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Tracing innovation efficiency: Review and bibliometric analysis

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Abstract:

While "innovation efficiency" has become widespread and intuitive to many over the past few decades, its definition, measurement, and understanding have evolved. This paper offers a review of the economic literature centred on the dynamics of the innovation efficiency concept. We conducted a bibliometric analysis of 5,123 scholarly publications on Scopus to broaden the understanding of innovation efficiency phenomena, complemented by an in-depth science map analysis of 764 publications. We illustrate the accelerated growth of literature in the innovation-efficiency domain in recent years. Despite this significant growth, research in this area remains fragmented, underscoring the need for the systematic approach undertaken in this study. Through the bibliometric analysis, we discerned that the focus of innovation-efficiency-related studies has shifted from internal organisational issues to a comprehensive perspective on innovation, encompassing exogenous elements and external sources of innovation. We delineate three periods in the evolution of central themes within the innovation efficiency domain from 1998-2022: Initial focus on individual firms' performance, progressing to external and network determinants of innovation, and recently, the link between innovation efficiency and green innovation in the third period. We also identified two primary research methodologies: (i) Qualitative surveys and (ii) Quantitative methods using regression analysis, mathematical models, and data envelopment analysis. Scientists, policymakers, and investors can utilise these findings to gain insights into the paramount aspects underpinning research in the innovation efficiency phenomena.

Keywords: **bibliometrix, bibliometrix analysis, economic growth, efficiency, innovation, technology.**

Classification numbers: ***2.2, 7***

Highlights

- The perception of innovation efficiency is dynamic.
- Bibliometric analysis is utilised to broaden the understanding of innovation efficiency phenomena.
- Three periods of evolution within the topic of innovation efficiency are identified.
- Innovation efficiency is being increasingly viewed as holistic and associated with sustainability.

1. Introduction

The term 'innovation' has been growing in popularity among economists, policymakers, and business leaders worldwide in recent decades. Innovation is often cited as a driver of technological progress, productivity enhancement, and economic growth, and is crucial for modern governance [1-6]. Whilst seemingly intuitive, the concept of innovation has been challenging to define and precisely measure [7, 8]. Efficiency is a pivotal concept in the innovation domain, as investing in innovation is not a desired activity per se: the outcomes or outputs of the innovation process are paramount for society, hence the emphasis on innovation efficiency. A. Nigg-Stock, et al. (2023) [9] articulated, "*In today's fast-changing world, it is essential not only to be innovative but also to innovate efficiently*".

Innovation efficiency has been the subject of study for some time. The inaugural attempt to explore innovation efficiency dates back to the 1960s when B.R. Mitchell and J. Schmookler introduced the idea

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(1968) [10]. Recently, due to the swift advancement and transformative influence of digital technologies, assessing the performance and efficiency of innovation systems has emerged as a focal topic in academic research and policy dialogues, especially considering the development of integrated benchmarking systems in knowledge-driven economies [11-14]. Despite the topic's evident growth in recent years, research in this realm remains disjointed [15, 16]. Therefore, a compelling case exists for this paper to pursue further systematic exploration.

This paper seeks to offer a comprehensive and systematic analysis of research on innovation efficiency. Specifically, we centre on the following research questions: (1) How is "innovation efficiency" characterised, and how has this notion evolved over time?; (2) What methodologies exist to measure innovation efficiency at diverse governance levels?; (3) Which key journals, authors, institutions, and regions are instrumental in this research domain?; (4) What are the principal topics, research trajectories, and evident lacunae in the literature on innovation efficiency, as unveiled through an examination of the prevailing body of work?

We perceive innovation efficiency as a multifaceted and evolving phenomenon. We address the initial two research questions via literature review, augmented by a bibliometric analysis pertinent to the third and fourth questions. Our method encompasses a bibliometric analysis of 5,132 scholarly publications on Scopus to enhance understanding of what innovation efficiency entails and its changing perception over time. Through the bibliometric approach, we scrutinise the trajectory of research on innovation efficiency, delve into the intellectual framework of the topic, and pinpoint emerging trends and gaps in the research domain.

Bibliometric analysis techniques are prevalent in economic and policy research [17, 18]. These methodologies encompass citation analysis, keyword co-occurrence analysis, conceptual structure, and thematic map analyses [19]. Contrary to meta-analysis, where the emphasis is on summarising literature by gauging the direction and intensity of variable relationships, bibliometric analysis concentrates on the social and structural relationships of research components such as authors, countries, and keywords [20].

The remainder of the paper is outlined as follows. Section 2 elucidates the definition and evolution of innovation efficiency and surveys existing literature. Section 3 details the research methodology for the bibliometric analysis. Section 4 presents analysis and discourse, and Section 5 culminates the paper, highlighting its contributions and suggesting avenues for subsequent research.

2. Background: Defining and measuring innovation efficiency

While the term "innovation" has been increasingly used in the literature and policies, there is a lack of consensus on its definition and the measures of innovation.

Academic literature often cites Joseph A. Schumpeter as the pioneer of the modern definition of innovation, the "technical change" in his words under his paradigm of "creative destruction" [21, 22]. In his definition, Schumpeter provided a list of changes such as new products, new production methods, new materials, etc., of which the central feature is novelty, or what is also referred to in the literature as "newness" [23]. More recently, a qualitative survey by S. Singh and Y. Aggarwal (2022) [24], undertaken in search of a consensus definition of innovation, also highlighted "newness" as the most common and critical dimension of innovation.

However, "newness" is a relatively broad and ambiguous concept, which is also challenging to measure. Newness does not encompass the intensity, sources, and results of innovation - important criteria needed to distinguish innovation from other changes in business operations or products.

