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Open science, open innovation? The role of open access in patenting activity

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Abstract

Scientific knowledge is a key driver of technological innovation, shaping industrial development and policy decisions worldwide. Understanding how patents incorporate scientific research is essential for assessing the role of academic discoveries in technological progress. Non-Patent References (NPRs) provide a useful indicator of this relationship by revealing the extent to which patents draw upon scientific literature. Using USPTO patent data on 497,098 patents and 3.2 million inventor-cited scientific references, matched to nearly one million distinct publications in the Marx–Fuegi (2020) database, we employ the Reliance on Science Index (RSI) and the Normalized Open Access Index (NOAI) to quantify both the dependence of patents on scientific research and the accessibility of the cited literature. We show that reliance on scientific research in patents varies significantly across regions and is strongly concentrated in science-based domains (especially biotechnology and pharmaceuticals). Oceania and Europe display stronger engagement with scientific knowledge, while the Americas exhibit lower reliance. Additionally, Open Access is over-represented in NPRs, specifically inventor-cited scientific references, and more likely to be cited than average (38%), a trend which intensifies when Sci-Hub availability is considered. These results highlight the transformative impact of Open Science on global innovation dynamics. By facilitating broader access to research, Open Science strengthens the link between academia and industry, underscoring the need for policies that promote equitable and science-based innovation, particularly in developing regions.

Keywords Open science · Open access · Innovation · Non-patent references · Patents

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Introduction

Innovation is widely recognized as a cornerstone of economic prosperity and societal progress (Bikard & Marx, 2020; Dickson, 1995; Jefferson et al., 2018; Wang & Li, 2021). Over the past decades, the global economy has increasingly relied on knowledge-intensive industries, where the ability to generate, absorb, and apply new knowledge determines competitiveness and long-term development (Czarnitzki et al., 2012; de las Heras-Rosas & Herrera, 2021; Jefferson et al., 2018; Mowery & Sampat, 2004). At the heart of this transformation lies science, a tool for innovative problem-solving. Across sectors, from healthcare to renewable energy and beyond, the ability to innovate has multifaceted and multi-level impacts shaping both institutional success and economic trajectory of nations and regions (Teng & Zhu, 2024).

Governments and policymakers increasingly emphasize fostering "innovation ecosystems", i.e. interconnected networks of research institutions, industries, funding bodies and regulations which drive knowledge transfer into technological advancement, so as to propel economic development and address societal challenges (Granstrand & Holgersson, 2020; Townes, 1983). At the heart of this dynamic is the symbiotic relationship between science and innovation. Scientific research provides the foundational knowledge and breakthroughs which form the basis of technological advancements, driving productivity and economic gains (Bryan & Ozcan, 2021a; Hausman, 2022). The primordial role of science in economic and social progress has been articulated by the European Commission (European Commission, 2000), which stated: "In the final years of the twentieth century, we entered a knowledge-based society" and that "Economic and social development will depend essentially on knowledge in its different forms, on the production, acquisition, and use of knowledge". This shift has led to a growing recognition of the need to integrate science policies with economic strategies, aligning research investments with innovation-driven objectives. Consequently, measuring the extent to which industries rely on scientific research has become an essential step in evaluating the impact of science on economic activity.

In this context, Non-Patent References (NPRs) cited in patent documents have emerged as a key proxy for quantifying such a reliance, offering insights into the intersection of science and innovation (Quemener et al., 2024; Wang & Verberne, 2021, 2024). Since the pioneering work of Carpenter and Narin (1983) (Carpenter & Narin, 1983) and Narin and Noma (1985) (Narin & Noma, 1985), NPRs have been widely analyzed to trace the knowledge sources which underlay technological advancements. Recent studies, such as those by Roach and Cohen (2013) (Roach & Cohen, 2013) and Ahmadpoor and Jones (2017) (Ahmadpoor & Jones, 2017), demonstrate the importance of NPRs in capturing knowledge flows from public research, i.e. publicly funded, to industrial innovation (Townes, 1983). NPRs are particularly relevant in identifying the proximity of scientific disciplines to the technological frontier, with fields such as biotechnology and virology often cited in patents (Ahmadpoor & Jones, 2017).

Furthermore, studies have distinguished between front-page and in-text NPRs. While front-page citations are frequently added for compliance with disclosure obligations, in-text NPRs are more closely tied to the inventive process (Bryan et al., 2020; Marx & Fuegi, 2022; Wang & Verberne, 2024). This distinction emphasized the need to refine methodologies for measuring knowledge transfer, particularly as NPRs also serve to assess the impacts of public funding on innovation (Quemener et al., 2024). Recently, research has also demonstrated a substantial, though indirect, contribution of government-funded science to patentable technologies, particularly in fields such as clean energy and biomedical research (Fleming et al., 2019; Li et al., 2017). Despite the growing body of literature, the extent to which openly accessible scientific research constitutes NPRs remains largely under explored (Bryan & Ozcan, 2021a). This gap is particularly relevant given the growing emphasis on Open Science in policy, scientific practice, economic and societal impacts (Lim et al., 2025; Ross-Hellauer, 2022).

