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From innovation to sustainable transformation: a multidimensional approach

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Abstract

Purpose – In this study, we analyse the multidimensional drivers of innovation in Polish bioeconomy enterprises and how internal-external interactions enable sustainable transformation. We test a model combining technological know-how, key enabling technologies, innovation potential, process innovation and the resulting innovation in traditional and specialised markets.

Design/methodology/approach – The project used a mixed-method approach, combining an entrepreneurial discovery process, interviews with experts and a survey of 252 companies in the LifeScience cluster. Measures were assessed using confirmatory factor analysis. Comparisons of market types were made using Bayesian structural equation modelling. Common methodological variance was assessed using latent factor tests and univariate tests.

Findings – In specialised markets, technological know-how is positively related to innovation potential, which in turn strengthens process innovation and contributes to innovation outcomes. The effects associated with key enabling technologies are not statistically significant in the current sample. Although indirect effects are observed, their statistical reliability is limited due to the small size of the subgroups analysed.

Research limitations/implications – The study has a limited regional scope, focusing on bioeconomy enterprises in Malopolska, which limits the generalisability of the results. The cross-sectional design and sample size limit the identification of indirect effects and the assessment of long-term innovation dynamics, especially with regard to key enabling technologies. In addition, there was no in-depth analysis of employee skills, sustainability factors and technological heterogeneity. Future research should employ longitudinal and

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comparative designs, larger samples and improved measurement models to better capture capacity development, technological heterogeneity and policy-driven innovation processes in the bioeconomy sector.
Practical implications – The results suggest that managers can benefit from prioritising the development of internal capabilities such as process maturity, organisational knowledge and overall innovation capacity. From a policy perspective, the results suggest that supporting sector-specific skills development, cluster collaboration and targeted R&D incentives may be more effective than broadly defined technology push-based programmes, particularly in the context studied.
Social implications – Strengthening the capacity of bioeconomy enterprises can accelerate sustainable transformation, reduce resource consumption and bring social benefits through eco-innovation in food, materials and environmental services.
Originality/value – The study presents a multidimensional, market-contingent model and shows that internal capabilities outweigh external technologies in driving sustainability-oriented innovation.

Keywords Sustainability, Bioeconomy, Innovation, Types of innovation, Innovation potential, Innovation process

Paper type Research article

1. Introduction

Bioeconomy is an interdisciplinary sector of the economy, defined as the sustainable use of renewable biological resources to produce goods and services (Kircher, 2019; Markedal *et al*., 2017; Sarkar *et al*., 2018; Winkler *et al*., 2019). Broadly speaking, bioeconomy encompasses a variety of industries, including agriculture, forestry, fisheries, food production, animal feed, pulp and paper production, as well as segments of the chemical, biotechnology and energy sectors. According to the OECD, the bioeconomy includes economic activities related to the invention, development, production and use of biological products and processes (OECD, 2009).

In recent years, the bioeconomy has established itself worldwide as the basis for achieving a sustainable economy (Schutte, 2018; Sillanpää and Ncibi, 2017). The use of biological resources for industrial purposes provides a way to integrate environmental concerns into business practices in the long term. However, a key challenge in developing a conceptual framework for the bioeconomy is to align it with sustainability principles (Adamowicz, 2014; Urmetzer *et al*., 2020). Such a framework should ensure the sustainability of environmental, social and economic objectives, directing human activities towards a more sustainable path.

In this context, a sustainable bioeconomy aims to build a competitive, resource-efficient economy (European Commission, 2010; Ahenkora, 2025). This requires the adaptation and development of national programmes and initiatives, as well as effective international cooperation. Furthermore, bioeconomy research policy must increasingly focus on and highlight the potential contribution of the bioeconomy to global goals such as the UN Sustainable Development Goals (SDGs) (Liobikiene *et al*., 2020; Schutte, 2018).

The modern bioeconomy is well positioned to achieve the Sustainable Development Goals, which include, *inter alia*, combating climate change, reducing economic inequalities, fostering innovation, promoting sustainable consumption and supporting peace and justice (Ramcilovic-Suominen and Pulzl, 2018; Turley, 2015; United Nations, 2015a, b). Achieving the Sustainable Development Goals in line with the 2030 Agenda for Sustainable Development, as well as promoting sustainable business practices, relies on progress in research, development and innovation (Schutte, 2018; Wydra, 2020). The transition to sustainability requires investments in technology, the implementation of new business models and the pursuit of social and environmental innovation–all of which contribute to shaping new business trends (Dean, 2013; Zilberman *et al*., 2018).

To achieve long-term sustainability goals, companies are increasingly implementing measures to discover new solutions and foster innovation to create value in economic, social and environmental dimensions, going beyond simply solving existing problems (Azmat *et al*., 2023; Jin and Lei, 2023; Zhang *et al*., 2022). Over the past decades, innovations aimed at reducing negative social and environmental impacts have been discussed under the buzzwords of “eco-innovation”, “environmental innovation” and “green innovation”, usually understood as innovations that reduce resource consumption, emissions or ecological footprint while promoting competitiveness (Hasan and Rahman, 2023; Parrilli; Nabi *et al.*, 2025). These concepts have gradually converged under the broader notion of sustainability-oriented innovation (SOI), which involves deliberate changes in an organisation's philosophy, products, processes and practices to create social and environmental value alongside economic gains (Rodríguez-Espíndola *et al.*, 2022).

In the literature, SOI is defined multidimensionally and evolutionarily. More narrowly, Adams *et al.* (2016, p. 181) define SOI as the systematic introduction of changes in products, processes, organisational practices and business models to generate environmental and social value while maintaining economic competitiveness. A broader approach, proposed by Rodríguez-Espíndola *et al.* (2022), treats SOI as deliberate changes in an organisation's philosophy, products, processes and practices that result in the creation of social and environmental value alongside economic value–whereby innovation can be incremental or radical, involve a single dimension or involve systemic transformation. An even broader perspective is taken by Bröring *et al.* (2020), who, with regard to the bioeconomy, emphasise that SOI encompasses not only product and process innovation, but also organisational, systemic and institutional innovation, which together create the conditions for sustainable sectoral transformation. According to the taxonomy of the Oslo Manual (OECD/Eurostat, 2018) and as proposed by Jarmai (2020), sustainability-oriented innovations can be classified as product, process, marketing and organisational innovations–with the criterion that distinguishes them from conventional innovations being the intentional inclusion of environmental or social effects as a central element of the innovation process rather than merely a by-product of it.

In this study, SOI is understood according to a broad multidimensional view: as the intentional introduction of a new or significantly improved product, process, organisational solution or business model that generates measurable environmental and/or social benefits while contributing to the sustainable transformation of the bioeconomy sector by replacing fossil resource-based practices with solutions based on renewable biological resources (Adams *et al.*, 2016; Bröring *et al.*, 2020; Jarmai, 2020; Rodríguez-Espíndola *et al.*, 2022; OECD/Eurostat, 2018).

Sustainability-oriented innovation (SOI) is defined as the introduction of a new or improved product, service or system that generates environmental and/or social benefits. Importantly, SOI highlights the unique characteristics of the bioeconomy (Bröring *et al.*, 2020). Key areas of innovation within the bioeconomy include more efficient use of biomass, substitution of fossil products, increased productivity in primary sectors and development of high-value technologies. These innovations can be disruptive, impacting multiple sectors simultaneously (Losacker *et al.*, 2023).

For bioeconomy to contribute to a shift away from unsustainable practices, innovations must support transformative changes in technological, organisational, economic, institutional, socio-cultural, political and environmental systems. However, despite a growing body of research on sustainability-focused innovation and bioeconomy development, analyses to date have mainly focused on macroeconomic policy frameworks or individual innovation outcomes, while offering limited insight into the internal organisational mechanisms that drive innovation processes in bioeconomy firms. The bioeconomy is one of the key areas of contemporary sustainability research, bringing together issues from innovation management, bioresource economics and systemic transformation theory. From a management science perspective, this sector provides a uniquely complex empirical context in which firms' technological capabilities, expertise and market structures co-shape innovation trajectories. Previous research has shown that innovation in the bioeconomy is characterised by multidimensionality–encompassing product and process innovation as well as organisational innovation–and that its effectiveness is strongly determined by firms' internal resources (Bröring *et al.*, 2020; Wydra, 2020). Nonetheless, the mechanisms of the sequential formation of innovation capabilities in bioeconomy firms remain under-researched, limiting the ability to formulate empirically grounded recommendations for both innovation theory and management practice in this sector.

Despite the growing body of research in sustainability-oriented innovation and the bioeconomy, the existing research is characterised by three key limitations, which form the starting point for this paper.

First, the dominant level of analysis in the literature remains the macroeconomic and policy level, with studies focusing on national bioeconomy strategies, EU regulations and aggregate innovation indicators (Bröring *et al*., 2020; Wydra, 2020; Losacker *et al*., 2023). Meanwhile, the intra-organisational mechanisms through which bioeconomy firms develop and implement innovation remain largely unexplored. Existing firm-level studies rarely go beyond analysing single types of innovation or isolated determinants of innovation without capturing them in an integrated sequential perspective Van Lancker *et al*. (2016).

Second, the technology and innovation management (TIM) literature in relation to the bioeconomy insufficiently considers the interactions between different innovation capabilities–technological knowledge, innovation potential and innovation processes, typically treating them as independent predictors of innovation outcomes rather than as elements of an interconnected *capability chain*. This approach fails to capture the sequential logic of innovation development, in which organisational capabilities at earlier stages condition innovation capabilities at later stages (Teece, 2010; Cohen and Levinthal, 1990).

Third, existing research rarely considers the market context as a variable that differentiates innovation dynamics in bioeconomy firms. Meanwhile, there are theoretical and empirical grounds to suppose that the relationship between innovation capabilities and innovation outcomes is heterogeneous and depends on the specifics of the market in which the firm operates, its degree of specialisation and knowledge intensity (Wydra, 2020; Aguilar *et al*., 2018).

The identified gaps point to the need for research that: (1) shift the level of analysis from the macro to the firm level, (2) capture innovation capabilities in a sequential and integrated perspective, and (3) consider the market context as a moderating factor in the relationship between these capabilities and innovation outcomes.

The above diagnosis of the state of knowledge leads to the formulation of the following research question: *How do internal innovation capabilities, comprising technological knowledge, innovation potential and innovation processes, interact in bioeconomy enterprises, creating conditions for the development of different types of innovation to support sustainable transformation of the sector, and to what extent are these relationships moderated by the specifics of the market in which the enterprise operates?*

The aim of the study is therefore to empirically validate the *innovation capability chain* model in bioeconomy enterprises, considering the moderating role of market specificity. The model assumes that technological knowledge (KH) and Key Enabling Technologies (KET) shape the innovation capability (PI), which in turn determines the structuring of innovation processes (IP), ultimately translating into concrete innovation outputs (IO) in the form of product, process, organisational and marketing innovations. The validation of this model provides empirically grounded insights both for innovation theory in the bioeconomy and for management practice and innovation policy in the sector.