International organisations and government bodies also define innovation in various ways. It is interesting to observe the evolution of the definition by the Organisation for Economic Cooperation and Development (OECD). The early definition by OECD (2015) [25] was *"... all those scientific, technical, commercial and financial steps necessary for the successful development and marketing of new or improved manufactured products, the commercial use of new or improved processes or equipment or the introduction of a new approach to social service. R&D is only one of these steps."* It is a complex definition tracing the journey from idea or invention to application in practice.

Not surprisingly, this definition posed difficulties in measuring and defining the stages of innovation. In the latest OECD series on instruction for innovation data collection, innovation is defined as *"a new or improved product or process (or a combination thereof) that differs significantly from the unit's*

previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)" [25]. Comparing the two OECD approaches, we see that the definition has been remarkably simplified and brought back to the essence of Schumpeter's definition - the newness. The latter definition is also centred around the results, which became a focus of several definitions of innovation. For instance, the concept of innovation by the Business Council of Australia (1993) [26] mentioned "*create added value either directly for the enterprise or indirectly for its customers*" in their definition of innovation.

Innovation efficiency is tied to the concept of productivity. Innovation efficiency improves when, with the same amount of innovation inputs, more innovation outputs are generated, or when fewer innovation inputs are needed for the same amount of innovation outputs. Innovation efficiency can thus be defined as the ability to transform innovation investments into outcomes such as products and profits [9, 27] In these terms, innovation efficiency and innovation productivity are closely related concepts, although not synonymous. Since applied economics research literature uses one to define the other [28, 29], we chose to use both terms as keywords ("innovation efficiency" and "innovation productivity") to ensure we capture the domain fully. While the definition of innovation efficiency seems intuitive, the task of measuring innovation efficiency is not straightforward. Different types of innovation require different investments (inputs) and return different outcomes (outputs), which are difficult to grasp both in theory and in practice. Several approaches and frameworks have been developed in the literature to measure innovation efficiency. They can be broadly categorised into qualitative and quantitative approaches. In this study, we focus on the quantitative approach to assess innovation efficiency.

The two primary quantitative evaluation methods for innovation efficiency are Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA). The SFA method is a parametric and deterministic approach based on economic theory, first presented by D. Aigner, et al. (1977) [30] and W. Meeusen, J. van Den Broeck (1977) [31]. This approach assumes a knowledge production function and uses econometrics to estimate unknown parameters to identify the potential frontier quantitatively.

In contrast, the DEA method is a non-parametric and non-deterministic methodology, first introduced by A. Charnes, et al. (1978) [32]. The distinct features of DEA are as follows: Firstly, it relaxes the restrictions of SFA on a specific production frontier and thus allows uncertainty in the production relationship between input and output variables. Secondly, it uses linear programming techniques to trace the efficiency frontier and thereby avoids the subjectivity of function choice. Thirdly, it accommodates scenarios of multiple inputs and outputs and non-linearity, which is more apt for estimating the efficiency of individual decision-making units. As a result, DEA has long been regarded as the preferred method to measure innovation efficiency in the literature.

The current literature has explored various evaluation methods of innovation efficiency based on DEA methods. Most of the early literature in the field focused on measuring innovation efficiency from a static perspective. This static perspective postulates a single-period framework for the innovation process and leans heavily on single-year analysis. However, static models do not allow for the incorporation of time into the analysis. Several studies have tried to extend these conventional models by dividing the entire innovation process into different production stages, leading to a series of network DEA models. One is to use the Malmquist index. For instance, L. Yun (2011) [33] employed the Malmquist index to evaluate innovation efficiency. Another is the dynamic network DEA models [34-36].

We discussed that innovation is a complex, dynamic phenomenon. However, innovation is also a multilevel concept since firm, regional, and national innovation systems coexist, co-evolve, and interrelate. There are distinct elements in each system. For example, national innovation systems involve mechanisms where co-national innovation systems form the framework for producing a country's innovation, while regions might follow different regimes and exploit innovation inputs differently. As a result, there are multiple quantitative approaches that assess innovation efficiency at the national, regional, sectoral, and firm levels. Literature studying innovation efficiency phenomena at different levels of governance utilises a concept of "innovation performance" to discuss and measure innovation efficiency [9, 37].

At the firm level, organisations apply key performance indicators (KPIs) to show performance and help manage innovation. At the regional level, the traditional approach would be to use indicators such as the number of patents, workforce size, innovative products, and share of research and development (R&D) activity. More recently, however, an increasing number of studies have shifted focus from traditional

linear indicators to delineating the diversity of resources required for innovation, the non-linearity of the innovation process, the varied meaning of innovation, and the innovators' connection to and dependence on global competitive market forces and their immediate socio-economic and institutional environment. Researchers argued that the regional and national knowledge infrastructure, perceived mainly as a mix of universities, research institutes, R&D workers, R&D expenditure, and regional technology policy, is crucial for firms' innovative performance. Digital technologies are also identified as key for innovation at the firm level [38].

One highlight in regional and national innovation studies is the spillover effect. X. Li (2009) [39] analysed innovation at the regional level and concluded that innovation activities are spatially heterogeneously distributed, and knowledge production tends to localise spatially. Other studies also confirmed the spatial agglomeration effect of regional innovation activities [33, 34, 39, 40].

At the national level, the National System of Innovation (NSI) concept emerged at the end of the 1980s [41, 42]. Since then, NSI has attracted interest from both academia and policymakers and become one of the most important concepts to emerge in studies in the domain of innovation efficiency. NSI focuses on the interaction of different stakeholders in the system and analyses how various social, economic, institutional, environmental, and technical factors affect those interactions [43].