This article, therefore, seeks to fill this gap by exploring two interrelated research questions: 1) How does science contribute to innovation? And 2) To what extent is this contribution based on Open Science? The first question will explore the extent to which patents depend on scientific research via reporting the Reliance on Science Index (RSI) at different levels; regions (macro), technological domain (meso) and institution (micro). RSI is a metric which evaluates the extent to which patents depend on scientific knowledge by analyzing the proportion of NPRs cited within patent documents. The second question will employ the Normalized Open Access Indicator (NOAI) to investigate the openness of scientific research cited in such patents.

Data and methods

Data were obtained from multiple large-scale sources. Patent metadata and inventor information were retrieved from the USPTO PatentsView database (December 2024 release). Scientific article matching and inventor-to-article citation data were obtained from the (Marx & Fuegi, 2023) database. OpenAlex metadata were used to retrieve publication characteristics and Open Access status (Priem et al., 2022). The Sci-Hub DOI coverage file used corresponds to the publicly available snapshot (2022-02-12), which represents the latest released version of this dataset (with 84,511,678 DOIs included). All data processing and statistical analyses were conducted using R version 4.4.. The patent data includes over 22.5 million inventors associated with 8.9 million patents, along with detailed metadata on 96,039 disambiguated locations and 8.2 million organizations. The citation data allows us to focus specifically on NPRs cited by inventors in the text or body of patents, encompassing 3.2 million NPRs cited by 497,098 patents and representing nearly one million distinct scientific publications.

Data preparation followed several steps. First, we identified non-patent literature references cited in the body of USPTO patents using the Marx–Fuegi citation dataset. We restricted the analysis to inventor-supplied references appearing in the patent text (“body” or “both”), excluding examiner-only citations.

Patent identifiers were then standardized and matched with the PatentsView disambiguated inventor and location tables in order to assign each patent to countries, regions, and organizations. When multiple inventors or locations were associated with a patent, fractional counting was applied so that the total contribution of each patent summed to one.

In parallel, cited scientific publications were matched to OpenAlex records in order to retrieve DOI identifiers, publication year, disciplinary classifications, and Open Access status. For publications associated with multiple disciplinary concepts, fractional weights proportional to OpenAlex concept scores were used so that each publication contributed a total weight of one across disciplines.

Finally, DOI lists were compared with the Sci-Hub coverage dataset to determine whether each cited publication was available through shadow library access. The resulting merged dataset links patents, inventors, locations, organizations, and cited scientific publications, forming the basis for the analysis.

To address our research questions, we employed two complementary indicators: the Reliance on Science Index (RSI) and the Normalized Open Access Index (NOAI). These indicators were specifically designed to analyze the relationship between patents and scientific literature, providing insights at multiple levels—macro (regions and countries), meso (sectors and classes), and micro (organizations).

The RSI quantifies the relative reliance of a given category (e.g., region, country, sector, or organization) on scientific literature, using a fractional count approach where the total contribution of a single patent to the indicator sums to 1. It is calculated as:

$$\mathrm{RSI}_i = \frac{\#\text{Patents citing NPRs}_i}{\#\text{Patents in all NPRs corpus}} \Big/ \frac{\#\text{Patents}_i\text{ (at USPTO)}}{\#\text{Patents in all USPTO}}.$$

Here, i represents the category under consideration. The numerator captures the share of patents citing NPRs in category i relative to the total patents citing NPRs in the entire corpus. The denominator represents the share of all patents from category iii relative to the total patents in the USPTO dataset. An RSI greater than 1 indicates a higher-than-average reliance on scientific literature, while an RSI below 1 signals a lower reliance.

To assess whether Open Access publications are disproportionately represented among the scientific references cited in patents, we use the Normalized Open Access Index (NOAI), following (Maddi, 2020). This indicator corrects for disciplinary differences in Open Access practices by comparing the Open Access share observed for a given unit to the corresponding Open Access share in the reference scientific population.

First, for each discipline j, the normalized Open Access share is computed as:

$$\text{OAS\_ij} = (\text{OA\_ij} / \text{x\_ij})/(\text{OA\_wj} / \text{X\_wj})$$

where OA_ij denotes the number of Open Access publications associated with unit i in discipline j, x_ij the total number of publications for that unit and discipline, OA_wj the number of Open Access publications worldwide in discipline j, and X_wj the total worldwide publications in that discipline.

In a second step, the overall Normalized Open Access Index is obtained as a weighted average across disciplines:

$$\text{NOAI\_i} = \Sigma(\text{OAS\_ij} \times \text{x\_ij})/\text{x\_i}$$

where x_i denotes the total number of publications for unit i.