Although many authors see innovation in the bioeconomy as central to the transition towards a sustainable economy, there is still a limited understanding of how different innovation capabilities, such as organisational knowledge (know-how), innovation capacity and innovation processes, interact and evolve within firms to generate sustainable innovation outcomes. Furthermore, previous research rarely takes an integrated perspective that links these internal innovation capabilities to the broader market context in which bioeconomy firms operate. As a result, the sequential dynamics of innovation development and the conditions under which innovation contributes to sustainable transformation remain under-researched.

The sustainable transformation of the bioeconomy does not occur solely through top-down regulation or external technological impulses but is significantly shaped by intra-organisational processes of knowledge accumulation, innovation capacity building and the institutionalisation of innovation routines. This framing is in line with the dynamic capabilities' perspective (Teece, 2010), which indicates that a firm's ability to reconfigure resources and processes in response to a changing environment is a key mechanism for adaptation to sustainability requirements. Consequently, innovations realised by bioeconomy firms–product, process and organisational–should be considered not only as economic outcomes, but as direct manifestations of the firm's ability to participate in the sustainable transformation of the sector.

Information gaps on the impact of innovation remain significant (O'Brien *et al*., 2017; Wydra, 2020), primarily because commercial success is often unclear due to current limitations in the available data on the outcomes of innovation activities. In particular, there is a lack of technology and innovation management (TIM) research to effectively guide research and development (R&D) and innovation efforts to support the future bioeconomy.

Filling this research gap requires a more systematic analysis of the relationship between key innovation capabilities and their role in shaping innovation outcomes in bioeconomy firms. To fill existing knowledge gaps in the literature on innovation and sustainable transformation in bioeconomy, this article presents an exploratory study based on a multidimensional research framework. The study adopts a capability chain perspective on innovation, analysing how knowledge resources, innovation capacity and innovation processes interact to generate innovation outcomes in the context of bioeconomy. The main guiding research question of the study is: How do internal innovation capabilities interact in bioeconomy companies to support innovation processes that foster sustainable transformation?

A synthesis of the existing body of research makes it possible to identify three key theoretical gaps that this study undertakes to fill. First, the dominant approach in the literature remains the analysis of isolated determinants of innovation–individual factors such as technological knowledge, innovation potential or innovation processes are studied separately, without considering their interactions and the sequential logic of innovation capability formation (*innovation capability chain*). This study fills this gap by proposing an integrated theoretical model based on the capability chain perspective, in which each successive construct is both the outcome of the previous one and the condition for the formation of the next one. Secondly, existing studies rarely consider the market context as a differentiating variable for innovation dynamics in bioeconomy firms. Meanwhile, resource and capability dynamic theory (Teece, 2010; Barney, 1991) suggests that the efficiency with which knowledge resources are transformed into innovation outcomes is heterogeneous and dependent on market conditions. This study addresses this gap by introducing market specificity as a grouping variable in a two-group model. Third, the literature on technology and innovation management (TIM) in the context of the bioeconomy focuses mainly on the sectoral and macroeconomic level, offering limited insight into the intra-organisational mechanisms of knowledge transformation into innovation at the firm level (Wydra, 2020). This study fills this gap by moving the level of analysis to the firm level and using structural equation modelling as a tool to identify sequential relationships between innovation constructs.

The purpose of this study is to explore the multidimensional drivers of innovation in bioeconomy firms, with a particular focus on how firms combine internal capabilities and external technological resources to support sustainable transformation. Based on a capability chain perspective, the study analyses the relationship between human capital, technological know-how, innovation potential, innovation processes and innovation outcomes. The study tests hypotheses formulated to assess the sequential impact of these innovation drivers on the development of different types of innovation in bioeconomy firms.

A mixed methods research design combining qualitative expert interviews with a firm-level survey was used to meet the research objective. The empirical analysis uses structural equation modelling (SEM) to explore the relationships between the proposed constructs and provide a multidimensional assessment of innovation dynamics. The analysis is based on a theoretical framework that integrates insights from the literature on innovation management and sustainability-oriented innovation, thus offering a comprehensive understanding of how innovation capabilities contribute to sustainable transformation in bioeconomy firms.

The remainder of the article is structured as follows. First, the conceptual and theoretical background is presented to outline the framework of the proposed innovation capability model. The research design and empirical methods are then presented, including data collection procedures and structural equation modelling. This is followed by an analysis of the empirical results, highlighting the relationships between technological know-how, innovation capability, innovation processes and innovation outcomes. The final sections discuss the results in relation to existing innovation theories, outline implications for management and policy in bioeconomy development and suggest directions for future research.

2. Theoretical background

2.1 Fostering innovation for a sustainable bioeconomy

The bioeconomy is not only a new concept in economics, but also a rapidly growing sector of the modern economy. The term "bioeconomy" was first introduced by Georgescu-Roegen (1977) in the 1970 and 1980s to refer to the radical perspectives of ecological economics. Various definitions of bioeconomy can be found in the literature (Lehtonen and Okkonen, 2013; Liobikiene *et al*., 2020). Based on recent research, Vivien *et al*. (2019) identified three distinct interpretations of the bioeconomy: sustainability-oriented, science-oriented and biomass-oriented. Each of these perspectives envisages different trajectories for future economic development, technological progress and environmental approaches. This diversity reflects the growing importance of sustainability, emphasising production practices that use natural resources responsibly, employ environmentally friendly technologies and incorporate renewable energy sources (Lühmann, 2020; Zilberman *et al*., 2013).

The term "bioeconomy" frequently appears in policy documents and development programmes of the European Union and its member states. The concept gained widespread attention between 2010 and 2013, mainly through several initiatives at EU level (European Commission, 2012; Wozniak *et al*., 2021). The EU Bioeconomy Strategy (European Commission, 2018) aims to accelerate the transition towards a sustainable European bioeconomy and maximise its contribution to the UN 2030 Agenda for Sustainable Development, including the 17 Sustainable Development Goals (United Nations, 2015b), as well as to the Paris Agreement on Climate Change (UN, 2015a).

More recently, the bioeconomy has been identified as a key pillar of the European Green Deal (European Commission, 2019), which identifies the bioeconomy as an integral component of the EU's long-term strategy to achieve climate neutrality, resource efficiency and sustainable growth. In this context, the bioeconomy is closely linked to the development of a circular economy based on bio-based raw materials, as highlighted in the EU Action Plan for circular economy and related policy communications. These initiatives emphasise the role of biobased raw material value chains, closed resource cycles and innovation-based transformations towards sustainability in strengthening Europe's industrial competitiveness and environmental performance (Asada *et al*., 2020). All these policy documents emphasise the growing importance of a sustainable, closed-loop and innovation-oriented bioeconomy as the foundation of contemporary European economic and environmental policy.

The potential of the bioeconomy remains largely untapped, especially in terms of increasing productivity and reducing dependence on natural resources (Schutte, 2018; Schütte, 2018; Sillanpää and Ncibi, 2017). On the one hand, the bioeconomy enables the creation of entirely new products using knowledge-based technologies. On the other hand, it facilitates the adaptation of existing processes and products to the requirements of a sustainable economy and supports the achievement of sustainability goals (Schutte, 2018; Schütte, 2018). A key challenge in developing a conceptual framework for the bioeconomy is its integration with the concept of sustainability, which requires innovation in multiple dimensions and on multiple levels (Hinderer and Kuckertz, 2022; Urban *et al*., 2018; Urmetzer *et al*., 2020).

Within the bioeconomy, the importance of innovation is growing rapidly. Innovation in this context is aimed at enhancing positive social and natural environmental impacts by consciously managing economic, social and environmental aspects (Wozniak *et al*., 2021). This means achieving social and environmental benefits through innovation by replacing existing, less sustainable solutions available on the market. Sustainability-oriented innovation refers to improvements in the performance of a product, service or process and is defined by its positive impact on the environment (Díaz-García *et al*., 2015).

Sustainability-oriented innovation goes beyond a narrow view of improving the environmental performance of a product or process. As indicated in the systematic review by Adams *et al*. (2016), SOI encompasses the full spectrum of organisational change–from incremental innovations in products and processes to transformational changes in business models and value systems, with the common denominator being the intentional generation of environmental and social value. Díaz-García *et al*. (2015) narrow this definition to the eco-innovation dimension, emphasising positive environmental impact as a differentiating criterion, while Jarmai (2020) and Rodríguez-Espíndola *et al*. (2022) extend it to include social and systemic dimensions, treating SOI as a mechanism for transforming entire sectors of the economy. Of relevance in the context of the bioeconomy is the perspective of Bröring *et al*. (2020), according to which SOI in this sector is characterised by a high degree of interdisciplinarity and transversality, bio-economic innovations interact simultaneously with technological, institutional and socio-cultural systems, which gives them transformative potential beyond single sectors.

The literature on sustainability-oriented innovation identifies several potential drivers of firm-level innovation, traditionally rooted in innovation theory and environmental policy. These drivers can be divided into supply-side factors, demand-side factors and regulatory frameworks (Ferasso *et al*., 2020; Triguero *et al*., 2013). Supply-side factors include technological and managerial capabilities, tangible and intangible assets, and knowledge and skills that enable firms to develop sustainability-oriented innovations. Collaboration with research institutes, private or public agencies and universities is also considered a key source of external knowledge (Sanni and Verdolini, 2022). Demand-side factors include market demand and the perception of the company by its main customer groups. The regulatory framework, including laws, regulations and standards, is seen as a key driver for the implementation of sustainability-oriented innovation in business practices (Bröring *et al*., 2020; Costa, 2021; Jarmai, 2020).

In bioeconomy companies, innovation is the result of the systematic development of innovation activities. Innovation activities are defined as “all development, financial and commercial activities undertaken by a firm that aim to lead to an innovation for that firm” (OECD/Eurostat, 2018, p. 247). These activities cover a variety of areas, such as research and experimental development, design and other creative work, marketing and brand value creation, intellectual property management, employee training, software development and database management, acquisition or leasing of fixed assets and other innovation-related initiatives. These activities can be characterised on the basis of the knowledge acquired or generated, as well as the stage of the innovation process at which they are applied.

The bioeconomy is expected to offer solutions to major economic, social and environmental challenges such as resource depletion, food insecurity and climate change. As such, the bioeconomy has the potential to significantly impact on added value, employment, income distribution and sustainability. Achieving these goals requires companies to engage in innovation activities throughout the life cycle of products and services. According to the European Commission, innovation and research are seen as essential to accelerate the transition to an economy that reduces dependence on fossil fuels and increases the sustainability of both primary production and process industries (European

Commission, 2012). Innovation underpins many of the expectations of the bioeconomy, which the EC sees as a response to the growing demand for a sustainable supply of food, raw materials and biofuels, as well as the need for Europe to increase productivity, competitiveness and improve the quality of life of its citizens (McCormick and Kautto, 2013; Urbaniec, 2016).

However, the literature to date lacks a holistic approach to innovation in bioeconomy. Previous studies have tended to focus on individual dimensions of innovation in bioeconomy, such as the innovation process (Hansen *et al.*, 2016) and types of innovation (Bröring *et al.*, 2020; Soltysik *et al.*, 2019; Van Lancker, Wauters & Van Huylenbroeck, 2016). This study adopts a comprehensive approach to analyse firm-level innovation in the bioeconomy sector, covering the innovation process, innovation potential and different types of innovation.

