Vol. 4, No. 3, 2024, 1-16. DOI: 10.47909/ijsmc.137

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ORIGINAL ARTICLE

Health and medical informatics research: Identifying international collaboration patterns at the country and institution level

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ABSTRACT

Objective. In this study, we employed a bibliometric approach to identify and analyze international collaboration trends between countries and institutions engaged in the publication of research on health and medical informatics over the past decade, spanning 2014 to 2023.

Design/Methodology/Approach. This study was designed with a particular emphasis on examining scientific productivity and analyzing social networks. We extracted the most relevant literature on the subject from the Scopus database. The data were organized to analyze productivity and citation impact by country and institution. In both cases, countries and institutions were ranked by the total number of papers and citations to identify the most productive and impactful nations and to facilitate a comparison of their performance on a regional and global scale. In the context of network analysis, we identified countries and institutions according to their prestige, influence, and importance. To this end, we employed centrality measures based on the data set representing node connections.

Results/Discussion. Scientific productivity in health and medical informatics is concentrated mainly in developed countries. Europe demonstrates a considerable presence, as evidenced by the contributions of countries such as France, Italy, Spain, and Switzerland. However, the leadership of the United States and the United Kingdom is a notable example of the relationship between productivity and citation impact. The United States is identified as the most centralized nation, with 115 direct connections. Other countries of note include the United Kingdom, Germany, Canada, and Switzerland. Regarding influence, Germany is the most prominent country, and in terms of prestige, the United States is once again the leader. The North American region is the most influential and prestigious in the field, while Europe is distinguished by its network structure's incredible diversity and collaboration. The countries that play a pivotal role in this context are Germany, the United Kingdom, France, the Netherlands, and Switzerland. Among the institutions that stand out for their high productivity are Harvard Medical School, the

Received: 13-07-2024. **Accepted:** 20-10-2024. **Published:** 31-10-2024.

How to cite: Oscuvilca Tapia, E. C., Albitres Infantes, J. J., Cadenas Calderón, P. C., Aguinaga Mendoza, G. M., Paredes Jiménez, H. R., & Andrade Girón, E. C. (2024). Health and medical informatics research: Identifying international collaboration patterns at the country and institution level. *Iberoamerican Journal of Science Measurement and Communication; 4*(3), 1-16. DOI: 10.47909/ijsmc.137

University of Washington, the Mayo Clinic, and the University of Toronto. Harvard Medical School is the most important institution on the map of institutional collaborations. The University of Washington also stands out, along with the Mayo Clinic and Columbia University. Regarding influence, Harvard Medical School and the Mayo Clinic are the most influential institutions. The University of Washington leads in prestige, along with the Vanderbilt University.

Conclusions. The analysis of scientific collaboration in health and medical informatics demonstrates that North America and Europe are the preeminent regions, exhibiting dense and well-connected networks that facilitate the global integration of scientific knowledge. Asia, with key countries such as India and the United Arab Emirates, is emerging as an essential region, especially regarding intermediation and prestige. While Latin America and Africa are less represented, there is potential for these regions to increase their participation by expanding their collaborative networks, which is critical to improving the impact and visibility of their research.

Keywords: medical informatics; health informatics; collaboration networks; scientific production; bibliometric analysis; telemedicine.

1. INTRODUCTION

Health and medical informatics can be defined as the application of information and communication technologies in the health and medical sector (Bath, 2008). Its interdisciplinary character is evidenced by applying theories and practices drawn from mathematics, engineering, information science, and select social sciences (Savel & Foldy, 2012). The proliferation of this field has led to significant advancements in clinical practice and research (Brewer *et al.,* 2020; Saucedo *et al.,* 2021), resulting in enhanced medical care and public health outcomes (Mantas *et al.,* 2010).

The numerous studies on medical and health informatics demonstrate the implementation of methodologies and models about machine and deep learning (Holzinger, 2016; Tyagi & Nair, 2021), artificial intelligence (Ahmed, Barua, & Begum, 2021; Lozano-Flores, 2023), mobile technology (Wac, 2012), big data (Sadineni, 2020), and data mining (Castellani, B., & Castellani, 2003), among others. The advancement of these technologies has occurred concurrently with the evolution of the fields above. Masic (2014) describes the development of this area in five historical periods:

- 1955-1965: Initial experiments with computing in medicine, highlighting early efforts in data processing.
- 1965-1975: Growth in automated data processing and hospital information systems.
- 1975-1985: Expansion of healthcare information systems with increased computer accessibility.
- 1985-1995: Integration of artificial intelligence and advanced diagnostics in medical informatics.
- 1995-present: Rapid technological advancement, with extensive use of networked systems in healthcare.

Concurrently, the quantity of scientific literature on the subject is growing in academic databases, including both multidisciplinary and specialized databases in the field of health. This has prompted various scholars to undertake bibliometric analyses of the literature on the subject. There are also studies on the subject area itself that adopt a more general approach. For example, Saheb & Saheb (2019) reviewed 30,115 articles on health informatics published between 1974 and 2018. This review aimed to identify the field's patterns, networks, and key themes. The authors' principal conclusions underscore the significance of informatics in ensuring patient safety, enhancing care quality, and facilitating healthcare decision-making. As part of their findings, the researchers demonstrated that since 2016, health informatics has shifted toward predictive, personalized, and preventive models of care. A study by Liu, Liu, and Zheng (2019) analyzed research trends between 2008 and 2017 using data from the Studies in Health Technology and Informatics series. The study revealed increased scientific productivity, with the United States, Germany, and Canada as the most active countries, and key topics such as "electronic health records" and "telemedicine." A keyword analysis revealed a growing interest in "big data" and "mHealth," reflecting the evolution of digital health research topics.