A NOAI value greater than 1 indicates that Open Access publications are overrepresented relative to disciplinary publishing practices, whereas values below 1 indicate underrepresentation.

Results

Reliance on science: macro, meso and micro

Figure 1A below illustrates the variation in Reliance on Science Index (RSI) by region (macro-level). Regions such as Oceania and Europe exhibit median RSI values consistently above the neutral threshold of 1. Asia and Africa also show notable reliance, with medians exceeding 1, though with greater variability. The Americas experience a median RSI slightly below 1, indicating that patents from this region tend to rely less on scientific publications compared to others. Figure 1B, which examines the top 30 patent-producing countries, reveals the differences within regions. Countries such as South

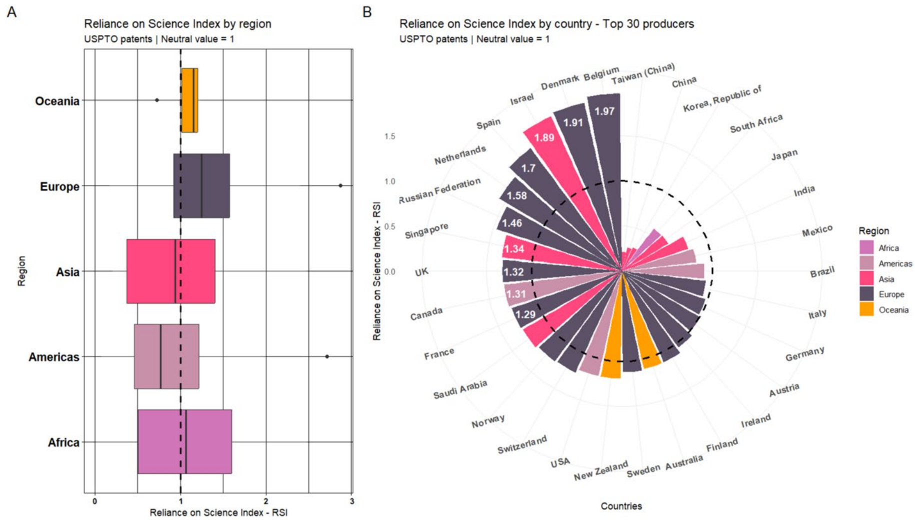

Fig. 1 Reliance on science index by region (**A**), and by country–Top 30 producers (**B**). An RSI value greater than 1 indicates a higher-than-average reliance on scientific literature, while values below 1 suggest a weaker connection between science and innovation

Korea, Taiwan, Singapore and Israel in Asia, and Denmark and Belgium in Europe, display particularly high RSI values. However, countries like South Africa, Mexico, Brazil, and Italy have RSI values below 1.

As for the meso-level (sector and class), Table 1 identifies the top 10 International Patent Classification (IPC) with the highest RSI values. All classes in the list show values between 4 and 15, indicating that their reliance on scientific literature is 4 to 15 times higher than average.

Biotechnology-related IPC classes, such as C07K (Peptides), C07H (Nucleic Acids and Sugars), and C12N (Microorganisms and Genetic Engineering), exhibit some of the highest Reliance Index values (12.34, 11.08, and 9.95, respectively). These fields rely extensively on scientific research to develop technologies such as peptide-based therapies, CRISPR gene-editing tools, and genetically engineered bacteria. The elevated RSI values reflect a significant role for academic studies and experimental research in advancing these domains, where the transition from discovery to application is often direct. For instance, innovations in C12N, such as microbial strains used in pharmaceuticals, naturally depend on basic scientific research. Similarly, C07H encompasses synthetic DNA sequences essential for vaccine development, highlighting how such advancements build upon a well-established body of scientific work (Cross et al., 2021).

In contrast, more applied or practical sectors such as B42F (filing appliances) or E02F (dredging) exhibit much lower RSI values, Table 2. Such industries, which focus on optimizing and innovating around existing technologies or improving manufacturing processes, have less direct reliance on fundamental scientific research. Their innovation is more likely to stem from engineering improvements, cost efficiency, and incremental technological advancements. For instance, in IPC classes like B25C (hand-held tools) or E06C (ladders), innovations are often more focused on product usability, ergonomic designs, or incremental material improvements, with less emphasis on groundbreaking scientific research.