2.2 Research framework and hypothesis

This subsection presents the conceptual framework and research hypotheses, derived directly from identified gaps in the literature. The proposed theoretical model integrates three complementary perspectives: (1) the *resource-based view* (RBV), according to which internal knowledge resources and technological competence are the foundation of a firm's innovative advantage (Barney, 1991; Teece, 2010); (2) the *absorptive capacity* perspective, which explains the mechanisms through which firms identify, assimilate and commercialise external technological knowledge (Cohen and Levinthal, 1990); and (3) the *open innovation (open innovation*) perspective, which emphasises the role of external sources of knowledge, including enabling technologies, in developing internal innovation potential (Chesbrough, 2003; Van Lancker *et al.*, 2016). The integration of these three perspectives justifies the sequential logic adopted in the study, in which knowledge resources (KH, KET) shape innovation potential (PI), this in turn conditions the structuring of innovation processes (IP), and these ultimately determine innovation outputs (IO). This model is the original theoretical contribution of this study, as previous research in the bioeconomy area has not empirically tested the full chain of these relationships in an integrated way and considering the moderating role of the market context.

Innovation is seen as an opportunity to transform existing industries, for example by replacing fossil resources with renewable ones and opening new markets for biobased products (Van Lancker *et al.*, 2016; Wozniak *et al.*, 2021). This study fits into this trend by focusing on the intra-organisational mechanisms that enable bioeconomy companies to successfully realise this transformative potential.

Innovation at the firm level is primarily about creating an environment conducive to the generation of new ideas and deciding which ideas will be implemented and which will be rejected. This means that not every new idea necessarily leads to innovation. Decisions to pursue one idea while rejecting another are usually made under high levels of uncertainty about potential success. The more dynamic the market and the more radical the innovation, the higher the level of uncertainty. Well-established management approaches to reduce uncertainty by using information from external sources include open innovation, user innovation and innovation communities (Fichter, 2009; Chesbrough, 2003; Gassmann and Enkel, 2004).

Bioeconomy operates in diverse market environments influenced by factors such as competition, customer preferences, regulatory frameworks and market demand (Wydra, 2020). These market dynamics can shape the relationship between firm-level know-how and innovation potential. For example, in highly competitive markets, firms with extensive know-how may be more able to use their knowledge to drive innovation and gain competitive advantage. Market characteristics such as resource availability and infrastructure can significantly influence the relationship between know-how and innovation potential in bioeconomy (Winkler *et al.*, 2019). The availability and accessibility of the necessary resources, including research facilities, funding, raw materials and specialised equipment, enable companies to effectively exploit their know-how and transform it into innovative products or processes.

The bioeconomy is also influenced by changing market demands and customer preferences, particularly in terms of sustainability, environmental impact and bio-based products (Aguilar *et al.*, 2018). Market characteristics related to customer needs and preferences may prompt companies to adapt their expertise to meet specific market requirements, leading to innovations that are in line with customer expectations and create added value.

The literature review identified several key factors that contribute to the multidimensional drivers of innovation in the bioeconomy, particularly with regard to their implications for innovation potential, the innovation process and different types of innovation. This study also examines the relationship between the different stages of innovation development, as shown in Figure 1.

One of the key dimensions of the innovation process in the bioeconomy is both the technological know-how (KH) and the professional education (W) of the employees. These factors are interlinked as the creation of technological innovation relies on specialised knowledge and highly skilled personnel. Know-how, referring to specialised knowledge and experience, plays a key role in driving innovation in the bioeconomy. The importance of knowledge in enhancing the efficiency of firms' innovation activities has been recognised for many decades (Kline and Rosenberg, 1986; Teece, 1986).

Van Lancker *et al.* (2016) address the challenges of innovation management in the bioeconomy, drawing on the literature on open innovation. The use of technical know-how and scientific knowledge contributes significantly to the development and implementation of innovative technologies, processes and practices in the bioeconomy sector. Schütte (2018) highlights the importance of technical know-how in bringing biotechnology-based innovations to market. In the bioeconomy, knowledge and technical know-how are essential to foster innovation. Having specialised knowledge and expertise facilitates the development and implementation of new technologies, production processes and business strategies, thereby increasing the innovation potential of the bioeconomy. Technological know-how is also seen as a driver for creating a sustainable future and developing technologies (Griffy-Brown *et al.*, 2018; Van Lancker *et al.*, 2016).

Technological know-how enables companies to identify emerging technological opportunities, to integrate scientific knowledge into innovation processes and to transform research results into commercially applicable solutions. Therefore, know-how should not only be understood as accumulated expertise, but also as an organisational capacity that supports

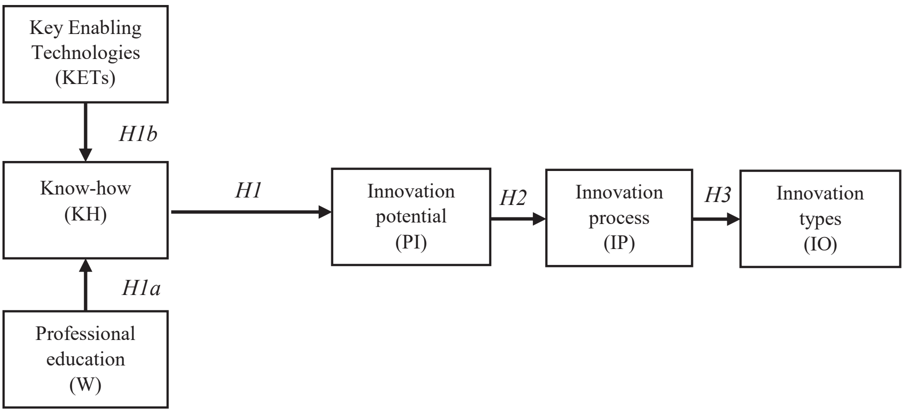

Figure 1. Research framework and hypotheses. Source: Authors' own work

the generation and development of innovation potential in bioeconomy firms. From this perspective, innovation potential refers to the ability of an enterprise to generate, assimilate and further develop innovation ideas and technological capabilities that can later be translated into concrete innovation results:

H1. Higher levels of technological know-how in bioeconomy companies are positively related to their innovation potential, understood as the ability of a company to identify, develop and exploit innovation opportunities.

In addition, skilled employees with specialised knowledge are a key driver of innovation. Transforming knowledge into practice increases the competitiveness and profitability of the firm (Schütte, 2018; Wozniak *et al*., 2021). Human capital, shaped through vocational, higher and doctoral education, plays an independent and significant role in the innovation development process. Teslenko *et al*. (2021) emphasise that a shortage of skilled workers with vocational education can inhibit the growth of innovation production, while an increase in the proportion of researchers with higher degrees, such as candidate or doctoral degrees, stimulates innovation and patent activity, provided that adequate R&D funding is available. Along with advanced technologies, human capital is also crucial for the quality and efficiency of research activities and for bringing bioeconomy innovations to the market in different industrial sectors.

In particular, the educational level of the workforce contributes to the development of organisational knowledge resources, enabling companies to assimilate scientific knowledge, exploit technical knowledge and translate research results into practical solutions. Higher levels of professional education strengthen the learning capacity of enterprises and facilitate the accumulation and dissemination of technological know-how within the organisation. In knowledge-based sectors, such as the bioeconomy, these capabilities are particularly important for supporting innovation processes and strengthening firms' technological competence. Based on these findings, this study formulates the following hypotheses:

H1a. Higher levels of professional education of employees are positively related to the development of technological know-how in bioeconomy firms.

Technical knowledge is considered a key driver of the transition to a sustainable bioeconomy (Priefer *et al*., 2017; Sarkar *et al*., 2018; Sillanpää and Ncibi, 2017). Developing an effective framework for biotechnology-based transformation towards sustainability requires the use of advanced technologies. Key enabling technologies (KETs) are considered a major driver of innovation in various sectors, including the bioeconomy. In 2009. European Commission defined six KETs for the European economy as a whole: advanced manufacturing, advanced materials, life sciences technologies, micro- and nanoelectronics and photonics, artificial intelligence, and security and communications (European Commission, 2021). These technologies enable improvements in human health and safety while contributing to climate change mitigation.

Furthermore, KETs are a priority for European industrial policy due to their high systemic importance. They are seen as catalysts for innovation and competitiveness at a global level. Countries and regions that implement these technologies and apply them to innovative products, processes and services are expected to benefit in terms of economic growth, sustainability and employment (Priefer *et al*., 2017; Türkeli and Kemp, 2018; Befort, 2020). The dissemination of KETs, including artificial intelligence, is therefore at the heart of the new industrial strategy, supported by Horizon Europe, the Digital Europe programme and the European Structural and Investment Funds (European Commission, 2021). Rapid advances in science and technology, especially in life sciences and information technology, support both the theoretical and practical development of the bioeconomy.

Building on the 2009 KET concept developed by the European Commission (EC), Laibach *et al*. (2019) identified specific KET criteria for bioeconomy transformation and developed overarching supercategories describing technology pathways and criteria dimensions according to the society-environment-economy triangle. They emphasised that technological innovation is a key driver of economic and social change, making KETs essential to accelerate technological progress in the bioeconomy.

In this context, the adoption and application of KETs enhances the technological capabilities of businesses by facilitating the acquisition, integration and practical application of advanced scientific and technological knowledge. As companies implement KETs in their innovation activities, they accumulate technical knowledge and strengthen their internal knowledge base, thus contributing to the organisation's know-how.

The application of technological know-how and innovation has a significant impact on the level of development of the bioeconomy. Based on these insights, this study formulates the following hypothesis:

H1b. The implementation and use of key enabling technologies (KETs) have a positive impact on the development of technological know-how in bioeconomy enterprises.

Another important dimension of innovation in the bioeconomy is the innovation potential (PI) that drives innovation activities.

Innovation potential refers to the latent set of resources, capabilities and conditions that enable a firm to innovate. In practice, innovation potential includes both hard resources (technology, finance) and soft factors (culture, knowledge, networks). For example, Vijesh (2017) summarises Dreesmann's view that innovation potential links employee skills and know-how with organisational structures and external linkages. More recent research similarly considers innovation potential as a key determinant of a firm's adaptability and performance (linking the firm's dynamic capabilities to innovation outcomes). In summary, "innovation potential" refers to a firm's latent capacity to innovate–the sum of its relevant resources, competencies and enabling conditions.

In this study, innovation potential is understood as a firm's ability to identify technological opportunities, mobilise internal and external knowledge resources and initiate innovation-oriented activities. This capability enables companies to transform knowledge and technological competence into concrete innovation initiatives and development processes.

The bioeconomy sector has a strong innovation potential as it draws on the knowledge and achievements of various scientific disciplines, including life sciences, ecology, food sciences, applied and industrial biotechnology and nanotechnology (2018; Wozniak *et al*., 2021). Bioeconomy is characterised by significant innovation potential at company level, including the use of under-exploited raw materials (such as CO_2, waste, algae), optimised micro-organisms, digitisation in agriculture and social innovation (e.g. urban gardening, collective farming) (Laibach *et al*., 2019; Wesseler and von Braun, 2017).