In their study, Nadri *et al.* (2017) systematically identified the 100 most cited articles in medical informatics. This method allowed them to gain valuable insights into the field's most influential topics and research trends. The most prominent subjects addressed included electronic health record systems, big data analytics, and telemedicine. Furthermore, the article examined citation trends to understand these papers' impact and significant contributions in health informatics. Meanwhile, Spreckelsen, Deserno, and Spitzer (2011) examined the impact of new bibliometric indexes and databases on the visibility of health informatics, comparing journal and author data coverage and metrics. The findings indicated that databases such as Scopus enhance the visibility of the field compared to ISI/Thomson Reuters (now Web of Science from Clarivate Analytics). Liang *et al.* (2020) conducted a comparative analysis of medical informatics publications in Chinese and international journals between 2008 and 2018, focusing on specific topics and papers. The findings indicated that Chinese journals prioritize technological and practical applications within hospital settings, whereas Western journals prioritize theoretical and statistical research. Furthermore, most authors in China are affiliated with hospitals, whereas authors from Western countries tend to be academics with a higher percentage of advanced studies. This reflects the disparate approaches to medical digitization observed across regions.

Several bibliometric studies have been conducted with a more narrow focus on specific technological topics. For example, Yu *et al.* (2024) conducted a review of the applications of large language models (LLMs) in biomedical and health informatics (BHI), with a particular focus on their capacity to enhance data analysis, patient care, and research. A review of 1,698 articles revealed the potential of LLMs for clinical decision-making and medical document analysis. In their 2024 bibliometric case study, Lin, Ford, and Willett (2024) examined the scholarly communication between the fields of information systems (IS) and health informatics (HI) in the context of health information systems (HIS) research. A citation analysis of articles published between 2000 and 2020 reveals that, despite the existence of shared interests, communication between the two fields could be more extensive and cohesive. This indicates the potential for collaboration to integrate concepts and enhance HIS research, particularly in system adoption, implementation, and evaluation domains. In their analysis of the success factors of electronic medical record (EMR) system implementation in the United States, Bansard *et al.* (2007) identified the significance of staff involvement, training, and technical support. The authors underscore the necessity of meticulous planning and adapting systems to user requirements as pivotal factors in optimizing the adoption and utilization of EMRs in clinical settings.

Additionally, case studies of regional studies are available. For instance, the study conducted by Tapera and Singh (2021) presents a bibliometric overview of medical informatics and telemedicine research in sub-Saharan Africa and the BRIC countries. This analysis focuses on the growth of mHealth from 1999 to 2018. The findings indicate that South Africa and China are at the vanguard of scientific output, with mHealth emerging as a pivotal domain for combating infectious and chronic diseases in Africa. The expansion of these studies underscores the significance of technology in enhancing healthcare services in regions with high healthcare needs. Enakrire (2020) studied publication patterns in health informatics in Africa from 1987 to 2018. The research underscores the significance of informatics in enhancing medical practice, with a discernible expansion in domains such as human-computer interaction and health data management. Among the findings is the identification of South Africa as a significant contributor to the field, with the NIH and the Gates Foundation serving as the primary funding sources. The study encourages the exchange of ideas and the advancement of knowledge management in the region. In conclusion, we would like to cite the research conducted by Binkheder, Aldekhyyel, and Almulhem (2021), who analyzed trends in health informatics publications in Saudi Arabia over 24 years. Their findings revealed a significant increase since 2010 and a predominant focus on clinical informatics, particularly on topics such as electronic medical records. Furthermore, these studies align with the Saudi Ministry of

Health's digital health goals, suggesting future directions in artificial intelligence and smart health enterprises.
In this study, we will employ a bibliometric approach to identify and analyze international collaboration trends between countries and institutions engaged in the publication of research on health and medical informatics over the past decade, spanning 2014 to 2023.

2. METHODOLOGY

This study was designed with a particular emphasis on examining scientific productivity and analyzing social networks. We extracted the most relevant literature on the subject to explore the collaborative networks of countries and institutions in health and medical informatics. To this end, the Scopus database was employed as the source from which data were extracted. A series of parameters were established to retrieve the indexed literature, including a coverage period of the last ten years (2014-2023) and a focus on research and review articles (documentary typology: article, review, conference article, conference review, and chapter). The terms used allowed us to retrieve the most accurate literature. The terms "medical informatics" and "health informatics" were used in the title, abstract, and keywords fields. Concerning the terms, the Boolean operator OR was employed, resulting in the following search terms: (TITLE-ABS-KEY ("health informatics") OR TITLE-ABS-KEY ("medical informatics")). The final sample consisted of 19,583 documents entered into a local database for normalization. As our indicators were based on collaboration by country and institution, we undertook a homogenization process to eliminate any potential noise sources during the results' processing, visualization, and analysis.

