedstock, BBF production supports local job creation and stimulates rural economies (FAO, 2018). The involvement of local stakeholders, including farmers and waste processors, fosters community engagement and strengthens local value chains. In terms of health and safety, hygienization-focused BBFs mitigate health risks related to salt and heavy metal accumulation from synthetic fertilizers, which can be absorbed by plants (Kurniawati et al., 2023; Smol, 2021). BBFs further promote fair competition by offering sustainable alternatives to synthetic fertilizers, empowering farmers to adopt environmentally friendly practices.

3.2. Value creation and delivery in sustainable business models for BBFs

3.2.1. Market

Customers segments

Market segmentation divides the market into distinct groups with shared needs, enabling targeted marketing strategies. Stimulating demand for BBFs requires a deep understanding of behavior influenced by values, ethics, self-interest, product features, and policies. This complexity demands an interdisciplinary approach involving psychology, economics, and sociology (Nejadrezaei et al., 2024). While farmers are primary BBF users, other groups, like nurserymen, also show interest in adopting waste-based fertilizers, supporting the circular economy (Smol, 2021). Key product attributes influencing BBF adoption among farmers include nutrient content, high organic matter, cost, and ease of application (Kvakkestad et al., 2023; Egan et al., 2022; Tur-Cardona et al., 2018). Generally, BBFs must offer comparable properties to mineral fertilizers at a competitive price.

As sustainable practices gain momentum, BBFs are becoming more desirable, especially among environmentally conscious farmers seeking alternatives to mineral fertilizers (Tur-Cardona et al., 2018). However, a significant barrier is public knowledge and confidence, which can be addressed through effective education and communication on the benefits of bio-economy products (Bröring and Vanacker, 2022; Reim et al., 2019). Convincing consumers of BBF advantages remains challenging, as many farmers prefer synthetic fertilizers for their quick results, despite the availability of eco-friendly alternatives at similar prices (Ruth et al., 2020). Companies struggle to measure and communicate sustainability due to limited data and tools (Bröring and Vanacker, 2022). Field trial data on nitrogen release from BBFs could significantly enhance adoption by providing farmers with evidence of their performance and reliability (Kvakkestad et al., 2023).

Research by Morgan et al. (2015) highlights that anticipated financial gains and self-efficacy—farmers' belief in their ability to achieve desired outcomes—are key drivers for adopting Low-Emission Agricultural Practices (LEAP). This insight is highly relevant for BBFs, as improving farmers' self-efficacy through targeted educational programs, technical support, and demonstration trials could encourage their adoption. Morgan et al.'s study identifies four farmer categories—Non-Green Dismissive, Uncommitted, Green Adopters, and Profit-Driven Adopters—each with distinct attitudes towards climate change, environmental values, time orientation, place attachment, and knowledge self-efficacy. Tailored engagement strategies, such as showcasing the economic and environmental benefits of BBFs to Profit-Driven Adopters or emphasizing sustainability to Green Adopters, could help overcome resistance in different farmer groups. Similarly, Gazdecki et al.

(2021) categorize consumers by their sustainability approach into Doers, Conscious, and Reluctant groups. These categories can be linked to BBF adoption by targeting Doers and Conscious consumers—who are more inclined to adopt sustainable alternatives—through eco-labeling, certification, and branding strategies that emphasize BBFs' environmental value. Addressing the concerns of Reluctant consumers through education and communication campaigns could further strengthen market adoption.

Targeting "premium" segments willing to pay more for environmentally and socially valuable products is essential (Reim et al., 2019). Studies identify a "green premium" where consumers pay more for bio-based products, and a "certified green premium," where willingness to pay (WTP) increases for certified bio-based options (Morone et al., 2021). Standards, certifications, and eco-labeling could improve BBF market penetration by verifying sustainability, supporting green purchasing, and reinforcing consumer trust (Reim et al., 2019; Yenipazarli, 2015). Branding also affects BBF acceptance, as terms like "biosolids" over "treated sewage sludge" can positively shape consumer perceptions (Álvarez Salas et al., 2024).