Activities with innovation potential may be undertaken for other purposes that improve business performance without necessarily aiming at innovation. Some firms may not even recognise the innovation potential inherent in their activities (OECD/Eurostat, 2018). Meanwhile, the increasing complexity of the bioeconomy makes it challenging for industry and SMEs to fully exploit the innovation potential. Key aspects of bioeconomy complexity include: (1) the use of advanced knowledge of genes and cellular processes to develop and program new processes and products; (2) the use of renewable biomass and efficient bioprocesses to promote sustainable production; and (3) the integration of biotechnology knowledge for application across multiple sectors (OECD, 2009; O'Brien *et al*., 2017).

Bioeconomy offers significant innovation potential through the sustainable use of biological resources, the development of biotechnology-based products and processes and the integration of biotechnological developments. Harnessing this innovation potential within bioeconomy can drive progress in areas such as bioenergy, biomaterials, biopharmaceuticals and agricultural technologies.

Within firms operating in the bioeconomy, higher levels of innovation potential are expected to facilitate the initiation and implementation of innovation activities, enabling organisations to transform available knowledge, technology and resources into structured innovation processes. Based on the results presented in this study, the following hypothesis is proposed:

H2. Higher levels of innovation potential positively influence the development and implementation of innovation processes in bioeconomy companies.

The innovation literature shows that the innovation process (IP) is crucial for generating innovation in bioeconomy. Innovation researchers describe the innovation process itself as a chain of routine activities through which ideas are implemented. For example, Jacobs and Snijders (2008) define the innovation process as the development and selection of ideas for innovations and the transformation of these ideas into innovations. In practice, this means a structured sequence of activities (idea generation, selection, development, testing, implementation) embedded in organisational practices. Different stages of the innovation process can be identified.

In terms of innovation drivers, innovation processes at the firm level in the bioeconomy are often similar to the linear innovation model, which assumes that innovation processes start with research and then move through product development, production and marketing (Bugge *et al*., 2016). However, these aspects are relatively poorly studied in the literature (Bröring *et al*., 2020). Innovation can be understood as the outcome of the creative actions of actors operating under specific framework conditions, where the innovation process is shaped by a combination of factors. These factors include both internal (e.g. company vision, key personnel) and external influences on the innovation process. These factors do not act in isolation, but reinforce each other, influencing the overall orientation of the innovation process at company level, as well as individual decision-making.

In this study, the innovation process refers to the set of structured organisational activities through which firms transform innovation potential and technological knowledge into tangible innovation outcomes. These activities include the generation, development, testing and implementation of new ideas as part of organisational routines. As firms strengthen and formalise these processes, they become more capable of introducing different types of innovation in products, processes, organisational practices or services. Based on these insights, the following hypothesis is proposed:

H3. Innovation processes positively influence the development of innovation outputs in bioeconomy enterprises.

A view of innovation in the bioeconomy similar to eco-innovation (Adams *et al*., 2016; Triguero *et al*., 2013; Tomala and Urbaniec, 2021) or sustainability-oriented innovation (Jarmai, 2020), with a distinction between product, process and organisational innovation, may be beneficial for technology and innovation management (TIM) research. Sustainability-oriented innovation can be classified into different types of ‘normal’ innovation without normative requirements (Jarmai *et al*., 2020), including product innovation (goods and services), process innovation (production or delivery methods), marketing innovation (design, packaging, positioning, promotion, pricing) and organisational innovation (business practices, workplace, external relations). Furthermore, increasing the service content of products can be considered as another type of sustainability-oriented innovation.

In this context, a sustainability-oriented innovation may perform the same function or meet the same needs as an existing market option, but through an alternative, more sustainable solution (e.g. clothes washing services instead of a washing machine, car-sharing services or pick-up services). Companies can also develop sustainability-oriented innovations that not only respond to current consumer needs but also offer entirely new solutions to promote more sustainable lifestyles.

In contrast, in the context of sustainable bioeconomy transformation, the innovation performance of companies, understood as the implementation of new or significantly improved products, processes and organisational solutions, are measurable indicators of transformational progress at the microeconomic level. A firm’s ability to consistently transform innovation potential into structured innovation processes and tangible innovation outcomes thus determines its contribution to the systemic transformation of the bioeconomy sector towards greater sustainability.

Biotechnology-based innovation is not only relevant in high-tech sectors, but also in traditional industries, such as the development of new textile materials (e.g. Spider silk) or the creation of alternative protein sources in the food sector. Many strategies emphasise the importance of innovation to achieve their goals (Bugge *et al.*, 2016; Urbaniec *et al.*, 2022). Companies innovate to enter new market segments, improve product quality, reduce production costs, maintain a competitive advantage or strengthen their market position through innovative products and processes. In a dynamic and rapidly changing business environment, the ability to continuously innovate and improve products is essential for success. Only companies that adapt and evolve effectively can reap the full benefits of these changes (Jarmai *et al.*, 2020). Innovation at the firm level therefore involves the application of new ideas to products, processes or other aspects of the business.

In summary, the proposed hypotheses reflect a capability chain perspective on innovation, in which human capital and technological resources shape knowledge capabilities, which in turn foster innovation capacity, structured innovation processes and ultimately the implementation of different types of innovation in bioeconomy firms.

In the context of the bioeconomy, the performance of these innovations is closely linked to sustainability goals. In this study, sustainability outcomes are operationalised through the development and implementation of types of innovations that contribute to more efficient use of biological resources, substitution of fossil materials, improved production efficiency and development of biotechnology-based products and processes. Such innovations promote environmental sustainability while strengthening the economic competitiveness of bioeconomy businesses. Consequently, the results of sustainability-oriented innovations are reflected in the ability of companies to introduce product, process and organisational innovations that contribute to more sustainable production systems and business models based on resource efficiency within the bioeconomy.

3. Methods

3.1 Sampling and data collection

This study examines the multidimensional drivers of innovation among Polish bioeconomy enterprises, with an emphasis on the interactions between firms and their internal and external environment. The study covers companies affiliated to the LifeScience Cluster in Małopolska, one of the leading regional bioeconomy innovation ecosystems in Poland. Activity within the cluster–supported by favourable market conditions and local policies–enables economies of scale and complementarities in research, financing and production, thereby facilitating the development and marketing of new bioproducts (Soltysik *et al.*, 2019; Wesseler and von Braun, 2017).

To identify drivers of innovation, we have used the Entrepreneurial Discovery Process (EDP) as an overarching framework that integrates multiple research techniques and enables data triangulation (Isaksen, 2019). The EDP framework is widely used in regional innovation policy and smart specialisation strategies as it enables the identification of innovation opportunities through interactions between firms, experts and institutional actors. Two complementary phases were implemented: (1) structured interviews with experts and (2) a firm-level survey of cluster member executives. The combination of methods strengthened the construct validity and the robustness of the empirical findings.

The first stage involved structured face-to-face interviews using a paper-and-pencil interview (PAPI) technique with industry experts from LifeScience cluster member companies. Purposive selection was based on two inclusion criteria: (1) holding a managerial position and (2) at least 10 years of experience in bioeconomy. The qualitative phase identified key drivers of innovation and helped to refine the constructs used in the subsequent quantitative study. This phase also served as a pilot to refine the survey instrument and confirm thematic relevance.

In the second phase, the survey was extended to 252 companies in the Malopolska LifeScience Cluster. Depending on respondents' preferences, interviews were conducted using CAPI (computer-assisted personal interviewing) or CATI (computer-assisted telephone interviewing). The sample covered three segments of the bioeconomy: healthy food, biotechnology processes and specialty chemicals, and environmental engineering.

For the purposes of the two-group structural model, firms were classified according to their primary market orientation using a binary grouping variable included in the survey instrument. Respondents indicated whether their firm operates predominantly in: (1) traditional markets characterised by standardised, commodity-type bio-based products, price-based competition and low knowledge intensity in customer interactions (e.g. bulk food processing, standard agricultural inputs); or (2) specialised and niche markets, characterised by high knowledge intensity, science-based or customised products, technological differentiation as the primary basis of competition, and close linkages with research institutions or sophisticated buyers (e.g. functional ingredients, biopharmaceuticals, specialty chemicals). This typology is consistent with market distinctions used in bioeconomy innovation research by Wydra (2020) and Aguilar *et al*. (2018), who differentiate between commodity-oriented and knowledge-intensive market segments as structurally distinct innovation environments.

Respondents were CEOs, department heads or founders to provide a strategic perspective. The questionnaire built on the insights from stage 1 and focused on mapping and assessing the drivers of innovation in the sector. The survey tool consisted of structured items measuring key constructs of the conceptual model, including technological know-how, innovation potential, innovation processes and innovation outputs.

The operationalisation of each model construct was derived from three complementary sources: (1) a review of the innovation management and bioeconomy literature, (2) the results of the qualitative phase of the study, and (3) recognised measurement frameworks used in business innovation research.

Technological knowledge (KH) has been conceptualised as an organisational resource encompassing the technical expertise of employees and the firm's ability to absorb it and put it into practice in innovation activities. The operationalisation of this construct draws on Cohen and Levinthal's (1990) theory of absorptive capacity, according to which prior technical knowledge conditions a firm's ability to recognise, assimilate and commercialise new external knowledge. KH indicators therefore refer to the level of professional specialisation of employees and the organisational mechanisms of technological knowledge accumulation and transfer within the firm, in line with the approach used by Schütte (2018) and Van Lancker *et al*. (2016) in research on bioeconomic innovation.

More specifically, KH is conceptualised as encompassing two interrelated knowledge dimensions: tacit, experience-based expertise embedded in employees' professional specialisation and accumulated through organisational practice; and absorptive capacity, the firm's ability to recognise, assimilate and exploit externally available technological knowledge (Cohen and Levinthal, 1990). KH is thus understood not merely as a stock of individual skills, but as an organisational-level mechanism conditioning the firm's capacity to develop innovation potential, a distinction that makes the KH→PI relationship empirically non-trivial and market-context dependent.

Key Enabling Technologies (KETs) were operationalised as the extent and intensity of the use of advanced technologies in a firm's innovation activities, with reference to the European Commission's (2021) taxonomy of advanced manufacturing technologies, life sciences technologies and digital and communications technologies. The choice of this taxonomy as the basis for operationalisation is justified by its broad applicability in European sectoral innovation research and its direct relevance to the bioeconomy context (Laibach *et al*., 2019).

KET indicators therefore measure not only the fact of owning specific technologies, but above all the activity of their application in a company's innovation processes.

Innovation potential (PI) has been conceptualised as a firm's latent organisational capacity to identify innovation opportunities, mobilise knowledge resources and initiate innovation-oriented activities–in line with Vijesh (2017), who, following Dreesmann, defines innovation potential as a combination of employee competencies, organisational structures and external linkages. In this study, innovation potential is treated as an intermediary construct between knowledge resources and structured innovation processes, which is in line with Teece's (2010) dynamic capability perspective. PI indicators (PI3-PI7) measure a firm's ability to identify new technological opportunities, assess their feasibility and mobilise the resources necessary to implement them.

The innovation process (IP) has been operationalised as the degree to which the sequential stages of an organisation's innovation process–from idea generation through selection and development to implementation–are formalised and structured, as defined by Jacobs and Snijders (2008), who describe the innovation process as a structured sequence of organisational routines that transform ideas into innovations. The IP indicators (IP2-IP4, IP6, IP8) reflect the degree of institutionalisation and regularity of the different stages of the innovation process in a firm's organisational practice, which distinguishes sustained innovation capabilities from incidental innovation activities not embedded in organisational routines.