Table 1 IPC classes with highest Reliance on Science Index

IPC Code	IPC Label	Example of R&D | inventions	# Patents citing NPRs	Share in patents citing NPRs (%)	Reliance on Science Index - RSI
C07K	Peptides	Peptide-based cancer vaccines; Insulin analogs for diabetes management	17,590	3.54%	12.34
C07H	Sugars; Derivatives thereof; Nucleosides; Nucleotides; Nucleic acids	CRISPR technology for genetic editing; Synthetic DNA sequences for vaccines	10,725	2.16%	11.08
C12N	Microorganisms or enzymes; Mutation or genetic engineering; Tissue culture	Genetically modified bacteria for insulin production; Microbial strains for probiotic products	30,575	6.15%	9.95
C12P	Fermentation processes or processes using enzymes for synthesizing chemical compounds	Production of ethanol from corn using yeast; Enzyme-assisted lactose-free milk production	10,263	2.06%	9.74
C12Q	Measuring or testing processes involving enzymes or microorganisms	COVID-19 diagnostic test kits; Microbial contamination sensors for food safety	14,915	3.00%	9.29
A61K	Preparations for medical, dental, or hygienic purposes	Antibiotics for bacterial infections; Anti-inflammatory ointments	67,969	13.67%	6.45
A01N	Preservation of human or animal bodies or plants; Biocides; Attractants or repellents for animals; Plant growth regulators	Insecticides for crop protection; Antifungal agents for plants	7,316	1.47%	4.61
C07D	Heterocyclic compounds	Development of antiviral drugs containing nitrogen heterocycles; Anti-inflammatory medications	19,763	3.98%	4.54
C07F	Acyclic, carbocyclic, or heterocyclic compounds containing elements other than carbon, hydrogen, halogen, oxygen, nitrogen, sulfur, selenium, or tellurium	Development of organometallic catalysts for polymerization; Silicon-based compounds for semiconductors	3,240	0.65%	4.19
A61P	Specific therapeutic activity of chemical compounds or medicinal preparations	Chemotherapy drugs for cancer treatment; Antiviral medications for HIV	3,152	0.63%	4.17

On the micro-level, Table 3A illustrates the analysis of the top 20 organizations listed based on RSI. The values exceeding 11 reflect the role of basic research in driving advancements across various sectors and institutions. Biopharmaceutical companies dominate this list, with institutions such as Ionis Pharmaceuticals, Incyte Pharmaceuticals, and Biogen Idec achieving the highest indices, ranging from 13 to 15. These organizations rely heavily on cutting-edge scientific research in fields such as genetic engineering, peptide-based therapies, and molecular biology to develop novel drugs and therapies.

Organizations with the lowest RSI in Table 3B, such as those in more traditional or manufacturing-oriented industries, tend to rely less on scientific research for their innovation processes. This is logical, as their focus is often on optimizing existing technologies, improving production efficiency, or advancing in areas which require less direct scientific breakthrough. For example, companies such as Bank of America or Suzuki Motor Corporation, which are primarily involved in financial services and automotive manufacturing, perhaps prioritize business models and product development strategies which do not hinge on basic scientific research. This pattern is consistent with the lower RSI observed in countries such as Japan, Germany, and China, where such types of industries coexist alongside more research-intensive sectors. Thus, the variation in RSI scores across countries can be largely attributed to the different industrial profiles, with countries having a larger

Table 2 IPC classes with the lowest Reliance on Science Index

IPC Code	IPC Label	Example of R&D | inventions	# Patents citing NPRs (fractional count)	# All US Patents (fractional count)	Reliance on Science Index - RSI
E02F	Dredging; Soil-shifting	Development of autonomous dredging systems for coastal engineering projects.	0.3	2,163.51	0.002
B42F	Sheets temporarily attached together; Filing appliances	Innovative binders and filing systems for office and educational use.	0.3	2,056.32	0.002
E06C	Ladders	Foldable, lightweight ladders with integrated safety mechanisms.	0.3	1,969.82	0.002
B25C	Hand-held nailing or stapling tools	Ergonomic, battery-powered nail guns for construction.	0.5	3,317.64	0.003
D05B	Sewing	Advanced sewing machines with AI-assisted stitching for complex patterns.	0.8	5,297.84	0.003
H10B	Electronic memory devices	Development of non-volatile memory for high-speed data storage.	0.3	1,922.64	0.003
D06F	Laundering, drying, ironing, pressing or folding textile articles	Smart laundry systems integrating fabric-specific drying and folding technologies.	0.5	2,337.59	0.003
E05F	Devices for moving wings into open or closed position; Checks for wings; Wing fittings not otherwise provided for, concerned with the functioning of the wing	Automatic sliding door systems with energy-efficient sensors.	0.3	1,259.87	0.004
F01L	Cyclically operating valves for machines or engines	High-durability valves for industrial machinery with improved flow regulation.	0.3	1,163.86	0.004
E03F	Sewers; Cesspools	Eco-friendly sewage treatment systems with integrated filtration.	0.2	714.63	0.005
E03C	Domestic plumbing installations	Smart plumbing systems with water-saving features and leak detection.	0.6	1,948.6	0.005

proportion of high-tech and biopharmaceutical firms showing higher RSI scores, while those with more traditional industries display lower reliance on science for innovation.