The Regional Systems of Innovation (RSI) concept rests on the relationship between technology, innovation, and industrial location [44]. Each region has its assets, strengths, competitive advantages, and capabilities. Studies on regional innovation systems focus on assessing the spillover effect of innovation across regions, and factors that affect regional innovation efficiency [34]. Although many aspects of the NSI approach can be applied at the regional level, the RSI approach differs significantly from the former [45]. The issues commonly explored at a regional level include the relationships between firms, the role of the public sector and public policy, as well as the institutional set-up of industries and sectors of the economy.

Overall, the background study of the literature demonstrates that the concept of innovation efficiency, along with the approaches to measure innovation efficiency, is complex and dynamic. However, the literature is fragmented, and systematisation is required to unveil the specifics of these dynamics. The following bibliometric analysis aims to address this gap.

Having defined innovation efficiency as a focal topic of this study, we also acknowledge its strong connection to the concepts of "innovation performance" and "innovation productivity," which tend to dominate in certain areas of the domain literature. This conclusion will form a basis for shaping the methodology and selection of search keywords for the bibliometric analysis to follow.

3. Data and methodology

The methodology of this study is summarised in Fig. 1 and includes four steps: (i) data collection and cleaning; (ii) performance analysis; (iii) science mapping; and (iv) synthesis of research implications. The detail of our methodology is described below.

Data collection: The data for this bibliometric analysis are sourced from Scopus. Introduced in 2004,

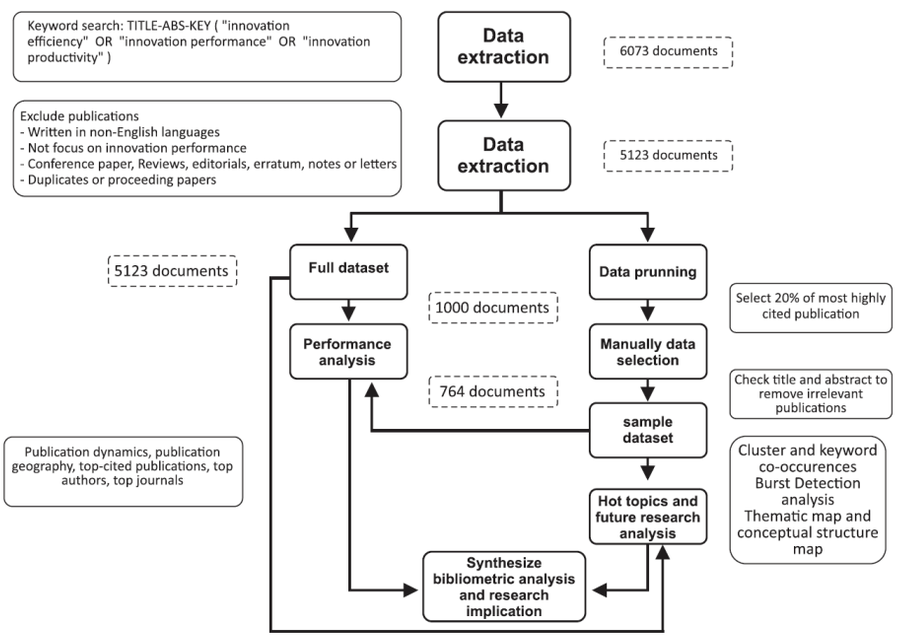


Fig. 1. Methodology framework.

Scopus is amongst the largest abstract and citation databases of peer-reviewed scientific works [46], with comprehensive coverage of disciplines including social sciences and humanities [47]. As of 2020, the Scopus dataset covered approximately 78 million publications from 1969, over 9.8 million conference papers, and 44 million patents. About 3 million new scientific works are added to the dataset each year, sourced from more than 23,000 journals [47].

Based on the literature review, we identified the following keywords for the search - "innovation efficiency," "innovation productivity," and "innovation performance." The search returned 6073 publications between 1995 and 2022. We then performed filtering of the data by document types (only articles were included), language (English only), and source type (only journal). The filtering resulted in 5123 publications.

Based on the approach of Z. Xu, et al. (2021) [48], we further ranked the publications by the number of citations and selected the top 20% of the most cited publications (1000 publications) for analysis. The next step included a manual screening of titles and abstracts of the selected list of publications to verify the selection and remove irrelevant papers from the list. Screening returned 764 publications (Fig. 1).

Bibliometric analysis: Bibliometric analysis is a family of analytical methods within the field of informetric research and research evaluation that allows for quantitative analysis of written publications and investigation of their impact using statistical tools [19, 49]. Bibliometric analysis is increasingly used across research fields (e.g., business [50], environment [51], medicine [52, 53], and engineering [54], among others) and is rapidly advancing with the development of large scientific datasets, availability of bibliometric software such as VOSviewer, Gephi, and the advancement of the analysis methodologies. To conduct the bibliometric analysis, we used the package Bibliometrix in R and CiteSpace program [20]. Bibliometrix allows for performing descriptive analysis on bibliometric datasets [20, 55], while CiteSpace is used to identify citation hotspots, network patterns, and fast-growing topics. Both packages are well-known for effective detection and visualisation of trends and changes in research topics [17].

In this study, the bibliometric analysis focuses on two main aspects:

- Performance analysis - descriptive analysis of the research performance. In this study, a number of indicators are utilised for performance analysis, including influence indicators and productivity indicators such as annual scientific production, top publications by citation, most productive authors' countries, total citation per country, and most relevant sources.

- Science mapping analysis that explores the relationship between research constituents, identifies the intellectual structural connections and their evolution over time [56]. In this study, the following science mapping analysis techniques were used:

+ Conceptual structure map to visualise the topic's conceptual structure using the Multiple Correspondence Analysis (MCA) algorithm [57] to examine the relationship between keywords.