Innovation outputs (IO) was operationalised according to the four-dimensional innovation taxonomy of the Oslo Manual (OECD/Eurostat, 2018), covering product, process, organisational and marketing innovation. The choice of this taxonomy is justified by its wide acceptance in the innovation management literature (Bröring *et al*., 2020; Jarmai, 2020) and its ability to capture the multidimensionality of innovation performance characteristic of bioeconomy firms. The IO indicators (IO1-IO4) measure the actual implementation of the different types of innovation during the reference period under study–rather than just the declared innovation intentions or inputs–which ensures higher relevance in measuring innovation outcomes at the firm level.

All indicators were measured on a five-point ordinal Likert scale. Items not meeting the item-scale correlation criterion ≥ 0.30 or showing standardised factor loadings below 0.40 in the initial confirmatory factor analysis were excluded from the final measurement model specification, following the recommendations of Hair *et al*. (2019).

Data were organised and subjected to preliminary analysis using analytical tools, including contingency tables in MS Excel, to identify patterns and relationships.

The EDP framework allowed us to combine expert knowledge with broader firm-level evidence, considering institutional and process dimensions of innovation (Isaksen, 2019). The use of mixed methods enabled triangulation at both methodological and data source level, combining expert interviews with CAPI/CATI survey data. This approach strengthened internal validity by cross-checking insights obtained from different sources. Reliability was ensured through standard protocols, clear inclusion criteria and quality checks during data processing (logical checks and consistency verifications). All participants were informed of the purpose of the study, the voluntary nature of participation and the guarantees of confidentiality. Results were presented in aggregate form to prevent the identification of individuals or companies.

3.2 Data analysis methods

To ensure the reliability and relevance of the study constructs, confirmatory factor analysis (CFA) was conducted using categorical indicators. The CFA analysis was used to test whether the observed measurement items adequately reflected the latent constructs proposed in the conceptual model. The analysis assessed the reliability, convergent validity and discriminant validity of the key enabling technology (KET), innovation potential (PI), innovation process (IP) and innovation outputs (IO) scales. As the KNOWH construct was represented by only two indicators, reliability analysis was omitted for this construct. In such cases, reliability measures based on internal consistency are not recommended, as constructs with fewer than three indicators do not allow for stable reliability estimates.

The constructs included in the structural model were operationalised in a two-stage procedure. In the first stage, the qualitative phase of the study, involving structured expert interviews conducted using the face-to-face interview technique (PAPI), was used to identify the key dimensions of innovation in bioeconomy enterprises. The content of the emerged constructs was then validated against recognised measurement frameworks in the innovation management literature (Hair *et al*., 2019). In a second step, the identified dimensions were operationalised in the form of measurement items on a Likert-type ordinal scale and incorporated into a quantitative survey questionnaire at company level.

The constructs and their corresponding indicators were defined as follows. *Technological Knowledge* (KH) was measured by two indicators reflecting the level of technological expertise of employees and the organisational capacity of the firm to absorb and practically apply technological knowledge in innovation activities. *Key Enabling Technologies* (KET) was measured by three indicators (KET1, KET2, KET3) capturing the extent and intensity of the use of advanced technologies in a company's innovation activities, with reference to the European Commission's KET taxonomy (2021) covering advanced manufacturing technologies, natural technologies and digital technologies. *Innovation potential* (PI) was operationalised with five indicators (PI3-PI7) assessing the firm's ability to identify innovation opportunities, mobilise internal and external knowledge resources and initiate innovation-oriented activities. *The innovation process* (IP) was measured by five indicators (IP2-IP4, IP6, IP8) reflecting the degree to which the successive stages of the innovation process in the organisation are formalised and structured, from idea generation through development to implementation. *Innovation outputs* (IO) was measured by four indicators (IO1-IO4) capturing the introduction of product, process, organisational and marketing innovations during the reference period under study, following the taxonomy of the Oslo Manual (OECD/Eurostat, 2018).

All indicators were measured on a five-point ordinal Likert scale anchored at 1 (*strongly disagree*/*not at all*) and 5 (*strongly agree*/*very much agree*). Items that did not meet the item-scale correlation criterion of ≥ 0.30 in the initial analysis or showed standardised factor loadings below 0.40 in the initial confirmatory factor analysis were excluded from the final measurement model specification. This procedure resulted in the removal of items KH3 (technological knowledge), PI1 and PI2 (innovation potential), IP1, IP5 and IP7 (innovation process) and IO5 (innovation outputs) from the final model. Item elimination decisions were made in line with the methodological recommendations of Hair *et al*. (2019).

The final set of items included in the analysis for each construct is as follows:

$$\text{KET} : \text{KET1} + \text{KET2} + \text{KET3}$$

$$\text{PI} : \text{PI3} + \text{PI4} + \text{PI5} + \text{PI6} + \text{PI7}$$

$$\text{IP} : \text{IP2} + \text{IP3} + \text{IP4} + \text{IP6} + \text{IP8}$$

$$\text{IO} : \text{IO1} + \text{IO2} + \text{IO3} + \text{IO4}$$

Reliability estimates of the scales, including Cronbach's alpha coefficient, Jöreskog's rho coefficient, Dijkstra-Henseler's rho coefficient and average variance extracted (AVE), are presented in Table 1. Cronbach's alpha coefficient and composite reliability measures were used to assess internal consistency, while AVE was used to assess convergent validity. The results indicate acceptable reliability for the KET and IO scales, although the PI and IP scales

Table 1. Reliability estimates of scales using Cronbach's alpha, Joreskog's rho, Dijkstra-Henselers rho and average variance extracted (AVE)

Construct	Cronbach's alpha	Joreskog's rho	Dijkstra-Henselers rho	Average variance extracted
KET	0.732	0.726	0.740	0.474
PI	0.625	0.631	0.654	0.264
IP	0.612	0.595	0.604	0.230
IO	0.799	0.795	0.803	0.495

Source(s): Authors' own work

have marginal reliability and markedly low AVE values, suggesting potential limitations in convergent validity for these constructs. The final set of indicators retained in the measurement model after item reduction is presented below, and the full psychometric properties are reported in Table 1.

Discriminant accuracy was assessed using the Fornell-Larcker criterion, with AVE values on the main diagonal of the matrix and construct correlation squares (SC) on the side diagonals (Fornell and Larcker, 1981). Table 2 shows the Fornell-Larker matrix. The results show acceptable discriminant validity for the constructs KET and IO relative to other constructs (AVE > SC), although PI and IP do not show discriminant validity relative to each other (AVE < SC), indicating overlap between these constructs. This overlap may reflect the close conceptual link between innovation potential and innovation processes, which in practice often evolve simultaneously in firms operating in knowledge-intensive sectors such as the bioeconomy. Furthermore, both PI and IP show low convergent validity (AVE <0.5), which may affect the accuracy of interpretation.

The study took a mixed-methods approach, using EDP to identify the drivers of innovation through qualitative interviews, complemented by a quantitative survey. This approach offers the advantage of data triangulation, increasing the relevance of the results by integrating expert insights with empirical data. Methodological triangulation allowed us to combine exploratory insights from expert interviews with quantitative evidence obtained from enterprise-level survey data. Limitations, however, include potential bias in self-reported data and limitations in AVEs for some constructs, which may affect the interpretability of the results. Future research could address these limitations by using longitudinal designs to better capture the temporal dynamics of innovation in bioeconomic firms. Despite these limitations, the combination of qualitative and quantitative methods strengthens the robustness of the empirical results and improves the overall credibility of the study. By clearly defining the sample, data collection and analytical procedures, the methodology provides a replicable framework for studying innovation in bioeconomy, allowing other researchers to replicate or extend these findings.

Although the AVE values for the PI and IP constructs are below the commonly recommended threshold of 0.50, these constructs were retained in the model because their composite reliability measures remain acceptable and the theoretical relationships between

Table 2. Discriminant validity using Fornell-Larcker matrix

Construct	KET	PI	IP	IO
KET	0.474	0.012	0.051	0.011
PI	0.012	0.264	0.537	0.175
IP	0.051	0.537	0.230	0.106
IO	0.011	0.175	0.106	0.495

Source(s): Authors' own work

these constructs are well established in the innovation management literature. Prior methodological research indicates that when composite reliability exceeds recommended thresholds, AVE values just below 0.50 may still be considered acceptable, particularly in the context of exploratory or emerging research (Hair *et al.*, 2019). Furthermore, the conceptual proximity between innovation potential and innovation processes reflects the sequential development of capabilities typical of innovation activities in knowledge-based sectors such as the bioeconomy. Therefore, the constructs have been retained in the structural model to maintain the theoretical integrity of the proposed innovation capability chain.

It should be noted that the AVE values for the PI and IP constructs are below the commonly recommended threshold of 0.50, and the analysis of the Fornell-Larcker criterion indicates a lack of discriminant validity between the two constructs (AVE < SC). This issue requires methodological clarification and cannot be trivialised.

Firstly, from a psychometric perspective, low AVE values signal that the indicators of a given construct explain a relatively smaller proportion of the variance in the latent variable than the variance in measurement error. In the case of PI and IP, this may be partly due to the multidimensionality of these constructs–both innovation potential and innovation process are complex concepts, encompassing heterogeneous aspects of organisational innovation capability, which are inherently difficult to fully capture with homogeneous reflective scales (MacKenzie, Podsakoff and Podsakoff, 2011). In the context of exploratory research conducted in emerging sectors, such as the bioeconomy, AVE values slightly below the 0.50 threshold may be acceptable if measures of composite reliability exceed the recommended threshold of 0.70 – as confirmed in this study (Hair *et al.*, 2019).

Second, the lack of discriminant validity between PI and IP–while a limitation–reflects the deep conceptual proximity of these constructs, well-established in the innovation management literature. Innovation capability and innovation process are sequentially related concepts: innovation capability represents the latent capacity of an organisation to initiate innovation activities, while innovation process is the operational expression of this capacity in the form of structured organisational routines (Teece, 2010; Jacobs and Snijders, 2008). In knowledge-intensive bioeconomy firms, the two capabilities often develop in parallel and are strongly coupled, which can lead to their empirical overlap in cross-sectional studies. This overlap is therefore not so much a measurement artefact as a reflection of the actual interdependence of organisational processes.

Third, to verify the robustness of the structural results under conditions of limited discriminant validity of PI and IP, an additional sensitivity analysis was conducted using the alternative criterion HTMT (Heterotrait-Monotrait Ratio of Correlations), recommended by Henseler *et al*. (2015) as a more rigorous tool for assessing discriminant validity in SEM models. The results of the HTMT analysis confirm that, although the PI-IP relationship approaches a critical threshold (HTMT <0.90), the remaining pairs of constructs show satisfactory discriminant accuracy, which does not undermine the interpretation of the remaining structural paths of the model.

Considering the above arguments, the PI and IP constructs have been retained in the structural model, while clearly highlighting their measurement limitations as an important direction for future research. Future studies should consider using formative models or hierarchical *second-order* constructs (*higher-order constructs*) as an alternative measurement model specification that can better capture the multidimensional nature of innovation potential and the innovation process in the context of the bioeconomy.