Public and academic institutions, including the Sloan-Kettering Institute for Cancer Research, the Medical Research Council, and the U.S. Department of Health and Human Services, also exhibits high indices. These organizations bridge the gap between fundamental research and industrial application (Quemener et al., 2024; Wang & Verberne, 2024). For instance, their contributions often focus on addressing large-scale societal challenges, such as cancer treatment and pandemic preparedness, highlighting the interplay between public research and private sector applications. Specialized biotechnology firms, such as New England Biolabs and Danisco US Inc., show similarly elevated indices, reflecting their reliance on academic discoveries to develop enabling technologies. These

Table 3 Organizations with highest (A) and lowest (B) Reliance on Science Index

A - Organisations with the highest RSI

	# US Patents (fractional count)	Reliance on Science Index (RSI)
Isis Pharmaceuticals, Inc. (USA)	1024.00	15.06
Incyte Pharmaceuticals, Inc. (USA)	579.00	14.34
Dekalb Genetics Corporation (USA)	200.00	14.24
Biogen Idec MA Inc. (USA)	196.00	14.00
Immunomedics, Inc. (USA)	406.00	13.35
Actelion Pharmaceuticals Ltd (Switzerland)	213.00	13.22
New England Biolabs, Inc. (USA)	330.00	12.88
Danisco US Inc. (USA)	413.00	12.46
Novartis Vaccines and Diagnostics, Inc. (Switzerland)	284.00	12.32
Chiron Corporation (USA)	639.00	12.18
Immunex Corporation (USA)	445.00	11.99
Sloan-Kettering Institute for Cancer Research (USA)	454.00	11.95
Medical Research Council (UK)	235.00	11.75
Corixa Corporation (USA)	243.00	11.69
Board of Trustees Operating Michigan State University (USA)	397.00	11.65
The USA, as represented by the Dep. of Health and Human Services (USA)	2432.00	11.59
Whitehead Institute for Biomedical Research (USA)	238.00	11.55
Genentech, Inc. (USA)	3075.00	11.54
Thomas Jefferson University (USA)	488.00	11.37
Genetics Institute, LLC (USA)	369.00	11.26

B - Organisations with the lowest RSI

	# US Patents (fractional counting)	Reliance on Science Index (RSI)
Bank of America Corporation (USA)	5098.00	0.00
Toshiba Tec Kabushiki Kaisha (Japan)	4551.00	0.00
Illinois Tool Works Inc. (USA)	7198.00	0.00
Schaeffler Technologies AG & Co. KG (Germany)	3181.00	0.01
Suzuki Motor Corporation (Japan)	1402.00	0.01
Hitachi Construction Machinery Co., Ltd. (Japan)	1370.00	0.01
United Services Automobile Association (USAA) (USA)	2701.00	0.01
Mahle International GmbH (Germany)	1319.00	0.01
CNH Industrial America LLC (USA)	2602.00	0.01
Raytheon Technologies Corporation (United States)	2496.00	0.01
Black & Decker Inc. (USA)	4957.00	0.01
Wistron Corp. (Taiwan)	2328.00	0.01
Kia Motors Corporation (South Korea)	4119.00	0.01
Advics Co., Ltd. (Japan)	716.00	0.01
Fuji Jukogyo Kabushiki Kaisha (Japan)	2125.00	0.01
SMC Corporation (Japan)	1993.00	0.01
Oki Data Corporation (Japan)	1877.00	0.01
Cilag GmbH International (Switzerland)	1843.00	0.01
Guangdong Oppo Mobile Telecommunications Corp., Ltd. (China)	3636.00	0.01
Chengdu BOE Optoelectronics Technology Co., Ltd. (China)	873.00	0.01

companies operate in niche markets, producing tools and solutions for broader applications in biotechnology and agriculture.

Openness and disciplinary characterization of NPRs

The share of OA publications in NPRs is shown in Fig. 2A. Surprisingly, non-OA citations account for 71% of NPRs. While this might initially seem counterintuitive, the fact that 29% of NPRs are OA is still a substantial proportion. This aligns with the reality that, despite global efforts to promote Open Access, OA publications still constitute less than 50% of the overall scientific literature across various disciplines (Maddi et al., 2021). Additionally, our analysis is based on data from OpenAlex, which is a comprehensive database, though other sources may yield slightly different results. Interestingly, when black OA sources such as SciHub are included, the share of OA citations rises dramatically to 85%, highlighting the significant role of accessibility in shaping NPR patterns. The broader impact of OA on NPRs is better understood through the NOAI as it assesses the relative prevalence of OA publications within NPRs compared to their prevalence in the broader scientific corpus, in our case OpenAlex database.

The analysis of the Normalized OA Index (NOAI) in Fig. 2B indeed provides additional insights. Firstly, The overall NOAI value of 1.38 indicates that OA publications are 38% more prevalent in NPRs when compared to the broader OpenAlex database. This suggests that OA literature is actually particularly favored in patent citations, likely due to its accessibility and relevance to innovation. Secondly and perhaps more interestingly, when factoring in sources available through black OA, as shown in Fig. 2C, the accessibility of NPRs increases dramatically to more than three times.