Following the cleansing of the data, it was subjected to a series of reviews to guarantee its integrity. Subsequently, the data were organized to analyze citation productivity and impact by country and institution. In both cases, countries and institutions were ranked by the total number of papers and citations to identify the most productive and impactful nations and to facilitate a comparison of their performance on a regional and global scale. A comparative analysis was also conducted to elucidate the discrepancies between productivity and impact. The countries and institutions were sorted into four distinct categories following the productivity data. The assignment was made using quartiles to determine the thresholds for each group:

- Very high producer: countries with the highest number of publications (above the third quartile, more than 100 papers).
- High producer: Countries with a high number of documents but less than those in the highest group (between the second and third quartile, between 50 and 99 documents).
- Moderate producer: Countries with moderate productivity (between the first and second quartile, between 20 and 49 documents).
- Low producer: Countries with the lowest number of publications (below the first quartile, less than 20 documents).

In the context of network analysis, our objective was to identify countries and institutions according to their prestige, influence, and importance (see Table 3). To this end, we employed centrality measures based on the data set representing node connections. Prestige was evaluated by applying eigenvector centrality, which quantified the extent of a node's connectivity to other pivotal nodes. The influence was determined by applying betweenness centrality, which identified nodes that act as critical bridges within the network. The importance of a node was gauged through degree centrality, which reflected the number of direct connections it had. The metrics above were calculated using Gephi, a tool for generating collaboration maps. The country collaboration map comprised 134 nodes and 2009 links, while the institution's collaboration map comprised 290 nodes and 1533 links. Subsequently, the results were analyzed to elucidate the network's structure.

3. RESULTS AND DISCUSSION

3.1. Country-based approach

Our findings indicate that scientific productivity in health and medical informatics is concentrated mainly in developed countries (See Table 1). The United States is the foremost

Country	Documents	Citations
united states	6975	149076
united kingdom	1671	39023
germany	1513	16944
canada	1139	18754
china	1041	20519
australia	994	18873
france	733	8405
india	689	9140
italy	602	8422
spain	533	8460
netherlands	506	9471
switzerland	442	6343
japan	417	4551
brazil	387	4624
sweden	379	5709
austria	367	5247
south korea	348	6903
greece	331	3317
iran	298	4699
taiwan	284	3469
finland	276	3223
norway	273	3823
denmark	271	3620
saudi arabia	266	4077
portugal	258	2343
belgium	183	3896
argentina	168	1290
ireland	160	2524
turkey	149	2547
new zealand	147	2831
russian federation	146	826
israel	138	2808
singapore	138	4678
malaysia	131	2782
indonesia	124	776
south africa	121	1799
pakistan	111	1945
ukraine	109	595
hong kong	105	5396

Table 1. Countries whose productivity is more than 100 articles.

contributor, with 6,975 papers, and exhibits the highest citation impact (149,076). The United Kingdom is the following most productive country, with 1,671 papers and 39,023 citations. Beyond these English-speaking countries, other nations also demonstrate noteworthy productivity and impact, including Germany (1,513 papers), China (1,041 documents), and Canada (1,139 papers).

Regarding regional analysis, Europe demonstrates a considerable presence, as evidenced by the contributions of countries such as France, Italy, Spain, and Switzerland. In Asia, China, India, and Japan are the foremost contributors. China has many publications (1,041) and citations (20,519), which suggests a growing influence on the global research landscape. Several developing countries have also made noteworthy contributions compared to the aforementioned developed countries. To illustrate, in Latin America, Brazil (387 papers), Argentina (168 papers), and Mexico (71 papers) are particularly noteworthy. In Africa, South Africa has the highest number of documents, with 121, followed by Nigeria with 53 and Egypt with 69. Nevertheless, despite the endeavors of select emerging countries, the majority have published fewer than 100 times, with a few notable exceptions, including India (689), Brazil (387), and South Africa (121). The country ranking based on their productivity can be visible in Table 2.

As previously stated, the leadership of the United States and the United Kingdom is a notable example of the relationship between productivity and citation impact. Notwithstanding, Canada and Australia exemplify a combination of high productivity and impact. Canada has 1,139 papers with 18,754 citations, an average of 16.5 citations per paper. This places Canada in a productive position with a robust impact. Australia exhibits a comparable pattern, with 994 papers and 18,873 citations (yielding an average of 19 citations per paper). In contrast, countries with fewer publications tend to have more citations per paper. For example, Switzerland has a mere 442 papers and 6,343 citations, whereas the Netherlands has 506 papers and 9,471 citations. This also reflects research's high level of influence on global scientific output.

In examining the collaborative network of countries (See Figure 1), the United States is identified as the most centralized nation, with 115 direct connections. This indicates that it plays a significant role in scientific production and collaboration. Other countries of note include the United Kingdom, Germany, Canada, and Switzerland, which have a considerable number of direct connections, thereby demonstrating their capacity to interact and