Channels

Market channels describe the pathways through which a company delivers its value proposition to customers, yet they are relatively understudied in the bioeconomy context (Reim et al., 2018; Coughlan, 2006). Channels can be direct, like company websites or stores, or indirect, such as through retailers or distributors, and they comprise five phases: awareness, evaluation, purchase, delivery, and after-sales support (Osterwalder and Pigneur, 2010). The shift from traditional media to digital platforms has redefined how sustainable agricultural practices are promoted. A comprehensive channel strategy for bioeconomy products should incorporate both traditional and digital media to maximize reach. For farmers with limited digital access, traditional methods like print, radio, agricultural fairs, posters, conferences, and field demonstrations remain effective. Demonstrations, in particular, allow farmers to engage firsthand with new technologies and practices (Sutherland and Marchand, 2021). Digital marketing, meanwhile, can reach a broader audience via social media, influencer partnerships, email campaigns, webinars, and online advertising. Additional tools include agricultural apps and video content, which provide interactive and visual resources ideal for conveying complex information to farmers (Bentley et al., 2019). Digital training programs that build on existing farmer knowledge and practices are crucial for fostering adoption. These programs facilitate collaboration and knowledge co-creation by integrating traditional, indigenous, and scientific expertise, along with the expertise of farmers (Maurel et al., 2022).

Effective channel management also involves ensuring the timely delivery, proper handling, and optimal storage of products to maintain quality (Remondino and Zanin, 2022; Behzadi et al., 2017; Routroy and Behera, 2017). Efficient logistics and storage are necessary to handle the diverse and bulky bio-based materials, facilitating smooth operations (Donner et al., 2021). After-sales support, including technical assistance and application guidance, is essential to build trust and loyalty, encouraging repeat purchases (Rebello et al., 2021). Training for distributors and retailers is also vital, equipping them to effectively promote and sell BBFs, thus supporting wider adoption among farmers.

Customer Relationships

Customer relationships outline how a company establishes and maintains connections with specific segments to drive customer acquisition, retention, and sales growth. Many consumers are willing to pay a premium for environmentally sustainable, organic, chemical-free, and locally sourced products. Companies should identify these “bioeconomy customers” and tailor their offerings accordingly (Hatvani et al., 2022). Consumers play multiple roles in advancing a sustainable circular bioeconomy (Lang et al., 2023). As buyers they influence the market by selecting fertilizers, encouraging BBF producers to adapt products to meet customer demands; as lobbyists and influencers, they shape public perception; as partners they contribute to developing standards for BBF usage; and as co-creators they actively participate in value creation, providing feedback and ideas for product improvements. Farmers are increasingly recognized as vital co-creators in developing sustainable agricultural practices and innovations. Their local knowledge and experience make them essential in designing practical solutions. Researchers can also be involved in the co-creation process, identifying gaps that farmers may not have the resources or expertise to address (Ruth et al., 2020).

Effective customer relationship models require integrating information and communication technology (ICT) to educate farmers on the benefits of BBFs through high-quality content and examples of successful applications. Influencers can also promote sustainable practices by sharing trusted recommendations and educating farmers (Vilkaite-Vaitone, 2024). However, research shows that "peer farmers" are the most influential information source, as farmers often learn from each other through conversations and by observing practices (e.g., roadside farming) (Sutherland and Marchand, 2021). Peer influence, or the impact of social interactions within a group on individual behavior, is significant in shaping farmers' sustainable behavior (Garmendia-Lemus et al., 2024; Niu et al., 2022; Tran-Nam and Tiet, 2022; Bell et al., 2018). Translating traditional customer relationships into the virtual marketplace by establishing and maintaining online communities allows farmers to connect and share knowledge (Farquhar and Rowley, 2006). These communities, a key form of customer relationship alongside personal assistance, dedicated personal assistance, self-service, automated services, and co-creation, also help companies better understand their customers (Osterwalder and Pigneur, 2010).

3.2.2. Infrastructure

Key activities

Key activities encompass essential tasks a business must execute to create, deliver, and sustain value, generate revenue, and achieve its goals. In BBF production, key activities include raw material collection, nutrient recovery, and fertiliser production (granulation stage, and addition of non-microbial plant biostimulant (NMPB) or microbial plant biostimulant (MPB), with the requirement of a coating stage when the biostimulant is MPB) (Cazador et al., 2022; B-FERST Advanced Technology Brochure, 2024). Biostimulants improve nutrient efficiency, tolerance to abiotic stress, and crop quality traits, independent of their nutrient content (du Jardin, 2015). In the circular bioeconomy, particularly BBF production, core activities center on value recovery from waste (waste valorization), converting organic waste into BBFs while maintaining sustainability and resource efficiency. Production relies on secondary bio-based raw materials obtained through methods like composting, anaerobic digestion, and fermentation. Efficient logistics, storage, and quality control are essential for reusing byproducts and ensuring sufficient biomass supply (Reim et al., 2018). Logistics and supply chain models for bio-based products are complex due to the seasonal variability, dispersed distribution, and quality inconsistency of biomass sources. Challenges include biomass deterioration, diverse conversion technologies, and interdependencies among logistics operations (Stellingwerf et al., 2022). Resource volumes, particularly feedstocks from agriculture, can vary significantly, posing a challenge for markets like chemicals that are not typically exposed to such fluctuations (Hatvani et al., 2022). Collection across vast regions with varying quantities necessitates logistical adjustments and strategic planning (Bröring and