+ Thematic map to plot clusters of keywords in a 2D matrix in which the horizontal axis represents the relevance of keywords and the vertical axis represents the development degree. In this study, more than 500 keywords were considered with a minimum frequency of 5.

+ Co-occurrence-based burst detection (CiteSpace) to find the hotspots or areas of high research intensity over time. Burst detection allows tracking the evolution and decay of research topics over time through identification of ranked lists of word bursts and the time interval in which they occur [17]. Burst detection was conducted with a frequency of not less than ten and burst strength of not less than 2.

4. Analysis and discussion

4.1. Performance analysis

Publication evolution over time: The number of scientific publications on the topic of innovation efficiency has grown almost tenfold between 2008 and 2020 (see Fig. 2), above the growth rate in the total number of academic publications over that period. Whilst the number of papers on the topic was relatively small before 2003, the topic gained momentum as a research interest over 2004-2008 and has been on a steady growth trajectory since 2009 (see Fig. 2). In 2021, despite the impact of the pandemic, we observed the peak in the number of publications. This differs from the decline observed across multiple other research fields and topics during and post-pandemic [58-60].

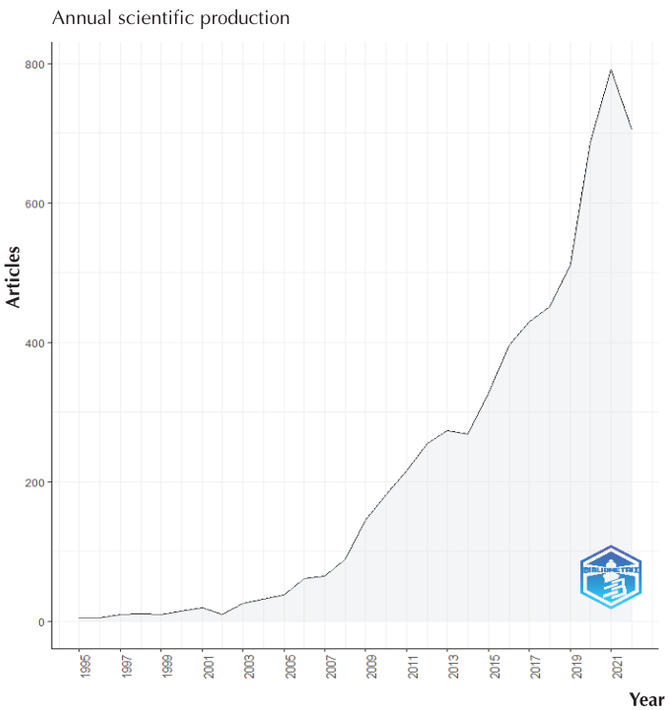


Fig. 2. Annual scientific production of publications on innovation efficiency. Note: The data for 2022 only covers the first nine months of the year.

High-impact research: The top journals by the count of innovation efficiency-focused publications are centred around technology, business management, and innovation. These include highly-ranked journals such as *Research Policy, Journal of Product Innovation Management, International Journal of Innovation Management, Technology Forecasting and Social Change, and Technovation* (Table 1). The most frequently cited outlets include *Strategic Management Journal, Research Policy, Academy of Management Journal, and Technovation.* The former two sources *(Strategic Management Journal and Research Policy)* have more than double the number of citations compared to the rest of the list. This is due to the presence of the most-cited papers on the topic in these journals, such as K. Laursen and A. Salter (2006) [61], G. Ahuja and R. Katila (2001) [62]. Over the observed period, the top-cited papers gained between 40 and 66 citations annually, with the outstanding work of K. Laursen and A. Salter (2006) [61] (Table 1).

The list of journals led by *Sustainability* (Switzerland) accounted for the total number of articles. This outlet outperformed peers only in 2021 as demonstrated by the analysis of source dynamics in Fig. 3. This indicates an increasing interest in sustainability and green technology within the field of innovation efficiency research as we will discuss in detail below.

Geographic distribution of authors in innovation efficiency: As in many fields of science and technology, China dominates the country list by the number of innovation-efficiency-related publications. The number of studies from China is higher than the total number of studies published by authors from the rest of the world. This result is not surprising, given the rates of economic and technological progress in

Table 1. Top academic journals and articles in innovation efficiency by publication and citation counts.

Most relevant sources	Articles	Top-cited papers	Total citation	Citations per year
Sustainability (Switzerland)	209	K. Laursen (2006), *Strategic Manage J.*	3604	212.0
Technology Analysis and Strategic Management	104	J.K. Han (1998), *J. Mark,*	1644	65.8
Research Policy	97	G. Ahuja (2001), *Strategic Manage J.*	1354	61.5
International Journal of Innovation Management	92	L. Pittaway (2004), *Int. J. Manage Rev.*	1036	54.5
Technological Forecasting and Social Change	90	N. Rosenbusch (2011), *J. Bus. Venturing*	1028	85.7
Journal of Business Research	86	K. Atuahene-Gima (2005), *J. Mark*	993	55.2
European Journal of Innovation Management	84	H. Li (2001), *Acad. Manage J.*	983	44.7
Technovation	69	Y.S. Chen (2006), *J. Bus. Ethics*	945	55.6
Journal of Product Innovation Management	58	H.F. Lin (2007), *Int. J. Manpow.*	901	56.3
International Journal of Technology Management	50	C.J. Chen (2009), *J. Bus. Res.*	839	59.9