Productivity	Countries (Documents)
Very high producer	argentina (168), australia (994), austria (367), belgium (183), brazil (387), canada (1139), china (1041), denmark (271), finland (276), france (733), germany (1513), greece (331), india (689), iran (298), ireland (160), israel (138), italy (602), japan (417), malaysia (131), netherlands (506), new zealand (147), norway (273), portugal (258), russian federation (146), saudi arabia (266), singapore (138), south korea (348), spain (533), sweden (379), switzerland (442), taiwan (284), turkey (149), united kingdom (1671), united states (6975)
High producer	bangladesh (76), bosnia and herzegovina (47), chile (59), colombia (60), croatia (40), czech republic (74), ecuador (28), egypt (69), ethiopia (39), hong kong (105), hungary (37), indonesia (124), jordan (59), kenya (53), kuwait (31), lebanon (36), mexico (71), morocco (39), nigeria (53), pakistan (111), peru (34), philippines (40), poland (82), qatar (63), romania (79), serbia (35), slovenia (51), south africa (121), sri lanka (30), thailand (94), tunisia (31), ukraine (109), united arab emirates (74), viet nam (36)
Moderate producer	algeria (17), botswana (14), bulgaria (24), burkina faso (17), cameroon (12), congo (8), costa rica (8), cuba (22), cyprus (27), estonia (15), georgia (17), ghana (19), iceland (15), iraq (21), kazakhstan (8), lithuania (13), luxembourg (20), macao (18), malawi (14), malta (9), montenegro (7), nepal (9), north macedonia (7), oman (13), palestine (14), paraguay (9), rwanda (12), senegal (17), slovakia (26), tanzania (14), uganda (23), uruguay (22), zambia (9)
Low producer	albania (3), armenia (2), azerbaijan (2), bahrain (6), barbados (2), belarus (2), benin (5), brunei darussalam (5), cambodia (3), cayman islands (2), chad (2), cote d'ivoire (5), dominican republic (3), durham (3), guatemala (2), jamaica (2), laos (2), latvia (6), libya (5), madagascar (2), mali (5), mauritius (3), mongolia (3), mozambique (3), myanmar (2), namibia (3), new york (2), niger (2), puerto rico (3), sinai (2), uzbekistan (2), venezuela (2), yemen (4), zimbabwe (5)

Table 2. Country ranking based on productivity.

Country	Degree centrality	Country	Betweenness centrality	Country	Eigenvector
united states	115	germany	365.834406	united states	1
united kingdom	97	canada	330.337241	united kingdom	0.924361
germany	89	india	305.61504	switzerland	0.584833
canada	84	france	291.616684	united arab emirates	0.557977
switzerland	77	netherlands	266.917974	sweden	0.540365
france	75	italy	206.267908	viet nam	0.533193
india	75	united states	196.773705	thailand	0.521596
spain	72	japan	193.022157	spain	0.500332
australia	71	portugal	165.642164	taiwan	0.487756
netherlands	71	norway	157.640136	turkey	0.472277
sweden	71	greece	139.836692	zambia	0.469382
china	70	sweden	130.131828	south korea	0.388654
italy	69	china	130.049184	uruguay	0.319644
greece	63	malaysia	120.935055	south africa	0.311328
austria	62	mexico	115.266814	saudi arabia	0.304863
norway	62	switzerland	113.849268	singapore	0.292304
south africa	62	south africa	102.581685	sri lanka	0.252293
belgium	61	united kingdom	100.363398	zimbabwe	0.222788
japan	60	singapore	96.529774	yemen	0.214007
singapore	59	kenya	87.967397	ukraine	0.201531

Table 3. Country centrality measures.

collaborate extensively with other countries. We are presented with a group of countries with a longstanding reputation as hubs of innovation and knowledge, with highly robust academic systems. Conversely, countries such as Armenia, Barbados, Belarus, Puerto Rico, and Uzbekistan exhibit the lowest degree of centrality, with a single direct connection. This suggests that these countries have made limited contributions to the network, potentially due to lower levels of investment in research or a lack of focus on this area of study.

Regarding influence, Germany is the most prominent country, with a centrality score of