Vanacker, 2022; Donner et al., 2021). Furthermore, nutrient recovery technologies in BBF production must address the inherent variability in product qualities, as BBFs need to meet diverse agronomic requirements and cater to a wide range of application contexts. This variability highlights the importance of technological flexibility and adaptability in production processes to ensure consistency and efficacy across different products. Future fertilizer plants must accommodate multiple biomass feedstocks using either single or a combination of integrated processes. Recycling and waste utilization require careful planning regarding collection, storage, transport, and pretreatment, depending on biomass volume and location (Cazador et al., 2022).

Ongoing R&D is crucial for cost-effective and high-quality production. Optimizing BBF production processes ensures efficiency, adaptability, and minimal environmental impact. In the bioeconomy—a sector characterized by high innovation and intensive research—advancements in new product applications, sidestream uses, and innovations toward bio-based and renewable resources play a critical role (Salvador et al., 2023). Scaling up newly developed technological solutions presents significant challenges. New technologies must be compatible with existing fossil-based infrastructure to ensure value creation. Additionally, navigating complex intellectual property issues, which can be costly and time-consuming, is essential for technology development (Bröring and Vanacker, 2022). Transitioning to a bioeconomy also involves internal transformation, requiring a cultural shift within established companies. Ongoing innovation and business model evaluation are critical for success (Reim et al., 2019).

Key resources

The key resources block identifies essential assets for a business model's success, encompassing tangible (e.g., financial, physical), intangible (e.g., technology, reputation), and human resources (e.g., skills, expertise) (Näyhä, 2020). The European Union relies heavily on externally sourced, non-renewable raw materials for fertilizer production, with natural gas as the primary energy source (B-Ferst Advanced Technology Brochure, 2024). Fertilizer production is highly energy-intensive, relying on fossil fuels (such as the Haber–Bosch process for nitrogen fertilizers) or fossil ore deposits (such as phosphate rock) (Chojnacka et al., 2020). Phosphate rock needed for production of phosphorus-based fertilizers is a finite and irreplaceable resource, concentrated in a few countries worldwide. Inefficient phosphorus use has pushed it beyond the planet's safe limits, and continued reliance on primary phosphorus resources threatens agricultural sustainability (Magaya et al., 2024). This underscores the urgent need for nutrient recovery from alternative sources.

Wastes, especially biomass, offer a large reservoir of materials that can be converted into fertilizers through various technologies. High-potential bio-wastes for BBF production include agricultural waste, food waste, sewage sludge, and plant residues (Chojnacka et al., 2019; 2020). Agricultural by-products like crop residues, plant trimmings and compost provide sources of essential nutrients. Animal by-products, such as manure and offal, and agri-food industry waste (e.g., fruit and vegetable peels, pulp, seeds) also serve as valuable inputs. Wastewater treatment plant (WWTP) sewage sludge, or the organic material left after wastewater treatment processes, such as ashes and struvite as a source of P and K, is another nutrient source. Factors such as quality, regulation, processing feasibility, logistics, product stability, economic feasibility and carbon footprint influence the viability of these biowastes (Cazador et al., 2022).

Bioeconomy business models encounter challenges with biomass quality and availability. The unsuitability or seasonality of raw materials, along with inadequate infrastructure and capacity, can make biomass supply unreliable, disrupting the value generation process. Furthermore, various industries compete for the same biomass resources. The heterogeneity of these raw materials, particularly when using harvest residues, affects the consistency and quality of the final product (Bröring and Vanacker, 2022). Biostimulants, which enhance plant growth and soil health, are key resources in BBF production (Soltaniband et al., 2022). These include both microbial and non-microbial biostimulants. Biodegradable biopolymer coatings can be used to guarantee the performance of certain biostimulants and enhance the performance of BBFs, ensuring controlled nutrient release and increased agronomic efficiency (Cazador et al., 2022; B-FERST Advanced Technology Brochure, 2024).