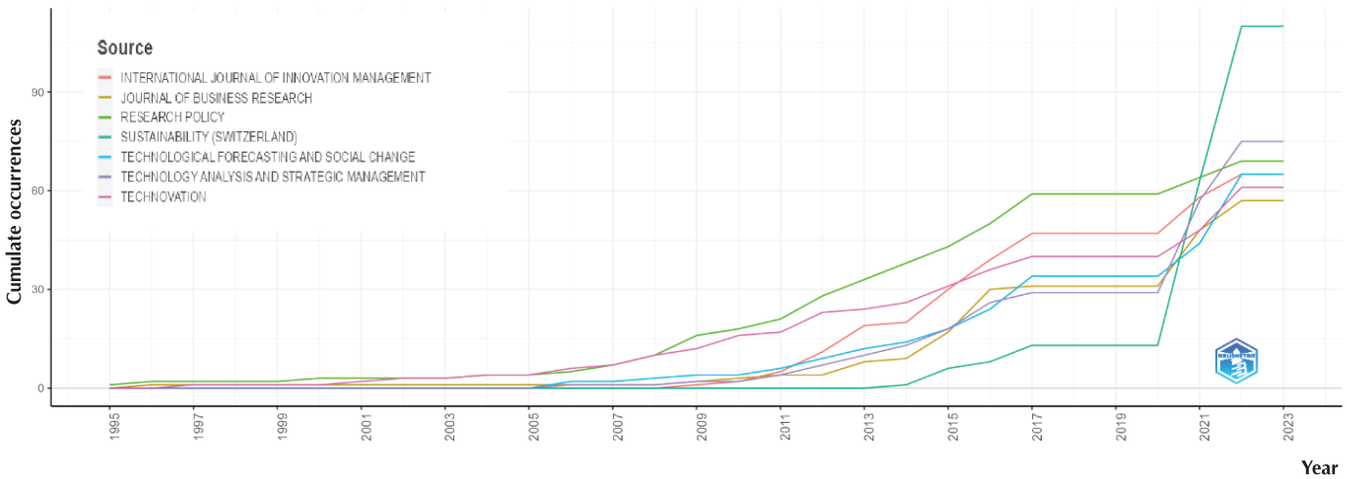


Fig. 3. Cumulative number of papers published by leading outlets per year.

China over the past two decades. Efficient resource allocation and cleaner production are among the priority objectives of China's government, and technological innovation is the key solution to achieve these objectives. Chinese authors are followed by authors from developed economies, including Spain, the USA, the United Kingdom, and the Republic of Korea (Fig. 4).

Authors affiliated with Chinese institutions also lead the list of author production over time (Fig. 5). Interestingly, the patterns of publications are similar across the top authors, with the first papers published around 2010, followed by at least one paper per year between 2010 and 2022. The number of citations of their papers has been gradually increasing over time.

4.2. Science map analysis

In the following section, we use the top 10% cited publications to analyse the trending topics in the innovation efficiency domain, identify research trends, and gaps.

Conceptual structure of literature in innovation efficiency domain: We performed co-occurrence analysis to identify the connection between keywords. Keywords are marked as co-occurring when they are used simultaneously by authors. Keywords are identified as keywords from author keywords, title, and abstract [63]. Fifty keywords were connected using the MCA as a dimensionality reduction technique. The result is reported in Fig. 6.

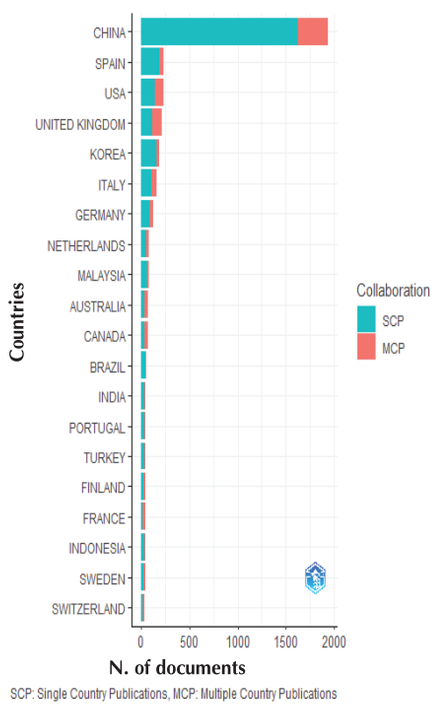


Fig. 4. Publications in the field of innovation efficiency by geographies of authors' affiliations. Notes: SCP: single country publications; MCP: multiple country publications.

The more co-occurrences are observed in the bibliometric dataset, the shorter the distance between words appearing on the map. Bubble sizes represent the frequency that the keywords are used by authors in the dataset. Different colours show different clusters of keywords.

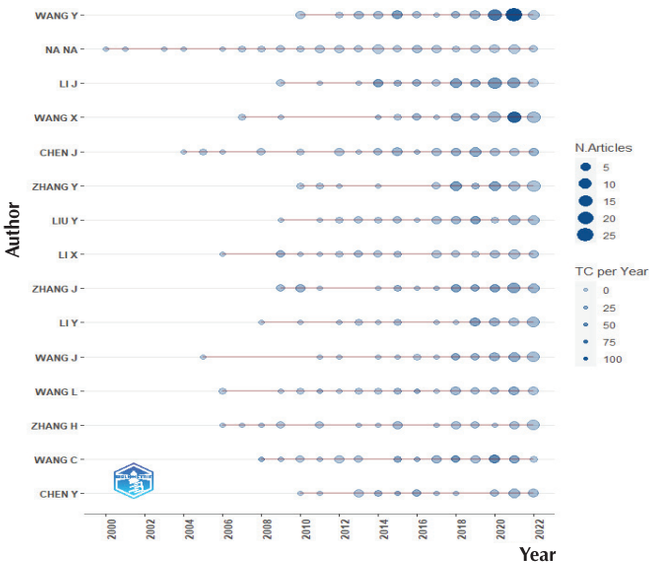


Fig. 5. The top authors in the innovation efficiency domain over time. Note: TC: total citations.