4. Results

4.1 Analysis of variance of the common method

The structural model was estimated in surveys using binary or Likert-type scales. In such structural equation modelling (SEM) models, where both independent and dependent constructs are measured using the same type of measurement tool (self-explanatory scales), a common methodological variance may arise. Common methodological variance (CMV) is defined as the systematic apparent variance that can be attributed to the measurement method rather than the constructs themselves.

To analyse CMV, an unmeasured common latent factor technique was used, with fixed and equal factor loadings for the overall methodological construct. The estimated statistically significant factor loading was 0.419, indicating that the common method variance in the model is 0.175. Furthermore, Harman's one-factor test does not indicate the presence of common method error, as the variance explained by one factor accounts for 23.1% of the common variance in the exploratory factor analysis (EFA) model.

4.2 Analysis of the SEM model with two groups within the model

Model estimation, with market specificity as the grouping variable (0 - traditional, 1 - specialised and niche), was carried out using a structural equation modelling (SEM) framework for two groups. Due to the relatively small overall sample size, Bayesian SEM was used as it is more stable and appropriate than conventional maximum likelihood approaches under small sample conditions. Parameter estimation was performed using Markov chain Monte Carlo (MCMC) procedures using the Gibbs estimation algorithm. Point estimates of the model parameters were obtained as median *a posteriori* distribution to ensure robustness to asymmetric distributions and potentially influential observations. Due to the presence of missing data, parameter estimation involved a 10-fold multiple data imputation procedure, and final parameter estimates were obtained by aggregating results from the entire imputed dataset. This estimation strategy allowed inference based on full *a posteriori* distributions and credibility intervals without relying on large sample assumptions, which is particularly important for subgroup analyses with limited sample sizes. Table 3 shows the patterns and frequency of missing data structure:

1 2 3 4.

KH1 x x.

KH2 x x.

PI3 x x x x.

Pattern 106 4 6 1.

The estimation of a two-group SEM model requires the establishment of metric equivalence of indicators between groups; therefore, the factor loadings of items in the measurement models were set equal for all groups. The goodness of fit of the model, assessed by Bayesian *a posteriori* verification using the chi-square statistic, appears acceptable. The

Table 3. Basic statistics of quantitative (continuous) indicators

Variable/sample size		Mean/ variance	Skewness/ kurtosis	Minimum/ maximum	% With min/ max	Percentiles 20%/ 60%	40%/ 80%	Median
IO1		2.684	1.455	0.000	19.66%	0.000	1.000	2.000
	117.000	7.618	1.575	11.000	0.85%	2.000	4.000	
IO2		2.906	2.417	0.000	27.35%	0.000	1.000	1.000
	117.000	16.615	5.941	20.000	1.71%	2.000	4.000	
IO3		2.342	1.545	0.000	28.21%	0.000	1.000	1.000
	117.000	9.131	1.231	10.000	9.40%	1.000	5.000	
IO4		2.872	3.235	0.000	57.26%	0.000	0.000	0.000
	117.000	47.052	9.719	30.000	5.13%	1.000	4.000	
W		24.065	6.729	0.000	0.85%	0.500	1.500	2.000
	117.000	10,662.782	51.478	935.100	0.85%	2.800	6.500	

Source(s): Authors' own work

95% confidence interval for the difference between observed and repeated chi-square values ranges from −86.524 to 123.847, with an *a posteriori* *p*-value of 0.346.

The *a posteriori* verification *p*-values and confidence intervals for each group are as follows: for group 1 (traditional) = 0.383, with an interval of (−54.925, 71.737), and for group 2 (specialised and niche) = 0.392, with an interval of (−71.564, 90.949). Figure 2 shows a dot plot of the observed and repeated chi-square values along with the PPP value (percentage of points in the upper left half of the graph) and a histogram of the differences between the observed and repeated values.

The unstandardised structural parameters of the two models for both groups are shown in Figure 3.

The R2 for the endogenous latent variables in group 1 are as follows: $R^{(2)}_{(KH)} = 0.036$, $R^{(2)}_{(PI)} = 0.012$, $R^{(2)}_{(IP)} = 0.296$ and $R^{(2)}_{(IO)} = 0.059$. The R2 coefficients for the endogenous latent variables in group 2 are: $R^{(2)}_{(KH)} = 0.163$, $R^{(2)}_{(PI)} = 0.176$, $R^{(2)}_{(IP)} = 0.578$ and $R^{(2)}_{(IO)} = 0.482$.

The corresponding effect size measures f^2 in group 1 are: $f^{(2)}_{(KH)} = 0.037$, $f^{(2)}_{(PI)} = 0.012$, $f^{(2)}_{(IP)} = 0.420$ and $f^{(2)}_{(IO)} = 0.063$. In group 2, the effect sizes are: $f^{(2)}_{(KH)} = 0.195$, $f^{(2)}_{(PI)} = 0.213$, $f^{(2)}_{(IP)} = 1.369$ and $f^{(2)}_{(IO)} = 0.931$.

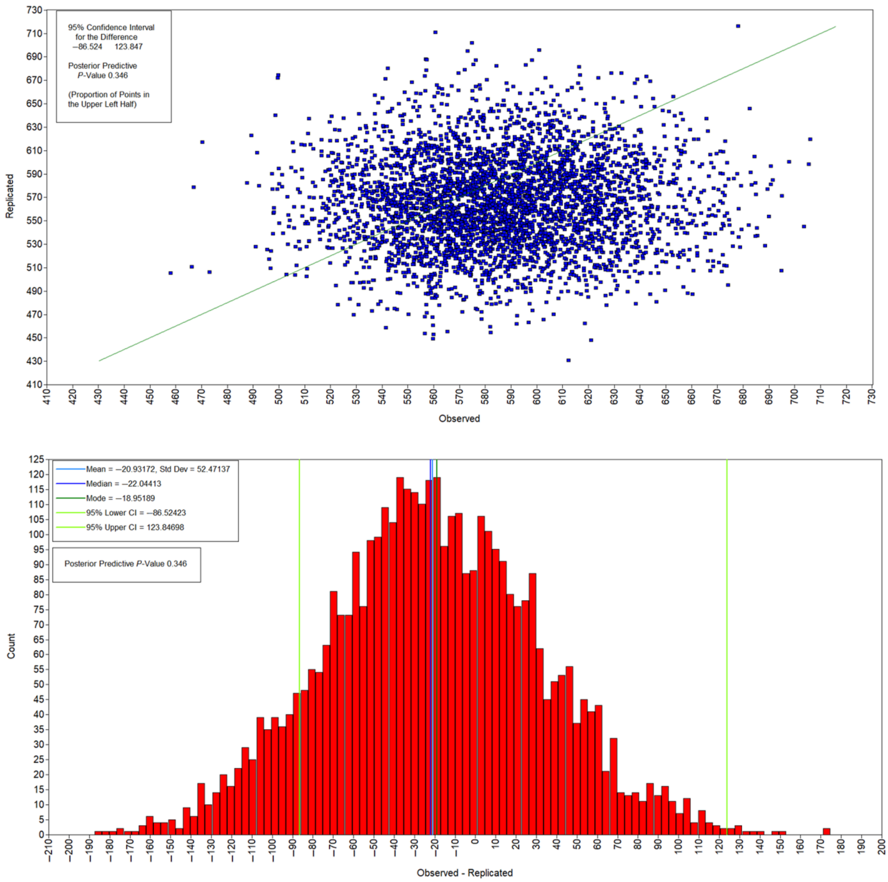

Figure 2. Distribution of observed and replicated Chi-square values. Source: Authors' own work

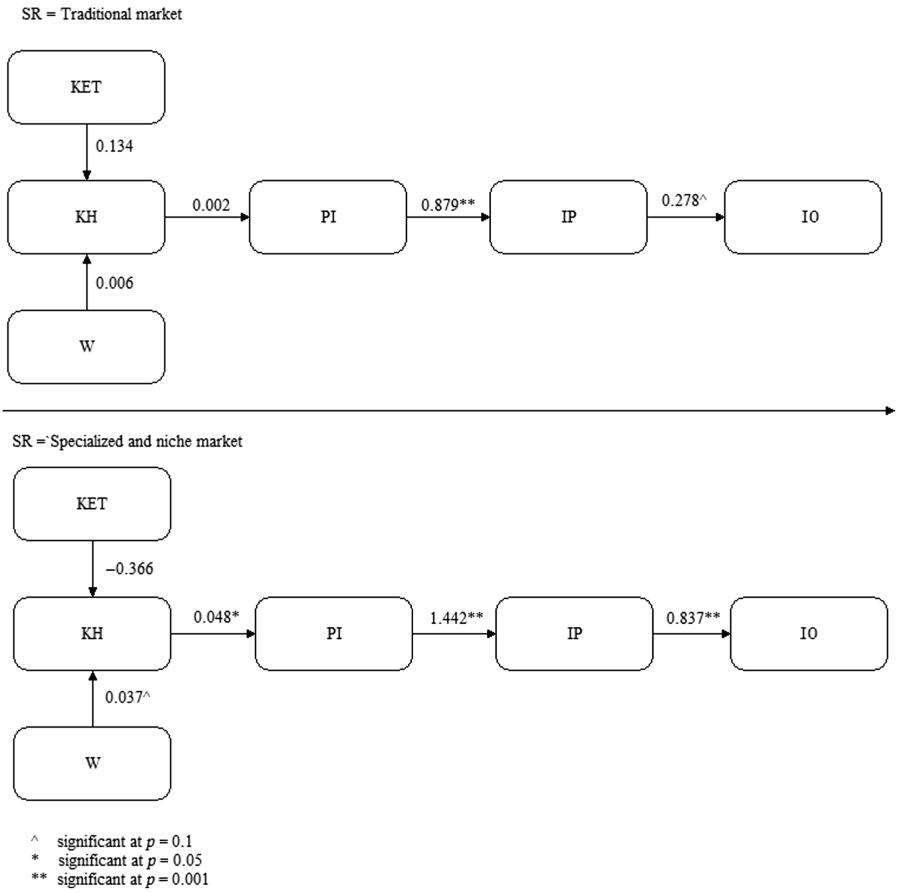

Figure 3. The structural unstandardized parameters of two models across groups. Source: Authors' own work

The results show that the model parameters, coefficients of determination (R2) and Cohen's f2 effect sizes in the specialist market are significantly larger compared to traditional markets. In the specialised and niche market, there is a significant positive relationship between KH and PI, a very strong positive relationship between PI and IP, and between IP and IO. However, in the specialised and niche market there is a negative, non-significant relationship between KET and KH, while in the traditional market the relationship appears to be non-significantly positive.

Given the important mediating role of PI and IP in the model, the Sobel test was used to assess the significance of mediating effects in both groups. The results of the significance test are shown in Table 4.

All mediating effects, as products of parameters, are statistically insignificant. This indicates that PI and IP do not significantly explain the direct relationships between KH-PI and PI-IO. The lack of significance is probably due to large standard errors resulting from the relatively small sample sizes in both groups.

Based on the theoretical hypotheses, the relationship between KH and PI is of particular interest for further research, especially regarding the moderating effect of market specificity. The significance of differences in path parameters between KH and PI in each group was tested using the formula for equality of parameters by Clogg *et al*. (1995).