The analysis of the distribution of Non-Patent References (NPRs) by discipline, is shown in Fig. 3A. On one side, disciplines such as Biology (27.14%), Chemistry (23.49%), and Medicine (16.34%) dominate in terms of their share of NPRs. This aligns with their inherent strong transferability and industrial applicability, particularly in areas such as pharmaceuticals, biotechnology, and chemical engineering. On the other side, disciplines such as art, history, geography, and sociology, each accounting

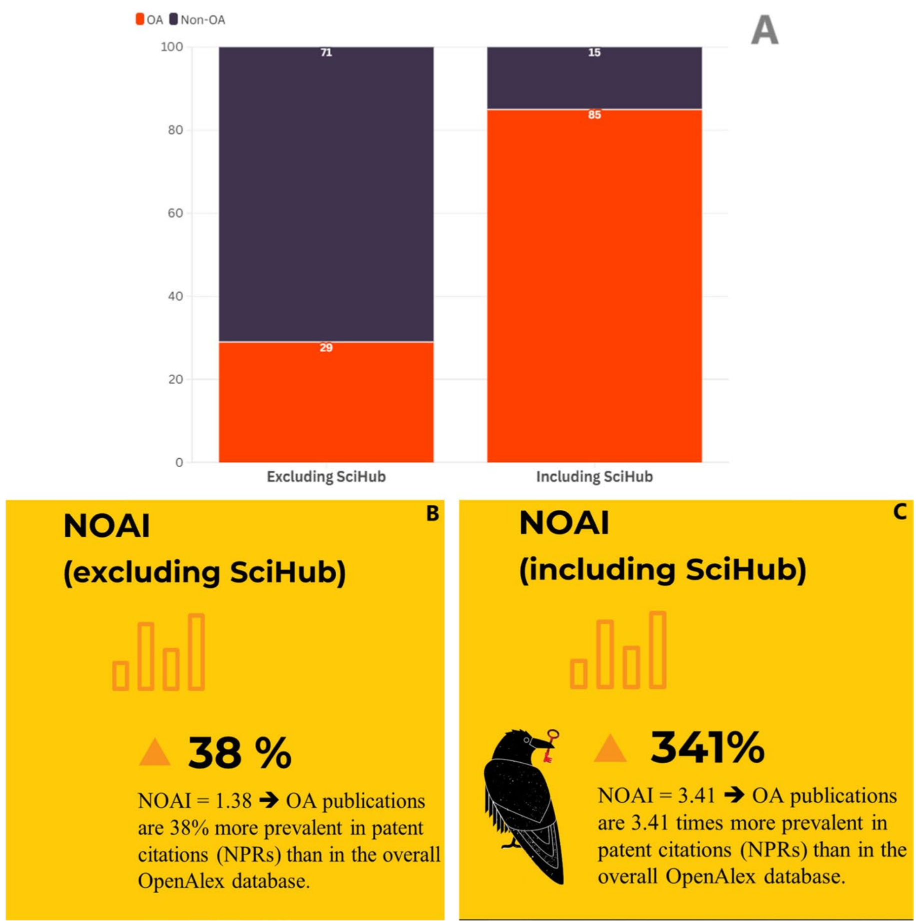

Fig. 2 Share of OA publications in NPRs (**A**), NOAI excluding SciHub (**B**), and NOAI including SciHub (**C**)

for less than 1% of NPRs, are less represented. This distribution reflects the practical and applicable orientation of NPRs, which tend to be cited in patents relevant to technological or industrial innovations. Furthermore, the discipline based NOAI values are shown in Fig. 3B. The differences may reflect either the degree of availability of OA publications in these fields or differences in their citation practices. Computer science and business, for instance, show higher-than-average NOAI values, despite their relatively modest shares of OA publications in the NPR dataset. This may indicate a selective but impactful use of OA resources, where open literature is leveraged for specific innovation-driven purposes. Interestingly, when availability via black OA is included, the NOAI values exceed 1 across all disciplines, Fig. 3C. This suggests that even in fields with lower formal OA integration, the practical availability of research literature is significantly enhanced through black OA.