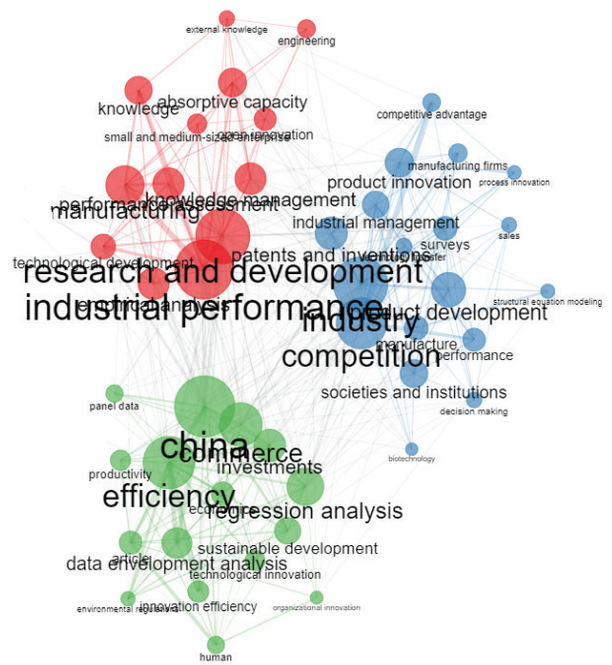


Fig. 6. Co-occurrence network for 10% of the most cited publications in innovation efficiency.

As can be seen, there are three clusters identified:

- Innovation and sustainable development (green) with more research using Chinese data and data envelopment analysis methodology.

- Innovation and research and development (red) with a focus on the manufacturing sector and absorptive capacity.

- Innovation and external factors (blue) with a focus on industrial management, performance, society, and institution.

To provide a more comprehensive analysis of key topics in the domain, we constructed a thematic map as presented in Fig. 7. The leading Eigenvalues algorithm was used for clustering; we also excluded common words (e.g., "innovation," "innovation performance," "article," and "human") to obtain cleaner results.

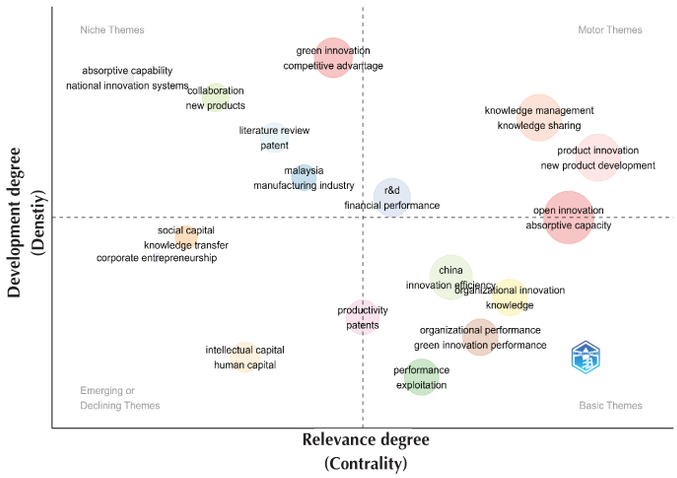


Fig. 7. Thematic map for the top 10% most cited publications in innovation efficiency.

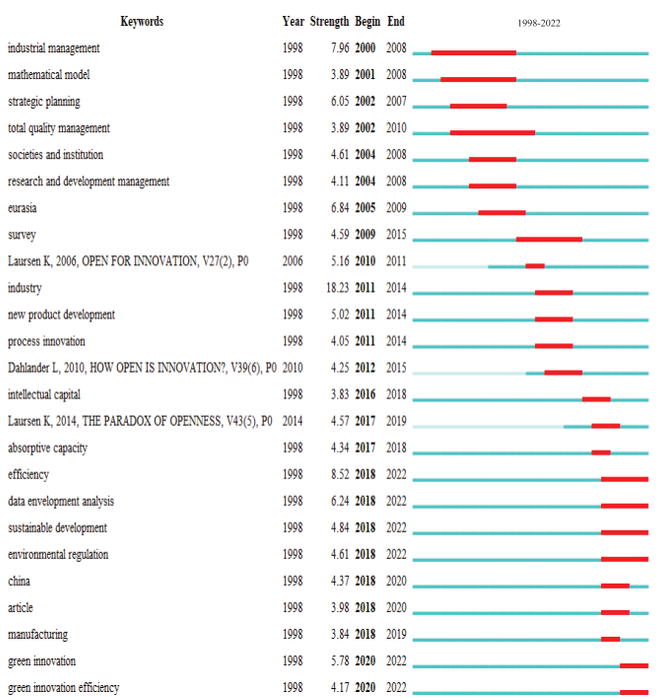
The thematic map has four different quadrants, identified by their centrality (horizontal axis) and density (vertical axis). Centrality measures how a topic connects to others, while density measures the level at which keywords in a cluster connect and thus define a hot topic. As such, the upper-right quadrant includes topics with high centrality and high density (i.e., topics that are well-researched and influential). Themes observed in this area concern knowledge sharing, management, and product innovation. Areas in the lower-left quadrant are either emerging or declining topics, as they have both low centrality and density. These include themes of human, intellectual, social capital and knowledge transfer.