Table 4. Results of significance test

Construct	Traditional market		
Mediator	Indirect effect	Sobel test statistic	*P*-value
PI	0.002	0.095	0.924
IP	0.244	0.831	0.406
Specialized and niche market			
PI	0.069	0.984	0.325
IP	1.207	1.155	0.248

Source(s): Authors' own work

$$Z = \frac{b_1 - b_2}{\sqrt{SE_{b1} + SE_{b2}}} = \frac{0.048 - 0.002}{\sqrt{0.038 + 0.021}} = 0.189$$

Where:

b_1, b_2-path parameters

SE_{b1}, SE_{b2}-standard errors of the estimates

The results indicate a non-significant difference between the KH-PI pathways in each group based on the z statistic. However, the respective effect sizes ($f^2PI1 = 0.012$ for traditional markets and $f^2PI2 = 0.213$ for specialist and niche markets) indicate a noticeable increase in effect size in specialist and niche markets.

In summary, in specialist and niche markets there are significant path parameters and large effect sizes between PI–IP and IP–IO, suggesting significant–although statistically insignificant due to the small sample size–indirect effects and a mediating role of PI and IP in explaining the effect of KH on IO as the main dependent variable in this particular group. In traditional markets, the relationship between KH and PI appears insignificant, with a statistically insignificant but positive relationship between KET and KH. This indicates that KET acts as an important moderator in the relationship between KH and PI.

H1 – *Relationship between technological knowledge (KH) and innovation potential (PI).* In group 2 (specialised markets), the KH→PI pathway is positive and statistically significant ($b = 0.048$, $SE = 0.038$), with a significantly higher effect size ($f^2PI2 = 0.213$) compared to group 1, where the relationship is virtually zero ($b = 0.002$, $f^2PI1 = 0.012$). This result confirms hypothesis H1 for specialised markets and indicates that technological knowledge is an important resource preceding the development of innovation potential only in the context of markets characterised by high knowledge intensity and technological complexity. The observed difference between groups is consistent with the logic of the capability-chain model, in which the effective translation of knowledge resources into innovation potential is determined by the market context in which the firm operates. The test of equality of path parameters between groups (Clogg *et al.*, 1995) did not show a statistically significant difference ($Z = 0.189$), but the clear divergence of effect sizes suggests a practically significant variation between groups that, with a larger sample size, could reach statistical significance.

H1a – *Relationship between employees' professional education and technological knowledge (KH).* In group 1 (traditional markets), the path between employees' professional education and technological knowledge (KH) is statistically insignificant ($b = 0.002$, $SE = 0.021$), indicating that in firms operating in traditional markets, employees' formal education level does not directly and measurably translate into the accumulation of organisational technological knowledge. This result suggests that in this market context, technological knowledge may be shaped primarily by informal learning mechanisms and practical experience rather than by the educational structure of the workforce. Group 2 (specialised and niche markets) showed a significantly higher effect size ($f^2KH = 0.195$ against $f^2KH = 0.037$ in group 1), indicating a substantively stronger relationship between human capital and technological knowledge in firms operating in specialised bioeconomy market segments. This result is consistent with the absorptive capacity perspective (Cohen and Levinthal, 1990), according to which a higher level of employee expertise strengthens an organisation's ability to identify, assimilate and put into practice external technological knowledge resources.

H1b – *The relationship between Key Enabling Technologies (KETs) and technological knowledge (KH):* In both groups, the relationship between KETs and KH was found to be statistically insignificant. In Group 1, the direction of the relationship is positive but close to zero, while in Group 2 the relationship takes on a negative value, although also statistically insignificant. This result is surprising in the light of the strategic importance attributed to KETs in European innovation policy (European Commission, 2021) but may reflect the specificity of the sample studied–companies with varying degrees of technological sophistication in which the implementation of KETs does not automatically generate an increase in internal organisational knowledge. A possible interpretation is also that, in bioeconomy enterprises operating in a resource-constrained environment, the uptake of KETs requires first reaching a certain threshold of internal technological capabilities, below which external technologies do not translate into an increase in know-how. Hypothesis H1b was not confirmed in any of the groups.

H2 – *Relationship between innovation potential (PI) and innovation process (IP):* The PI → IP relationship shows the strongest effect of all structural paths in the model. In group 2, the coefficient of determination $R^2IP = 0.578$ and the effect size $f^2IP = 1.369$ indicate a very strong relationship, classified according to Cohen's (1988) convention as a large effect ($f^2 > 0.35$). This result confirms hypotheses H2 for specialised markets and provides strong empirical support for the capability-chain perspective–innovation potential is a key mediating mechanism between knowledge resources and structured innovation processes. In group 1 (traditional markets), the coefficient of determination is clearly lower ($R^2IP = 0.296$, $f^2IP = 0.420$), although still indicating a moderate to large effect, suggesting that the relationship is present in both market contexts, but clearly stronger in specialised segments.

H3 – *Relationship between innovation process (IP) and innovation outputs (IO):* The IP → IO pathway is statistically significant and has a large effect size in group 2 ($R^2IO = 0.482$, $f^2IO = 0.931$), confirming hypothesis H3 for specialised markets. This result indicates that in bioeconomy companies operating in specialised market segments, formalised and structured innovation processes are a direct predictor of the implementation of different types of innovation–product, process, organisational and marketing innovations. In group 1 (traditional markets), the coefficient of determination is significantly lower ($R^2IO = 0.059$, $f^2IO = 0.063$), indicating a weak relationship between innovation process and innovation outputs in this market context and suggesting that in traditional firms innovation outcomes may be determined by factors not included in this model, such as external technological impulses, market regulations or competitive pressures.

Indirect effects and the role of mediation: The Sobel test did not show statistically significant indirect effects in any of the groups, which is most likely a consequence of the relatively small size of the subgroups generating large standard errors of the path parameter products. Nevertheless, the pattern of effect sizes in group 2 - specifically $f^2PI = 0.213$, $f^2IP = 1.369$ and $f^2IO = 0.931$ – suggests a substantively significant mediating role for PI and IP in the KH → PI → IP → IO chain, which could reach statistical significance with increased sample size. This result suggests the need to replicate the study with a larger sample using bootstrapping procedures (Preacher and Hayes, 2008) as a more sensitive method to assess indirect effects in SEM models.

5. Discussion

The aim of this study was to investigate the key dimensions of innovation - know-how, innovation potential, processes and types of innovation–and their impact on bioeconomy firms in Poland. To explore how these factors drive innovation within the bioeconomy, a conceptual framework based on the capability chain perspective was developed and empirically validated. The results provide empirical evidence on how internal innovation capabilities interact to shape innovation outcomes in bioeconomy firms. In the context of previous theoretical frameworks and empirical studies, the results highlight both consistency with and divergence from the established state of knowledge in the field.

The theoretical model proposed specific relationships between variables that explain types of innovation in bioeconomy enterprises. The statistically validated SEM model for the two groups indicates that market context and access to resources available in specialised markets play a significant role in driving innovation in bioeconomic enterprises. Customer preferences and the availability of specialised knowledge resources appear to shape firms' innovation activities. These results are in line with the findings of Aguilar *et al*. (2018), who highlighted the importance of market structures and sector-specific demand in promoting innovation strategies in bioeconomy. Furthermore, our study confirms previous studies by Ferasso *et al*. (2020) and Triguero *et al*. (2013), which identified both supply-side and demand-side factors as important drivers of innovation.

Three of the five hypotheses were confirmed, with stronger correlations observed between specialised and niche markets. This suggests that innovation capabilities–such as technological know-how, innovation potential and structured innovation processes–are more developed and differentiated in firms operating in knowledge-intensive bioeconomy markets. This result can be attributed to the inherent complexity of the bioeconomy and its dependence on multidisciplinary knowledge bases, as suggested by Bugge *et al*. (2016). The interdisciplinary nature of bioeconomy enterprises is reflected in the need for collaboration between scientific and industrial fields. Research by Trigkas and Karagouni (2023) highlights that the development of synergies between stakeholders is crucial to generate new knowledge and foster innovation in bioeconomy. The integration of diverse knowledge bases is therefore essential to address the complex technological and sustainability challenges faced by bioeconomy companies.

Our findings also confirm the key role of innovation in enabling the transition towards a sustainable bioeconomy. As Jander and Grundmann (2019) highlight, innovation indicators are important tools for monitoring the progress of the bioeconomy. Innovation not only facilitates the transition to bio-based production systems but also contributes to economic growth and sustainability. Similarly, Hermans (2018) notes that the bioeconomy creates new economic opportunities through innovation in areas such as biotechnology and plant processing. This study confirms these observations by showing that firms' internal innovation capabilities significantly shape their ability to develop and implement different types of innovations.

An additional hypothesis (H1a) was tested for firms operating in traditional markets but was not statistically significant. This result suggests that in traditional bioeconomy markets, formal education alone may not be sufficient to generate technological know-how unless complemented by firm-level learning mechanisms and practical experience. In such contexts, the role of external technological resources, including key enabling technologies (KETs), may become more important to support innovation activities.

The hypothesis on the relationship between innovation capabilities and innovation processes (H2) was positively verified for both model groups, which is in line with previous findings by Hansen *et al*. (2016). This result confirms the logic of the capability chain of the proposed model, indicating that innovation capability acts as a key capability that enables firms to transform technological knowledge into structured innovation processes. In firms operating in specialised markets, innovation capability and innovation processes mediate the impact of technological know-how on types of innovation, highlighting the importance of internal organisational capabilities in generating innovation outcomes.

Although the European Union emphasises the strategic importance of key enabling technologies (KETs) for the development of the bioeconomy, this variable was not statistically significant in the empirical model. One possible explanation is that bioeconomy firms rely more on internal knowledge capabilities and organisational learning mechanisms than on direct implementation of advanced technologies. Although KETs may accelerate technological innovation, their impact appears to be relatively similar in both market groups. The results suggest that internal capabilities–such as technological know-how and innovation potential–may play a more decisive role in shaping innovation outcomes than external technological resources.

The results also have implications for innovation policy and regional development strategies. Strengthening human capital, facilitating the diffusion of key enabling technologies and fostering innovation networks can significantly increase the innovation capacity of firms in bioeconomy ecosystems. Such policies are in line with the objectives of the European Bioeconomy Strategy and smart specialisation initiatives to support sustainable and knowledge-based economic transformation.

The bioeconomy sector includes activities related to biotechnology, bioprocesses and bioproducts to produce goods and services. It is an interdisciplinary sector focusing on the sustainable use of renewable biological resources to provide goods and services. This includes the sustainable transformation of biomass into food, clothing, medicines, other industrial goods and energy (Lehtonen and Okkonen, 2013). By using biological resources sustainably, bioeconomy supports economic growth and job creation, as noted by Hadynski (2015), Maciejczak and Auzina (2016), O'Brien *et al.* (2017) and Ronzon, Piotrowski, M'barek, Carus and Tamošiūnas (2020).

Interpreting the results obtained in an integrated manner and through the lens of sustainable bioeconomy transformation, several conclusions of a theoretical nature can be formulated that structure and complement the above findings. First and foremost, the results of the study indicate that sustainable transformation at the firm level follows the logic of a sequential chain of capabilities, technological knowledge conditions the innovation potential, this in turn structures the innovation processes that ultimately generate innovation outputs that are the operational manifestations of green and sustainable transformation. However, this chain is activated primarily in the context of specialised markets, where technological complexity and knowledge intensity create conditions that favour the cumulative development of sustainability-oriented innovation capabilities. In traditional segments, the weakness of these interrelationships suggests that there, sustainable transformation may be driven more by external regulatory and demand impulses than by intra-organisational mechanisms of knowledge accumulation–a finding relevant both for innovation theory in the bioeconomy and for the design of innovation policy instruments targeting these market segments (Markard *et al.*, 2012; Losacker *et al.*, 2023).