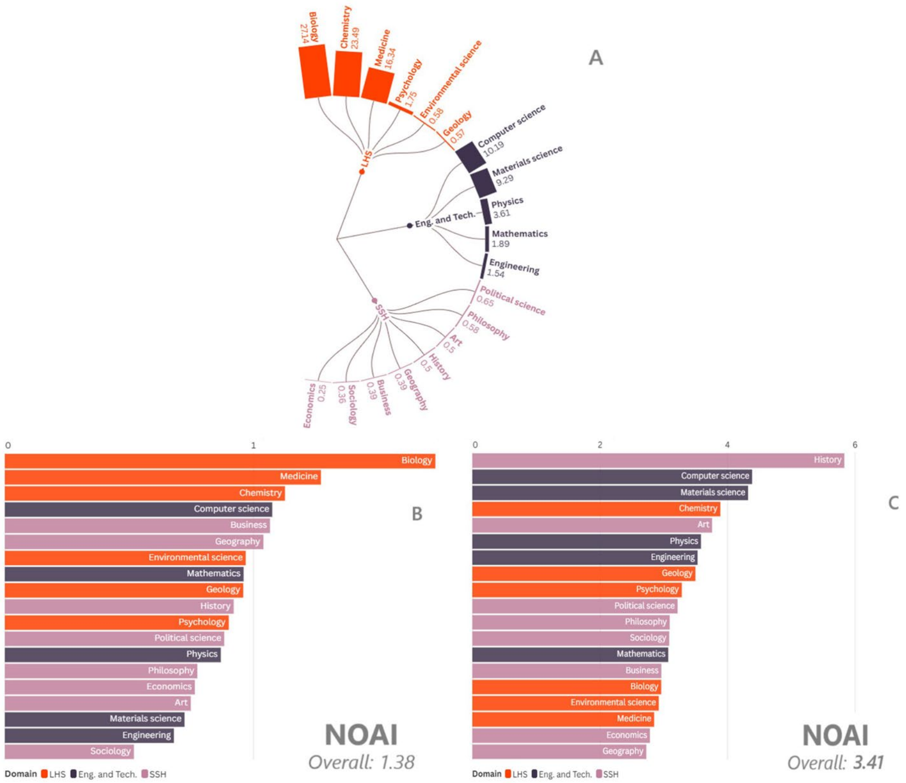

Fig. 3 Distribution of NPRs by discipline (**A**), and the NOAI with (**B**) and without SciHub (**C**)

Discussion and conclusions

The findings of this study provide a multi-level perspective on the relationship between scientific research, accessibility, and technological innovation, contributing to the expanding literature on science–technology linkages and Open Science. By examining reliance on science and accessibility simultaneously at macro, meso, and micro levels, this study extends prior work based on patent citations by explicitly quantifying how accessibility conditions the translation of research into innovation.

Patent-based indicators linking science and innovation have a long tradition. However, prior work emphasizes that citations in patents require careful interpretation as this process is usually legally mediated and can reflect a mix of inventor knowledge, attorney strategy, and examiner search practices, with important variation across patent offices (Jaffe & de Rassenfosse, 2017; Epo.Org, 2026; OECD, 2009). In this context, focusing on inventor-cited scientific references embedded in the patent text is increasingly viewed as a useful complement to front-page references. This is because in-text citations show limited overlap with front-page citations and are argued to more closely track knowledge inputs used in the inventive process (Alcácer & Gittelman, 2006; Bryan et al., 2020). Against this methodological backdrop, our results align with established evidence that science linkage is highest in science-based technologies such as biotechnology and pharmaceuticals, while also extending recent work on access by showing that openly accessible research is disproportionately represented (overrepresented) among the scientific publications that inventors cite (Jahn et al., 2022; Meyer-Krahmer & Schmoch, 1998). Here, the descriptive OA-overrepresentation is consistent with quasi-experimental evidence that OA mandates increase the use of funded research in patents, suggesting that reducing access barriers can measurably strengthen science-to-innovation translation (Bryan & Ozcan, 2021b; Probst et al., 2023).

At the macro level, the observed regional and country differences in the integration of scientific knowledge into patents are consistent with previous research showing that advanced innovation systems exhibit stronger science–technology coupling (Fleming et al., 2019; Harris et al., 2021; Marx & Fuegi, 2020, 2022; Gazni and Ghaseminik 2019). Countries with strong research infrastructures, sustained R&D investment, and dense university–industry collaboration networks show higher reliance on scientific publications. Lower reliance in some emerging economies aligns with studies highlighting the role of absorptive capacity, institutional resources, and access barriers in shaping innovation performance. Our results therefore reinforce the interpretation that global inequalities in innovation are partly mediated by unequal integration of accessible scientific knowledge. Recent descriptive studies similarly report substantial variation in the presence and intensity of non-patent literature references by inventor country and technology sector, with around one third of patent families containing at least one non-patent literature reference in 2010–2020 data (Jahn et al., 2022). In addition, longer-run evidence from USPTO patents shows that “science-related patents” and the number of cited papers per patent have increased substantially over recent decades, highlighting both the growing importance of science linkage and its heterogeneity across countries and fields (Gazni, 2020).