The upper left represents topics that are well developed but do not influence other themes, while the topics of the lower right are weakly established internally yet relatively influential to other topics. As seen in Fig. 7, topics in the lower right quadrant are important and cross-cutting. They have high centrality but low density. In other words, research in these areas is significant to other field topics. However, they are not fully developed and thus

present opportunities for future research. These themes encompass performance-related topics on exploitation, aspects of organisational innovation and performance, and green innovation.

Key topics of research over time: To understand the dynamics of the key topics in innovation efficiency, we performed a keyword burst analysis using CiteSpace software on the 10% of the most-cited publications from 1998-2022, resulting in 764 manuscripts. Keyword bursts are used as indicators of frontier topics or emerging trends; each bar records a keyword, its start and end burst date. Burst detection was conducted using Kleinberg's burst detection algorithm, which can identify sudden increases or "bursts" in the frequency of words used over time. As a result, 25 bursts were determined (Fig. 8). We further performed an analysis of trend topics with the Bibliometrix package, which confirmed and expanded the findings (see Fig. 9).

Through the analysis of methodology-related keywords, we identified two groups of research methodologies used across the domain of interest: (i) qualitative approaches through surveys and (ii) quantitative analysis using regression analysis, mathematical models, and data envelopment analysis. This aligns with the findings of the literature review (Section 2).



Keywords	Year	Strength	Begin	End	1998-2022
industrial management	1998	7.96	2000	2008	
mathematical model	1998	3.89	2001	2008	
strategic planning	1998	6.05	2002	2007	
total quality management	1998	3.89	2002	2010	
societies and institution	1998	4.61	2004	2008	
research and development management	1998	4.11	2004	2008	
eurasia	1998	6.84	2005	2009	
survey	1998	4.59	2009	2015	
Laursen K, 2006, OPEN FOR INNOVATION, V27(2), P0	2006	5.16	2010	2011	
industry	1998	18.23	2011	2014	
new product development	1998	5.02	2011	2014	
process innovation	1998	4.05	2011	2014	
Dahlander L, 2010, HOW OPEN IS INNOVATION?, V39(6), P0	2010	4.25	2012	2015	
intellectual capital	1998	3.83	2016	2018	
Laursen K, 2014, THE PARADOX OF OPENNESS, V43(5), P0	2014	4.57	2017	2019	
absorptive capacity	1998	4.34	2017	2018	
efficiency	1998	8.52	2018	2022	
data envelopment analysis	1998	6.24	2018	2022	
sustainable development	1998	4.84	2018	2022	
environmental regulation	1998	4.61	2018	2022	
china	1998	4.37	2018	2020	
article	1998	3.98	2018	2020	
manufacturing	1998	3.84	2018	2019	
green innovation	1998	5.78	2020	2022	
green innovation efficiency	1998	4.17	2020	2022	

Fig. 8. Top 25 keywords with the most robust citation bursts.

The bar graph in Fig. 8 demonstrates the evolution of key topics within the innovation efficiency domain over time. Fig. 9 depicts trend topics over time, with the length of the bar representing the period in which the keywords emerge, and the size of the dots indicating the frequency of keywords appearing in the sample.

We identified three periods in the evolution of innovation efficiency phenomena: 1998 to 2004, 2005 to 2015, and 2016 to 2022. In the first period, firm-level innovation performance garnered significant attention, with the core topics in the domain of interest being strategic planning, quality management, product design, marketing, and industrial management. This corresponded to the widespread application of quality management tools such as Total Quality Management, Lean, Six Sigma, among others [64]. During this time, attention was given to identifying the interrelation between innovation, business models, and firm performance [65]. The focus of studies centred on internal factors such as technology, capital, personnel, and organisation management [66].

Between 2005 and 2015, the dominant burst terms were open innovation, industry, and new product development. In this second period, the research focus shifted to the inflows and outflows of knowledge and external factors in the innovation process. Researchers delved deeply into the innovation process, which was perceived as a complex activity with various external factors influencing a firm's incentive and ability to innovate, the type of innovation it implements, efficiency, and the outcome of the innovation activities [67]. Some papers also examined elements of organisational culture, such as knowledge sharing in the company [68], team diversity [69], and leadership [70].

During this period, innovation was not viewed as the result of isolated business decisions but as an outcome of a co-creation process with knowledge flowing in and out of the broader economic and social environment. As a result, topics related to open innovation, networking, industrial performance, and competition emerged in the domain. Numerous papers in this literature focused on innovation networks and external spillover effects in innovation [71]. Towards the end of the second period, we noted a surge in research interest in externalities from innovation and the ability to absorb technology

and innovation (absorptive capacity) [61, 72, 73], along with evaluating the innovation performance of a country or a region [44, 74].

From 2016 onwards, the focal point in the innovation efficiency literature turned to sustainability and green innovation, with keyword bursts such as sustainable development, green innovation, and green innovation efficiency [75, 76]. Green innovation merges ideas of innovation and sustainable development, coining terms including environmental innovation and ecological innovation [76]. Examining the green innovation literature more closely, we observed a vast heterogeneity in the definition of drivers or proxies for green innovation. This stems from the variety of academic domains addressing this issue (management, economics, engineering, biology, environmental and ecological studies, etc.), showcasing the heightened interest that this research topic has garnered. This observation aligns with the results of the thematic map analysis provided earlier, placing green innovation among the topics with high potential for future research.

The third period also highlighted an increased use of a quantitative approach to assess innovation efficiency. The favoured empirical analysis method for investigating innovation efficiency was Data Envelopment Analysis. Structural equation modelling was another technique frequently employed to discern how innovation capability affects firm performance.

5. Conclusions

In this paper, we employed bibliometric methods and visualisation software to explore the evolution of research in the field of innovation efficiency. We analysed over 5000 publications in the field and conducted a detailed bibliometric analysis of the 764 most impactful publications in the domain published between 1998 and 2022.