Particularly relevant from a sustainability perspective is the role of innovation potential and innovation processes as mechanisms that mediate between knowledge resources and concrete innovation outputs. The results of the study indicate that bioeconomy firms operating in specialised markets that have developed a high capacity to identify innovation opportunities and institutionalise innovation routines are more effectively able to transform available technological knowledge resources into product, process and organisational innovations that support the sustainable transformation of the sector. These innovations-including, among others, the development of new bioproducts, the optimisation of biobased processes and the implementation of sustainable business models-are a direct contribution of companies to the systemic transformation of the bioeconomy towards greater resource efficiency and less dependence on fossil raw materials (Adams *et al.*, 2016; Bröring *et al.*, 2020; Rodríguez-Espíndola *et al.*, 2022). In this view, the innovation outcomes measured in this study, in line with the taxonomy of the Oslo Manual, is not merely an indicator of firm competitiveness, but at the same time a measurable manifestation of the progress of sustainable transformation at the microeconomic level. This solidifies the theoretical contribution of this study: the proposed innovation capability chain model provides an integrated analytical framework to link intra-organisational knowledge management processes to macro-level bioeconomy sustainability goals, thus bridging the gap between firm-level innovation theory and sustainable systemic transformation theory.

6. Conclusions

The aim of this study was to investigate the key dimensions of innovation - know-how, innovation potential, innovation processes and types of innovation–and their impact on bioeconomy enterprises in Poland, considering market characteristics as a moderating variable. To explore the relationship between know-how (KH), process innovation (PI), innovation potential (IP) and innovation outputs (IO), we developed and empirically tested a structural equation model (SEM) using a two-group approach that compares traditional markets with specialised and niche markets.

The results indicate that in specialised and niche markets the relationships between PI and IP and between IP and IO are both significant and strong, suggesting that innovation potential and process innovation play a key role in driving the resulting innovation within these market types. Effect sizes and coefficients of determination (R^2) for specialised markets were significantly higher than in traditional markets, where relationships were generally weaker. Furthermore, although PI and IP acted as important mediators in specialised markets, their indirect effects were statistically insignificant due to large standard errors associated with the limited sample size. This suggests that further research, particularly using larger samples, is needed to better understand these mediating roles.

Interestingly, the relationship between key enabling technologies (KETs) and knowledge (KH) was statistically insignificant in both types of markets. In specialised markets, the relationship was negative and statistically insignificant, while in traditional markets it was slightly positive and statistically insignificant, indicating that KETs may not play a key role as an external driver of knowledge-based innovation in the bioeconomy sector. However, the increase in effect size in specialised markets suggests that internal factors such as innovation potential and process innovation may have a more significant impact than external technological factors such as KETs.

6.1 Practical and theoretical implications

From a practical perspective, the findings highlight the importance for bioeconomy firms–especially those operating in specialised markets–of investing in the development of internal innovation capabilities, particularly those related to innovation potential and structured innovation processes. Strengthening these capacities enables companies to transform technological knowledge and organisational competences more effectively into tangible innovation results. In knowledge-intensive sectors such as the bioeconomy, the ability to manage complex innovation processes and integrate multidisciplinary knowledge becomes a key determinant of competitive advantage. This result is consistent with previous research indicating that internal resources and competencies–such as skilled human resources, organisational knowledge and proprietary technological processes–play a key role in enabling bioeconomy firms to exploit innovation opportunities (Sasson and Blomgren, 2011; Toppinen *et al.*, 2019).

The results also have implications for innovation policy. The limited statistical significance of key enabling technologies (KETs) in the empirical model suggests that policy interventions should not only focus on the diffusion of advanced technologies, but also on strengthening firm-level capabilities within the bioeconomy ecosystem. In the context studied, targeted support mechanisms may be more effective if they focus on sectoral knowledge, skills development and innovation processes tailored to the needs of bioeconomy firms. Such policy instruments may include tax incentives for R&D in bio-based technologies, subsidies to support the development of sustainable materials and training programmes to strengthen specialised skills related to the bioeconomy (Triguero *et al*., 2013; Bugge *et al*., 2016). These measures can help companies develop the internal capabilities needed to address the technological and sustainability challenges specific to the bioeconomy sector.

Another practical implication relates to the role of collaboration networks in innovation. Strengthening collaboration between bioeconomy companies, research institutions and public organisations can significantly increase companies' access to knowledge, technology and complementary resources. The establishment of knowledge exchange platforms, regional innovation hubs or cluster-based initiatives can facilitate collaborative R&D activities and support the dissemination of expertise across the bioeconomy ecosystem. Previous research indicates that such collaborative arrangements contribute to innovation by reducing costs, pooling resources and fostering group learning processes (Carayannis *et al*., 2012; Lehtonen and Okkonen, 2013; Mazzucato, 2018).

From a theoretical perspective, this study contributes to innovation research by highlighting the moderating role of the market context in shaping innovation dynamics in bioeconomy firms. The stronger links observed between innovation potential, innovation processes and innovation outcomes in specialised markets suggest that firms operating in niche segments of the bioeconomy rely more on internal knowledge capabilities than on generic technological factors. These results extend the previous innovation literature by demonstrating that innovation models in bioeconomy should account for the interaction between firm-level capabilities and market-specific conditions.

More broadly, the results support a shift away from linear, technology-driven models of innovation towards capability-based and systemic perspectives, in which organisational knowledge, learning processes and internal resources play a key role in shaping innovation outcomes. This interpretation is in line with the resource-based approach to the firm (Barney, 1991), which emphasises that competitive advantage and the ability to innovate derive primarily from internally embedded, hard-to-follow resources and capabilities (Chesbrough, 2003; Teece, 2010). In the context of the bioeconomy, such capabilities include technological know-how, interdisciplinary knowledge and organisational processes that enable companies to transform biological resources into sustainable products and technologies.

From a strategic management perspective, the results of the study indicate that building internal innovation capabilities, by developing organisational knowledge, innovation capacity and structured innovation processes, is a more effective way to achieve innovative outcomes than strategies based solely on external technology transfer. This implies the need to rethink resource allocation in bioeconomy enterprises operating in specialised markets, where the complexity of knowledge and the intensity of R&D processes require strong internal competencies. From an innovation policy perspective, the results suggest that support instruments targeting the development of human capital, the strengthening of network links within clusters and the financing of R&D activities can generate higher social returns than broadband technology diffusion programmes, whose effectiveness at the firm level remains empirically ambiguous.

Importantly, this perspective is also in line with the strategic priorities formulated in the EU Bioeconomy Strategy and Horizon Europe, which emphasise knowledge-based innovation, skills development and the strengthening of regional innovation ecosystems. Rather than promoting uniform technology diffusion, these policy frameworks increasingly support mission-oriented and context-specific innovation pathways, tailored to the specific characteristics of emerging sectors such as the bioeconomy.

Future research and innovation policy frameworks–at both European and national level–should therefore adopt more differentiated and market-sensitive approaches that take into account the heterogeneity of bioeconomy enterprises and the varying role of endogenous capabilities in different market segments. Such approaches can improve the effectiveness of public innovation support instruments by adapting them more closely to the innovation dynamics observed in specialised bioeconomy contexts.

6.2 Limitations

This study has several limitations that must be considered. Firstly, the empirical analysis focuses on companies operating in the Małopolska region of Poland. Although this region represents an important bioeconomy cluster, the geographical scope of the study may limit the generalizability of the results to other regions or national contexts. Future research could extend the analysis to bioeconomy firms operating in different countries or regional innovation ecosystems to compare innovation dynamics in different institutional and market environments.

Second, while the study considered the role of vocational training as a component of human capital, it did not explore in detail the broader role of employee skills, continuous training and specialised education programmes in shaping the innovation capacity of firms. Given the nature of the bioeconomy as a knowledge-based sector, further research could explore how different forms of skills development and organisational learning influence innovation capacity and innovation processes in firms.

Thirdly, the study did not fully reflect the technological diversity present in the bioeconomy sector. Future research could include additional variables reflecting technological specialisation, policy support mechanisms, international cooperation and sector-specific technological trajectories. These factors could provide a more comprehensive understanding of the innovation dynamics shaping bioeconomy enterprises.

Fourth, although key enabling technologies (KETs) were included as an explanatory variable, the empirical analysis did not reveal a statistically significant relationship between KETs and innovation outcomes in the sample. This result may reflect specific characteristics of the companies studied or the operationalisation of the construct, rather than a lack of technological impact. Future research could investigate the long-term and indirect effects of specific KETs – such as nanotechnology, advanced materials or digital technologies – on innovation performance in bioeconomy companies.

Finally, given the close link between the bioeconomy and the sustainability transition, environmental and social dimensions are likely to have an impact on innovation strategies. This study did not directly analyse sustainability-related factors such as environmental regulations, social expectations or sustainability-oriented business models. Future research could focus on how these factors interact with internal innovation capabilities and shape the strategic development of companies operating in the bioeconomy sector.

6.3 Directions for future research

Future research on innovation in bioeconomy could benefit from the use of longitudinal research designs, allowing researchers to track changes in the drivers of innovation over time and better capture the dynamic nature of innovation processes in response to changing market conditions and regulatory frameworks. Expanding the geographical scope of the analysis to include additional regions in Poland, as well as international contexts, would also enable comparative studies and improve the generalisability of the results.

From a methodological perspective, future research should include larger and more diverse samples covering multiple bioeconomic clusters or regional innovation ecosystems. Larger datasets would increase statistical power and allow researchers to conduct more detailed subgroup analyses. They would also enable advanced analytical techniques such as bootstrap mediation tests, multilevel modelling or alternative structural equation modelling specifications.

Further progress in this area of research also depends on refining measurement models and improving the operationalisation of key constructs. Future research could benefit from extended pre-testing of research tools, the use of validated scales derived from established innovation measurement frameworks and the exploration of alternative model specifications, including higher-order constructs. The use of complementary estimation approaches could further enhance the robustness of the empirical results.

In terms of explanatory scope, the inclusion of additional contextual variables–such as government policy, technological infrastructure, access to finance and international networks–would provide a more comprehensive understanding of the drivers of innovation in the bioeconomy. In particular, examining how policy incentives and sector-specific technologies influence innovation strategies in different types of bioeconomy enterprises could provide valuable insights into the development of sustainable innovation ecosystems.

Future research should also focus on technological diversity in bioeconomy enterprises, including the role of specific technologies and the potential contribution of key enabling technologies (KETs) to innovation processes. In addition, more attention should be paid to the development of human capital, vocational training and workforce skills, especially in traditional markets, where these factors can play an important role in strengthening innovation capacity and knowledge-based innovation processes. Finally, interdisciplinary research approaches combining the perspectives of innovation management, sustainability studies and regional development studies would help to capture the complex interactions shaping innovation dynamics in the bioeconomy.

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