Intangible and human resources play a vital role in the shift toward a circular bioeconomy. An innovative, adaptable, motivating organizational culture driven by "power people" and non-hierarchical leadership is essential. Communication, marketing skills, and team-driven innovations supported by diverse expertise are also critical (Näyhä, 2020). Many organizations struggle with implementing new business models due to the dominance of established frameworks and a lack of absorptive capacity to acquire new knowledge and skills that may relate to distant sectors. Additionally, business models requiring new skills face obstacles such as skilled workforce shortages or limited research facility access (Bröring and Vanacker, 2022). Advanced bio-based, product-oriented technologies are frequently required to facilitate new and complex conversion processes (Donner et al., 2021). Laboratories are also considered as a key resource or a key partnership, since bioeconomy is a highly innovative and research-intensive sector. Laboratories and pilot facilities, essential in the highly innovative and research-intensive bioeconomy sector, are key resources or partnerships for evaluating and scaling diverse nutrient recovery methods to produce high-quality BBFs tailored to varied market demands (Hatvani et al., 2022).

Key partners

The key partnerships block details the network of suppliers and collaborators essential for effective business operations. Partnerships allow companies to optimize operations, reduce risks, and access external resources and capabilities (Osterwalder and Pigneur, 2010). Unlike traditional models focused on shareholders and suppliers, sustainable business models broaden the partnership scope to include stakeholders who add economic, environmental, and social value. The bioeconomy demands high levels of collaboration, with value chains requiring alignment and proactive coordination among diverse stakeholders (Bröring and Vanacker, 2022). The Quintuple Helix Approach provides a framework for understanding this collaboration by incorporating five key sectors: economic actors, educational and research institutions, policymakers, civil society, and the natural environment (Hatvani et al., 2022). Key stakeholders in the BBF market include livestock and crop farmers, waste management firms, recycling fertilizer companies, garden owners, horticultural producers, governments, NGOs, investors, and scientists, all of whom contribute to raw material supply, technological development, and BBF commercialization (Álvarez Salas et al., 2024; De Keyser and Mathijs, 2023).

Securing a reliable biomass supply and managing logistics are vital for bio-based companies, often requiring partnerships across previously unconnected sectors, such as chemical companies and small-scale farmers. Primary producers are central to bioeconomy value chains, making collaboration between the agricultural and fertilizer sectors essential for developing sustainable management practices (Cazador et al., 2022). Strong relationships with farmers, supported by secure payments, timely transport, and financial support for infrastructure, are crucial for success (Hatvani et al., 2022). Engaging and benefiting biomass producers not only supports the supply chain but is also key to achieving social sustainability in the bioeconomy (Lange et al., 2021).

Farmers' influence on BBF supply and demand varies; livestock farmers are incentivized to use excess manure, while crop farmers hold more power, selectively accepting or rejecting recycled products based on their preferences (Álvarez Salas et al., 2024).

Transportation and logistics partners maintain a smooth supply chain, ensuring the delivery of raw materials to production facilities and fertilizers to distributors and retailers. Research institutions play a crucial role by collaborating on scientific studies and field research to foster trust and promote new solutions (Moshkin et al., 2023). Agricultural extension services are vital for supporting farmers in adopting BBFs and ensuring proper application, maximizing their value (Kvakkestad et al., 2023). Policymakers establish regulatory frameworks for BBF production and marketing, ensuring safety and environmental standards compliance (Ruth et al., 2020). Media and NGOs play a significant role in shaping consumer perceptions. Although farmers may be open to using recycled nutrients, skepticism from consumers and the food industry can hinder broader adoption. Educating consumers on the environmental benefits of BBFs is therefore essential to increase acceptance (Álvarez Salas et al., 2024).