We observed an intensification of publishing in the domain of innovation efficiency since 2003, with no signs of slowing down during and after the pandemic. The analysis demonstrated the dominance of China as a country of affiliation for the authors in the domain, as observed across other research literature domains. We also identified a group of top-cited authors and leading outlets in the domain. The top journals in the innovation efficiency domain focus on technology, business management, and innovation and include *Research Policy, Journal of Product Innovation Management, International Journal of Innovation Management, Technology Forecasting and Social Change, and Technovation.*

Through detailed bibliometric analysis of the 10% top-cited publications, we discovered that the focus of innovation-related studies has gradually shifted from issues internal to organisations to a more holistic view of innovation phenomena, incorporating

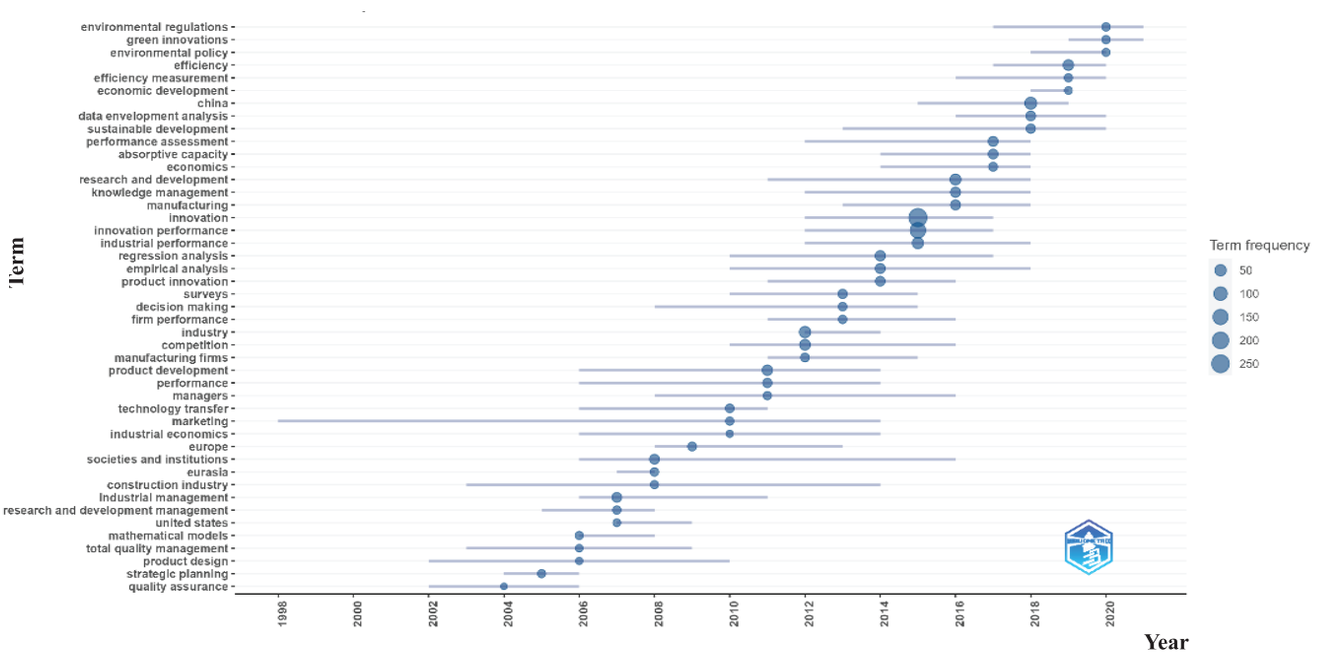


Fig. 9. Analysis of trend topics over time.

exogenous factors and external sources of innovation. Analysis enabled us to identify three periods in the evolution of innovation efficiency phenomena: 1998-2004, 2005-2015, and 2016-2022. In the recent one, green innovation has emerged as a dominant topic in the field with an increasing number of publications using innovation efficiency terms in conjunction with green innovations and in the context of environmental sustainability. Despite the rapid growth in the literature on green innovation within the domain of interest, there remains significant potential for future expansion. This was evidenced by the thematic map analysis. Green innovation and aspects of organisational performance are pinpointed as important for the domain of innovation efficiency literature but are still evolving. The bibliometric analysis, coupled with the literature review, revealed that innovation efficiency is multifaceted, and there is no universally established framework to assess innovation efficiency owing to its complexity. Identifying the appropriate set of input and output variables for the quantitative measurement of innovation efficiency is crucial for the field to progress. More research is needed using microdata with detailed information on innovation inputs and outputs that would allow us to better understand the firm innovation process. Discussing future research, the multidimensional measurement of innovation and innovation efficiency should be studied in a specific local context, taking into account externality and spillover effects, which are critical characteristics of innovation.

This study may benefit researchers, policymakers, and practitioners in several ways. A comprehensive review and the discerned intellectual structure of innovation efficiency via bibliometric analysis might aid scholars in better understanding the concept and applications of innovation efficiency. Policymakers, business, and industry leaders could reflect on the factors that have been discussed to better prioritise investment decisions and work towards enhancing the efficiency of innovation initiatives in their respective organisations and regions.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study is available on request from the corresponding author.

CRediT author statement

Hien Thu Pham: Conceptualisation, Methodology, Validation, Writing; Hoang Giang Nguyen: Data curation, Visualisation, Writing; Alexandra Bratanova: Data collection, Conceptualisation, Methodology, Validation, Writing - Review and Editing; Vu Hoang Dat: Data analyst, Visualisation, Writing.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

ETHICS

No sensitive or personal data was collected or used in the research associated with this paper.

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