At the meso level, the strong dependence on scientific literature observed in specific sectors such as biotechnology, pharmaceutical, and life-science technologies, confirms well-established findings identifying these sectors as science-based innovation regimes (Chen et al., 2024; Du et al., 2019; Graf & Menter, 2022; Leten et al., 2022). The concentration of high RSI values in biotechnology/pharmaceutical-related classes indeed mirrors classic science-based technologies findings, where patent-to-paper linkage is highest in life-science domains compared with many engineering-dominated fields (Meyer-Krahmer & Schmoch, 1998; OECD, 2009). Engineering-oriented sectors show more moderate reliance, consistent with literature emphasizing the importance of applied engineering knowledge, incremental design improvements, and tacit industrial capabilities. Importantly, our results show that accessibility patterns mirror these structural differences: technological domains that rely more strongly on science are also those where accessible publications are disproportionately cited.

A central contribution of this study concerns the role of accessibility itself. We find that Open Access publications are significantly overrepresented among scientific references cited in patents. The Normalized Open Access Index indicates that Open Access publications are, on average, 38% more likely to be cited in patents than expected from their baseline prevalence. When shadow-library availability (Sci-Hub) is taken into account, this relative representation increases dramatically, reaching 341%. These results provide strong empirical support for recent studies showing that Open Science practices enhance knowledge diffusion and technological uptake (Dorta-González et al., 2025; Ottonicar et al., 2020; Wang & Verberne, 2024). More broadly, they suggest that accessibility is not merely a dissemination feature but a structural determinant of how effectively scientific knowledge enters innovation processes.

Our estimate that 29% of inventor-cited NPRs are OA (excluding shadow-library availability) is close to large-scale estimates of baseline OA prevalence in the scholarly literature, but the NOAI indicates OA is nevertheless cited disproportionately relative to field-specific publishing baselines (Piwowar et al., 2018). Differences in headline OA shares in the available literature is also to be expected because prior work often uses patent families across multiple offices and some relies on front-page patent-to-paper linkage, whereas in our study we included only in-text inventor-cited scientific references. Nevertheless, both approaches find rising and substantial OA representation in patent-linked science.The finding that citation patterns intensify when access barriers are removed further indicates that informational frictions remain a non-trivial constraint on science–technology transfer. Our descriptive accessibility gradient in Fig. 2 is consistent with causal evidence from OA mandates: the NIH (National Institute of Health) public-access policy increased patent citations to NIH-funded research by about 12–27%, and a DOE (U.S. Department of Energy) mandate increased patent use of affected research by about 42% (Bryan & Ozcan, 2021b; Probst et al., 2023).

At the organizational level, the analysis confirms the central role of both leading science-intensive firms and public research institutions in the innovation ecosystem. Firms operating at the frontier of biotechnology and pharmaceuticals exhibit exceptionally high reliance on scientific knowledge, consistent with prior studies showing that internal research capability and academic collaboration significantly enhance innovation performance (Cassiman et al., 2018; Fabrizio, 2009). Simultaneously, a substantial share of the scientific publications incorporated into patented technologies originates from publicly funded research institutions. This observation reinforces existing evidence that publicly financed science constitutes a foundational input into private-sector technological development (Beck et al., 2022; Becker et al., 2023; Fleming et al., 2019).

These findings also raise important policy and ethical considerations. If publicly funded research systematically underpins commercially valuable patented technologies, questions arise concerning the distribution of the economic returns generated by this knowledge. While industry benefits from the accessibility of publicly financed research outputs, mechanisms ensuring reciprocal reinvestment into the scientific ecosystem remain uneven across countries and sectors. Policies strengthening Open Access mandates, supporting public research funding, and promoting structured university–industry partnerships may therefore not only enhance knowledge diffusion but also contribute to the long-term sustainability and equity of innovation systems. Recent reviews of the economic evidence base similarly conclude that Open Science, especially Open Access, can contribute to innovation outcomes, while also highlighting that effects may vary by sector and institutional context (Tsipouri et al., 2025).

Overall, our results suggest that the integration of Open Science practices is not simply correlated with innovation but may function as an enabling infrastructure shaping the intensity and direction of science–technology linkages. There is a compelling necessity to develop, adopt and implement holistic policies which account for regional, sectoral and organizational specificities. Enhancing accessibility to scientific knowledge and fostering broader integration of underrepresented disciplines and regions, may indeed maximize the impact of science on addressing urgent societal and technological challenges. Future research could further investigate how specific Open Science policies, funding structures, and collaboration mechanisms influence the accessibility–innovation relationship across different institutional and technological contexts.

Limitations

Our patent dataset is based on records from the United States Patent and Trademark Office (USPTO). Consequently, the analysis captures only patents filed for protection in the U.S. patent system. While the USPTO is one of the world's largest and most internationally used patent offices, it does not represent the entirety of global patenting activity. The geographical results reported in this study should therefore be interpreted as reflecting the distribution of patents from different countries that seek protection in the U.S. market, rather than the full domestic patenting output of each country.

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Declarations

Conflict of interest Authors have no conflicts of interest to declare.

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