3.3. Value capture in sustainable business models for BBFs

3.3.1. Finance

Revenue Streams

The revenue stream block defines cash flows from each customer segment, essential for profitability (Osterwalder and Pigneur, 2010). Primary revenue streams in the fertilizer industry include fertilizer sales, soil testing, agricultural consulting, distribution, specialty fertilizers, and licensing. For BBFs, revenue relies on pricing strategies and competitive positioning compared to mineral fertilizers, shaped by market demand, product availability, logistics, regulatory conditions, and regional fertilization practices (Álvarez Salas et al., 2024). Price reflects product quality and brand positioning, and must match customer expectations and willingness to pay. To facilitate market adoption and maximize market share, BBFs must be competitively priced. Research suggests pricing BBFs below mineral fertilizers to attract farmers; Tur-Cardona et al. (2018) recommend pricing BBFs at approximately 65% of the cost of mineral fertilizers. Similarly, Bonnichsen et al. (2020) found that farmers would prefer a price reduction of up to 50% compared to current mineral fertilizers. Moshkin et al. (2023), however, found that significant price reductions might primarily be needed for rapid market uptake rather than overall revenue maximization. Alternatively, pricing BBFs at levels similar to mineral fertilizers could maximize revenue even if initial market penetration is slower, provided marketing strategies effectively address customers' willingness to pay. Premium pricing can be an effective approach for bio-based products, especially when highlighting their environmental value, such as reducing reliance on fossil fuels. By positioning waste recovery as a value-added service and reducing production costs through waste inputs, BBFs can justify premium pricing due to their environmental benefits (Salvador et al., 2023). Market data indicate that while BBFs currently contribute a smaller share of global fertilizer revenue compared to mineral fertilizers, their market share is expected to grow steadily as demand for sustainable agricultural practices increases (Joshi and Gauraha, 2022). In 2023, the global biofertilizers market was valued at approximately USD 2.31 billion and is projected to reach USD 4.77 billion by 2032, reflecting a compound annual growth rate (CAGR) of 8.5% (Global Market Insights, 2024). In contrast, the overall global fertilizer market, valued at USD 202.20 billion in 2023, is projected to reach around USD 276.92 billion by 2034, with a CAGR of 2.9% from 2024 to 2034 (Precedence Research, 2024). Additionally, environmentally conscious consumers are willing to pay a higher but competitive price if the products not only deliver similar functionality but also address their unique demands and preferences (Hatvani et al., 2022).

Beyond fertilizer sales, additional revenue streams can be derived from value-added services, such as customer support, loyalty programs, and product optimization services. Subsidies can support revenue, but they should underscore long-term benefits, proving bioeconomy products' profitability beyond public funding reliance (Reim et al., 2018). Effective use of subsidies and taxes should reflect the socio-economic and environmental advantages not captured in market pricing. Larger companies often integrate bio-based products into their broader product range, enabling them to leverage internal financing from other profitable business areas. These firms also benefit from EU funds during the early development stages, supporting essential R&D efforts needed for future industrial-scale investments (COWI, Bio-Based World News and Ecologic Institute, 2019).

Cost Structure

To maximize growth and profitability, it is essential to understand cost structures, including both fixed and variable costs. Companies may adopt cost-driven models focused on efficiency or value-driven models that prioritize value creation and high-quality products, even at higher costs. In the bioeconomy, production costs and market feasibility are influenced by several factors, primarily the cost of biomass or feedstock, which must be procured competitively amid competition from other industries. Maintaining quality control and regulatory compliance also challenges BBFs' cost competitiveness with conventional fertilizers, highlighting the need for industry standardization. A major challenge for new bioeconomy business models is the high opportunity cost of substantial initial investments in technology development, with operations often remaining costly due to low production volumes and competition for limited resources (Reim et al., 2019). Many bio-based products lack economies of scale, limiting their competitiveness with fossil-based alternatives and slowing return on investment (Bröring and Vanacker, 2022).

The cost structure of BBFs varies significantly based on the technologies employed, such as composting, thermal processing, nutrient recovery, and advanced coating technologies. Each technology presents unique cost drivers, including energy use, material requirements, and regulatory compliance. Sourcing large quantities of bio-based materials from diverse locations introduces logistical challenges, complicating supply chains and driving up costs, particularly when production rates at specific sites are limited (e.g., struvite) (Bröring and Vanacker, 2022). Additionally, navigating varied European safety and logistics regulations increases operational expenses, impacting overall economic feasibility. The commercialization of BBFs entails a lengthy approval process, requiring extensive scientific data collection that adds to operational costs (Giuliani, 2023). Technology development must be complemented by strategic marketing, public relations, and specialized sales to emphasize product benefits, with marketing costs often exceeding development expenses but frequently overlooked in cost analyses (Hatvani et al., 2022). Packaging costs are also significant, especially when designing premium packaging to differentiate BBFs from conventional fertilizers. On a positive note, efficient production strategies can create economies of scale, reducing per-unit costs and boosting profitability. Using high-quality, concentrated biobased materials can streamline production processes, potentially minimizing costs associated with quality control and material waste (Cazador et al., 2022). Currently, phosphorus recovery is expensive and energy-intensive, involving high-temperature processes and costly reagents (Giuliani, 2023). Technological innovation, especially in developing cost-effective nutrient recovery methods, such as for phosphorus, can also optimize costs. By optimizing production and logistics, companies can reduce costs, enhance profitability, and support competitive pricing.