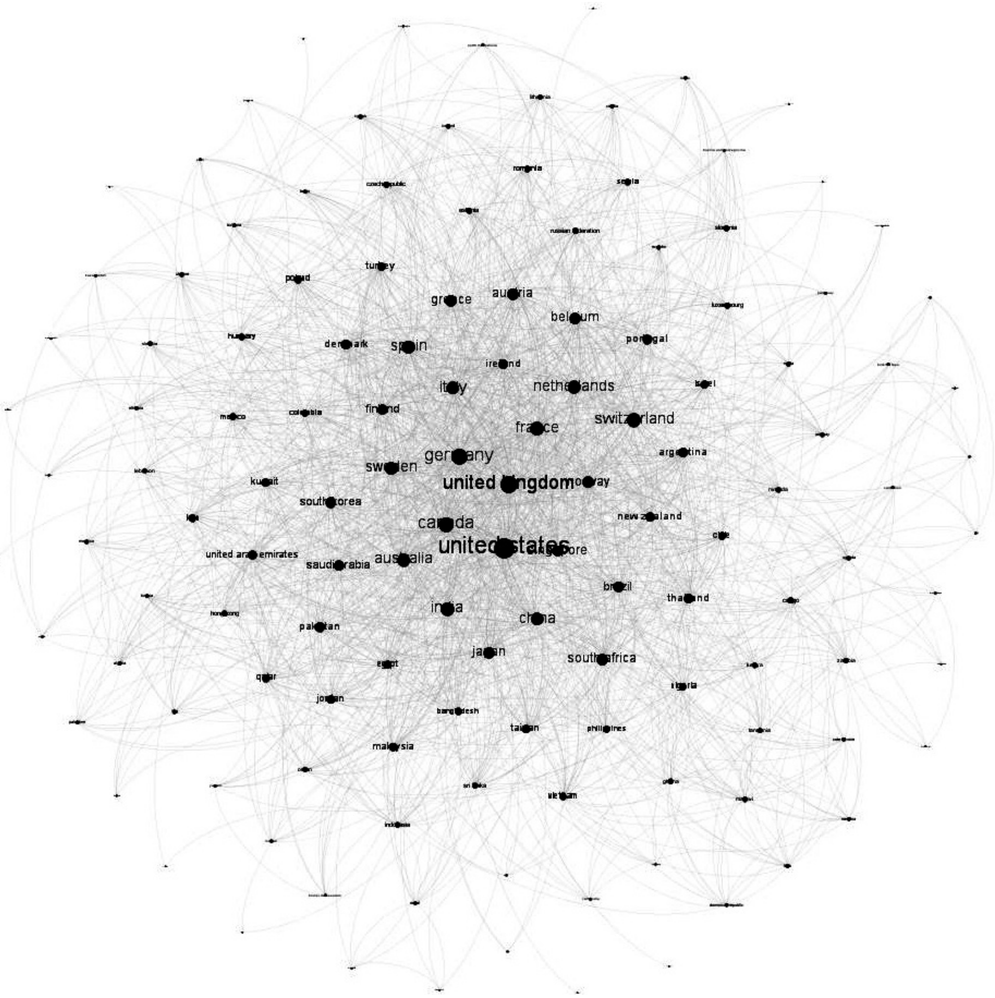

Figure 1. Country collaboration map.

365.83 for betweenness centrality. This indicates that this nation is pivotal for facilitating interconnections within the network. Additionally, Canada and India exhibit a considerable degree of intermediation centrality. France and the Netherlands represent the remaining two countries on the list of the five most influential. This indicates that these countries are not only significant contributors to the production of knowledge but also serve as facilitators, assisting in disseminating information and coordinating global research endeavors. Conversely, countries such as Albania, Algeria, Argentina, Armenia, and Azerbaijan have an intermediation centrality of zero, indicating that they do not act as intermediaries within the network. This may be attributed to their collaborative efforts primarily confined to local or more circumscribed contexts.

In terms of prestige, the United States is once again the leader, with a maximum eigenvector value of 1.00. Moreover, this country has numerous connections with other highly influential and prestigious nodes. The United Kingdom is situated close to the leader, reflecting its historic position as a world leader in research. Additionally, Switzerland, the United Arab Emirates, and Sweden are identified as countries with high prestige. This suggests that, despite not having the highest number of direct connections, those they possess are strategically valuable, conferring upon them a central position within the network. However, countries such as Albania, Algeria, Argentina, Armenia, and Azerbaijan have an eigenvector centrality of zero, indicating that their connections are not linked to other important countries. This lack of prestige constrains their visibility and impact within the global scientific network. For these countries, improving prestige would necessitate increasing the number of collaborations and focusing on partnerships with key players who already occupy a strong position within the network.

A further examination of the network reveals considerable variation in the extent of scientific collaboration across different world regions. To illustrate, the North American region, comprising the United States and Canada, is the most influential and prestigious health and medical informatics area. The United States is the dominant player in all centrality measures, demonstrating the most direct connections, acting as a crucial bridging node, and being connected to other important nodes. Meanwhile, Canada reinforces this influence, ranking as the second most influential country in the region thanks to its high intermediation centrality. This indicates North America generates a substantial volume of research output and fosters global collaboration, integrating other regions through strategic partnerships.

Europe region is distinguished by its network structure's incredible diversity and collaboration. In this case, all centrality measures are emphasized as well. The countries that play a pivotal role in this context are Germany, the United Kingdom, France, the Netherlands, and Switzerland. The high centrality observed in countries such as the United Kingdom and Germany suggests that Europe is a hub for knowledge production. In contrast, its elevated intermediation centrality indicates that it acts as a conduit for connecting disparate elements within the global network. France and the Netherlands also serve as pivotal intermediaries.

Moreover, the elevated prestige of countries such as Switzerland and Sweden suggests that Europe is home to nodes strategically linked to other pivotal nodes, reinforcing the region's status as a hub for high-quality research. However, the network displays a disparate set of patterns in Asia. Conversely, India and the United Arab Emirates demonstrate elevated centrality of intermediation and prestige, indicating that they serve as pivotal connection points and are integrated with esteemed nodes. India, in particular, is distinguished by its intermediary role, facilitating communication and collaboration between other regions. However, it is essential to note that different countries in the area have a more limited level of participation.

Latin America and Africa regions exhibit the most significant limitations in collaboration within the global network. For instance, Argentina, Brazil, and Chile occupy a moderate yet substantial position within the broader context of Latin America. While Brazil and Argentina have established connections, their intermediation centrality is relatively low. This suggests that their collaborations are primarily local and less integrated with other parts of the global network. While this indicates scientific output, the region still has scope for further international cooperation. In the African region, South Africa and, to a lesser extent, Nigeria are countries that contribute to scientific output and have some critical connections. However, their role in intermediation is limited, and they do not act as significant connection points in the network.