4. CONCLUSIONS

This paper addresses the research gap on sustainable business models for BBFs by applying the BMC framework to provide a comprehensive overview of key elements and considerations related to BBF business models, integrating economic, environmental, and social dimensions. It highlights the significant environmental impact of conventional chemical fertilizers and the need for sustainable alternatives, as underscored by EU strategies like Farm to Fork and the EU Fertilizing Product Regulation. BBFs offer potential solutions through nutrient recycling and soil health improvement, but a transition to bioeconomy requires substantial business model transformation, with sustainability as a core objective.

The BMC framework facilitates a structured analysis of value proposition, value creation and delivery, and value capture specific to BBFs (Table 1). The value proposition of BBFs combines economic, environmental, and social benefits. BBFs support comparable or superior plant growth to conventional fertilizers while integrating services like nutrient management and logistics to enhance adoption. Environmentally, BBFs reduce reliance on fossil-based resources, recycle bio-waste, lower GHG emissions, and improve soil health, addressing ecological challenges in agriculture. Socially, BBFs foster local job creation, stimulate rural economies, and enhance health and safety through hygienization processes. However, challenges such as nutrient variability, timing of nutrient availability, and potential health risks require mitigation strategies to maximize their potential as sustainable fertilizer alternatives.

Market blocks, as critical components of value creation and delivery, play a pivotal role in driving the adoption of BBFs. Market adoption requires understanding behavioral drivers, including financial motivations, self-efficacy, attitudes toward climate change, and the key product attributes like nutrient content, organic matter, cost, and ease of application. Targeted marketing, certification, eco-labeling, and branding are essential for building trust, particularly among environmentally aware consumers. Effective channel management, combining traditional and digital media, training programs based on farmers' existing knowledge and practices, and tailored after-sales support are key to enhancing product awareness, market adoption and customer loyalty. Peer influence and online communities also play crucial roles in customer relationship management by promoting knowledge exchange, collaboration and co-creation. Key activities like nutrient recovery, ongoing R&D, and logistical management are critical for BBF production, while resources—including biowaste, biostimulants, coatings tailored for controlled nutrient release, flexible nutrient recovery technologies, skilled expertise, research facilities, funds, and innovative organizational culture—are essential for the model's success. Diverse and adaptable nutrient recovery methods must address the variability in waste sources and product qualities, ensuring consistent performance across varied agricultural applications. Collaborations with stakeholders like farmers, policymakers, researchers, and NGOs support resource acquisition, technology development, and BBF commercialization. Partnerships between the fertilizer and biomass-supplying sectors are crucial for value chain coordination. Competitive pricing relative to mineral fertilizers supports market penetration, while premium pricing can be justified by emphasizing BBFs' environmental benefits. Additional revenue sources, including value-added services and subsidies, are important for long-term sustainability, helping make bio-based products financially viable. To remain competitive, companies must optimize production processes and logistics, use high quality concentrated biobased material and innovate cost-effective nutrient recovery methods.

This paper contributes to the literature by presenting the BMC as a comprehensive tool to examine the status of all key aspects and considerations related to commercialization of BBFs, integrating a holistic perspective on value proposition, value creation and delivery, and value capture with sustainability as a central objective. It has potential for providing valuable insights for stakeholders in the fertilizer and agricultural sectors, policymakers, and the research community, providing a foundation for developing strategies to transition towards sustainable circular bioeconomy. Future studies should explore the entire TLBMC in the context of BBFs to integrate sustainability principles. Since the market-related segments of the BMC are less explored in bioeconomy literature, further research could focus on these areas, leveraging behavioral economics to provide deeper insights into farmer adoption behavior. Finally, developing effective education and training programs that build upon farmers' existing knowledge and practices to improve BBF adoption, remains a vital avenue for future exploration. An effective educational approach is necessary not only for farmers but also for the broader public, including policymakers, businesses, and citizens. As Christian Patermann, widely recognized as the “father of the bioeconomy,” highlights, the greatest challenge in advancing the bioeconomy is its inherent complexity and the need to translate this complexity into accessible understanding (Giuliani, 2022).

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