The United Arab Emirates and Qatar notably represent the Middle East region. The United Arab Emirates is distinguished by its prestige, which suggests that its connections are strategic and with significant actors. However, this region has fewer connections than in North America or Europe. As its intermediary role expands, so does its influence on integration into the global network.

3.2. Institucion-based approach

Among the institutions that stand out for their high productivity is Harvard Medical School, which has 243 documents. This makes it the institution with the highest scholarly production in the field. This high productivity is consistent with its worldwide reputation as a leader in medical research. In addition, institutions such as the University of Washington (133 papers), the Mayo Clinic (131 papers), and the University of Toronto (129 papers) also show high levels of scholarly activity. Columbia University and Vanderbilt University are among the most productive, with 156 and 106 papers, respectively (see Table 4).

Regarding citation impact, Harvard Medical School once again leads the field with 6,660 citations, confirming its position as the most influential center in this area of research. The research produced is numbered and widely

Institution	Documents	Citations
harvard medical school	243	6660
columbia university	156	4421
university of victoria	156	925
university of washington	133	2659
mayo clinic	131	3268
university of toronto	129	1865
university of utah	113	1943
vanderbilt university	106	2432
university of michigan, ann arbor	102	2430
vanderbilt university medical center	100	1498
university of texas health science center at houston	97	1538
brigham and women's hospital	88	2248
university of pennsylvania	88	1396
university of pittsburgh	86	1810
university of california, san francisco	84	2206
university college london	78	2339
university of oxford	73	1361
macquarie university	72	1355
university of minnesota	71	703
indiana university, indianapolis	68	1272
national and kapodistrian university of athens	68	165
stanford university	67	1918
hannover medical school	66	217
imperial college london	64	4110
regenstrief institute, inc	63	1752
university of florida	63	1048
greater paris university hospitals	61	160
duke university	60	1345
hospital italiano de buenos aires	60	360
king's college london	59	1498
icahn school of medicine at mount sinai	58	461
ohio state university	57	1140
university of melbourne	54	696
university of ottawa	54	537
massachusetts general hospital	53	1054
university of manchester	53	1320
university of edinburgh	52	963

Table 4. Institutions whose productivity is more than 50 documents.

referenced by other studies. The Mayo Clinic follows closely with 3,268 citations, while the University of Washington (2,659 citations) and Vanderbilt University (2,432 citations) also significantly impact this field. It is interesting to highlight institutions that do not lead in the number of papers but have a high impact as measured by citations, indicating that they produce high-quality research. This is the case of the Massachusetts Institute of Technology (MIT), which has 871 citations from 24 papers. This suggests that the research conducted at MIT is highly influential, although fewer in number. On the other hand, the Alan Turing Institute, with ten papers and 517 citations, stands out for the quality of its research.

In some cases, some institutions produce a high volume of papers, but the impact measured by the number of citations is not as high in proportion to their productivity. Columbia University is an example of this trend, with 156 papers receiving 4,421 citations. While still receiving significant recognition, the average number of citations per paper is lower than that of other leading institutions, such as Harvard. The University of Toronto, with 129 papers and 1,865 citations, reflects a similar dynamic. Its productivity is high, but its impact is moderate. The institution ranking based on their productivity can be visible in Table 5.

On the map of institutional collaborations (See Figure 2 and Table 6), Harvard Medical School (degree centrality: 96) is the most important institution with the highest number of direct links. This position makes it a central node in the network, with the ability to interact and collaborate with many other institutions, facilitating the exchange of knowledge and resources. The University of Washington (centrality score: 65) also stands out, consolidating itself as one of the critical institutions with multiple partnerships. In addition, Mayo Clinic (grade centrality: 65) and Columbia University (grade centrality: 59) follow in the list, demonstrating that they are essential players within the network by the number of direct interactions. Other relevant institutions in this category include the University of Utah (degree centrality: 56), Vanderbilt University (degree centrality: 54), and the University of Michigan, Ann Arbor (degree centrality: 50), all with a strong focus on maintaining numerous direct connections.

Productivity	Institutions (Documents)
High producer	university of texas health science center at houston (97), brigham and women's hospital (88), university of pennsylvania (88), university of pittsburgh (86), university of california, san francisco (84), university college london (78), university of oxford (73), macquarie university (72), university of minnesota (71), imperial college london (69), indiana university, indianapolis (68), national and kapodistrian university of athens (68), stanford university (67), hannover medical school (66), regenstrief institute, inc (63), university of florida (63), greater paris university hospitals (61), duke university (60), hospital italiano de buenos aires (60), king's college london (59), icahn school of medicine at mount sinai (58), ohio state university (57), university of ottawa (54), university of melbourne (54), massachusetts general hospital (53), university of manchester (53), university of edinburgh (52)
Low producer	vanderbilt university medical center (100), university of eastern finland (19), university of portsmouth (19), university of maryland, baltimore (19), university of alabama at birmingham (19), drexel university (19), king faisal specialist hospital and research center (19), johns hopkins university (19), south london and maudsley nhs foundation trust (19), beth israel deaconess medical center (18), university of bergen (18), mahasarakham university (17), monash university (17), university of bristol (17), ait austrian institute of technology gmbh (17), academy of medical sciences of bosnia and herzegovina (17), medical university of south carolina (17), aalto university (16), national university of singapore (16), northwestern university, evanston (16), universite de lille (16), university of tokyo (16), uppsala university (16), university of glasgow (15), rand corporation (15), university of southampton (15), university of california, san diego (15), ministry of health, argentina (15), oxford university hospitals nhs trust (15), medexter healthcare gmbh (15), karolinska institutet (15), northeastern university (15), seattle children's hospital (14), university of regensburg (14), university of freiburg (14), university of california, irvine (14), université de paris (14), kaiser permanente washington health research institute (14), hellenic open university (14), cincinnati children's hospital medical center (14), boston children's hospital (14), telkom university (13), university of braunschweig (13), university of illinois at chicago (13), university of new south wales (13), university of oklahoma (13), university of south florida (13), university of nottingham (12), wuhan university (12), university of thessaly (12), university of texas southwestern medical center (12), university of southern california (12), university of piraeus (12), deggendorf institute of technology (12), university of massachusetts medical school (12), university of basel (12), university hospitals of geneva (12), sismanogleio general hospital (12), queensland university of technology (12), ludwig boltzmann institute for digital health and prevention, salzburg, austria (12), virginia commonwealth university (11), utrecht university (11), university of texas health science center at san antonio (11), university of texas at austin (11), university of miami (11), university of bern (11), university of huddersfield (11), tampere university (11), university of agder (11), sorbonne université (11), sichuan university (11), norwegian centre for e-health research, tromsø, norway (11), king saud bin abdulaziz university for health sciences (11), sungkyunkwan university (11), moi university (10), university of twente (10), university of kentucky (10), peking university (10), national institute for health and welfare (10), university of connecticut (10), mcgill university (10), itmo university, saint petersburg, russian federation (10), canada health infoway (10), asan medical center seoul (10), alan turing institute (10), american medical informatics association, bethesda, md, united states (9), health data research uk, london, united kingdom (9), queen's university belfast (9), university of british columbia (9), university of maryland, college park (9), university of california, davis (8), xi'an jiaotong university (8), university of wisconsin-milwaukee (8), university of technology sydney (8), university of north carolina at charlotte (8), university of manitoba, department of computer science, winnipeg, mb, canada (8), medical college of wisconsin (8), university of bradford (8), ibm watson health, cambridge, ma, united states (8), gecko institute, heilbronn university of applied sciences, heilbronn, germany (8), aristotle university of thessaloniki (8), school of nursing, university of auckland, auckland, new zealand (8), university of massachusetts, lowell (7), school of systems and enterprises, stevens institute of technology, hoboken, nj, united states (7), tomsk state university (7), turku university hospital, turku, finland (7), univ rennes, chu rennes, inserm, ltsi - umr 1099, rennes, f-35000, france (7), university health network, toronto, on, canada (7), university of cambridge (7), university of geneva, switzerland (7), university of wales trinity saint david (7), university of south africa (7), university of windsor (7), va salt lake city health care system (7), vienna university of technology (7), western university (7), worcester polytechnic institute (7), national institutes of health, bethesda, md, united states (7), purdue university (7), department of medical informatics, university medical center göttingen, göttingen, germany (7), nanjing university of chinese medicine (7), department of electrical, computer and biomedical engineering, university of pavia, italy (7), michael smith foundation for health research, canada (7), almazov national medical research centre (7), american medical association, chicago, il, united states (7), boston university (7), burdenko neurosurgery institute of the russian academy of medical sciences (7), department of computation, university of a coruña, spain (7), cerner corporation, kansas city, mo, united states (7), alliance pour la recherche en cancérologie (7), dublin city university (7), german cancer research center (7), harvard university (7), health informatics research group, university as osnabrück, germany (7), infoclin inc, toronto, on, canada (7), leiden university medical center, leiden, netherlands (7), university of arizona, tucson, az, united states (6), politecnico di torino (6), tomsk polytechnic university (6), ugmlc, german center for lung research (dzl), justus-liebig-university, giessen, germany (6), univ. grenoble alpes, cnrs, grenoble inp, lig, grenoble, 38000, france (6), universidad peruana cayetano heredia, lima, peru (6), university of applied sciences western switzerland (hes-so), sierre, switzerland (6), visiting nurse service of new york (6), university of chinese academy of sciences (6),

Productivity	Institutions (Documents)
Low producer	university of minho (6), university of south australia (6), university of tsukuba (6), university of zagreb (6), victoria university (6), medical university of vienna (6), nyu langone health (6), institute of medical informatics, medical faculty, rwth aachen university, germany (6), md anderson cancer center, houston, tx, united states (6), department of health sciences, university of genoa, genoa, italy (6), institute of biomedical informatics, national yang-ming university, taipei, taiwan (6), american health information management association (6), auburn university, auburn, al, united states (6), bruyère research institute (6), department of community health sciences, university of calgary, calgary, ab, canada (6), department of health information technology and management, school of allied medical sciences, shahid beheshti university of medical sciences, tehran, iran (6), case western reserve university, cleveland, oh, united states (6), department of industrial engineering, tsinghua university, beijing, china (6), elsinki university hospital (6), georgetown university, washington, dc, united states (6), graduate school of public health, st. luke's international university, tokyo, japan (6), healthropy s.r.l., savona, italy (6), human sciences, new public health, university osnabrück, germany (6), medical informatics department, school of medicine, hamamatsu university, shizuoka, japan (5), rti international (5), oulu university hospital, oulu, finland (5), niversity of udine (5), nazi boni university, bobo-dioulasso, burkina faso (5), mohammed v university (5), michigan state university (5), instituto de salud carlos iii (5), mcmaster university, hamilton, on, canada (5), maynooth university, maynooth, ireland (5), maastricht university, netherlands (5), leeds teaching hospitals nhs trust, leeds, united kingdom (5), la trobe university, australia (5), school of medical informatics and engineering, southwest medical university, luzhou, china (5), ryerson university, toronto, on, canada (5), universidad de sevilla, seville, spain (5), school of medicine and health management, tongji medical college, huazhong university of science and technology, wuhan, china (5), smith consortium of the german medical informatics initiative, leipzig, germany (5), symantec, cambridge, ma, united states (5), teranga software, paris, france (5), the australian national university, canberra, act, australia (5), tufts university school of medicine, boston, ma, united states (5), institute of medical informatics, umit - private university for health sciences, medical informatics and technology, hall in tirol, austria (5), universidad politécnica de madrid, madrid, spain (5), university at buffalo, buffalo, ny, united states (5), university of alberta, edmonton, ab, canada (5), university of georgia (5), universitätsklinikum erlangen (5), va boston healthcare system (5), va palo alto health care system, palo alto, ca, united states (5), victor babes university of medicine and pharmacy, timisoara, romania (5), institute of medical information, chinese academy of medical sciences, beijing, china (5), escola nacional de saúde pública sergio arouca, fundação oswaldo cruz, rio de janeiro, brazil (5), institute of information and communication technologies, bulgarian academy of sciences, sofia, bulgaria (5), independent power transmission operator s.a. (5), aami (5), australian patient safety foundation, adelaide, australia (5), berlin institute of health (bih), germany (5), boston medical center (5), center for biomedical informatics, brown university, providence, ri, united states (5), centre for development of advanced computing, noida, india (5), children's hospital of philadelphia (5), cintesis, center for health technology and services research, portugal (5), city university of hong kong, hong kong (5), cleveland clinic, united states (5), college of life information science and instrument engineering, hangzhou dianzi university, hangzhou, 310018, china (5), college of nursing and health sciences, flinders university, adelaide, sa, australia (5), dakota state university, united states (5), dana-farber cancer institute, boston, ma, united states (5), deakin university, melbourne, vic, australia (5), deib, politecnico di milano university, italy (5), department of computer and systems sciences, stockholm university, stockholm, sweden (5), department of computer science, uit the arctic university of norway, tromsø, norway (5), department of education, ict and learning, østfold university college, halden, norway (5), department of medical informatics, carl von ossietzky university, oldenburg, germany (5), department of medical informatics, erasmus university medical center, rotterdam, netherlands (5), department of primary care medicine, faculty of medicine, university of malaya, kuala lumpur, malaysia (5), department of public health, university of naples federico ii, naples, italy (5), dept of computer science, george mason university, united states (5), digital health cooperative research centre, australian government, sydney, nsw, australia (5), european federation for medical informatics, lausanne, switzerland (5), hanoi university of industry, hanoi, viet nam (5), health informatics unit, dasman diabetes institute, kuwait (5), ibm t.j. watson research center, yorktown heights, ny, united states (5), vit university (5)
Moderate producer	university of turku (49), university of north carolina at chapel hill (47), aalborg university (46), bern university of applied sciences (46), georgia institute of technology (46), weill cornell medicine (45), emory university (45), yale university (43), iran university of medical sciences (42), u.s. national library of medicine (40), university of leeds (39), university of warwick (37), university of wisconsin-madison (37), friedrich-alexander-universität erlangen-nürnberg (36), lviv polytechnic national university (36), university of virginia (36), university of münster (35), university of amsterdam (35), medical university of graz (34), oregon health and science university (34), seoul national university (34), tehran university of medical sciences (34), university of missouri (34), hamad bin khalifa university (32), dalhousie university (31), heidelberg university (31), partners healthcare (30), linköping university (30), ibm research (30), university of aveiro (29), york university (29), centre for addiction and mental health (28), london school of hygiene and tropical medicine (28), mashhad university of medical sciences (28), university hospital of north norway (28), university of sydney (28), university of southern denmark (27),

Productivity	Institutions (Documents)
Moderate producer	taipei medical university (27), university of leipzig (27), kerman university of medical sciences (27), arizona state university (26), baylor college of medicine (26), centers for disease control and prevention (26), florida state university (26), heidelberg university hospital (26), university of lübeck (26), world health organization (26), university of surrey (25), graz university of technology (25), carnegie mellon university (24), university of waterloo (24), zhejiang university (24), massachusetts institute of technology (24), university of california, los angeles (23), university of sarajevo (23), memorial sloan kettering cancer center (22), technische universität dresden (22), university of arkansas for medical sciences (22), university of chicago (22), university of oulu (21), university of tasmania (21), centre for research and technology hellas (21), university of cincinnati (21), university of california, berkeley (21), osnabrück university (20), university of oslo (20)
Very high producer	harvard medical school (243), university of victoria (156), columbia university (156), university of washington (133), mayo clinic (131), university of toronto (129), university of utah (113), vanderbilt university (106), university of michigan, ann arbor (102)

Table 5. Institution ranking based on productivity.

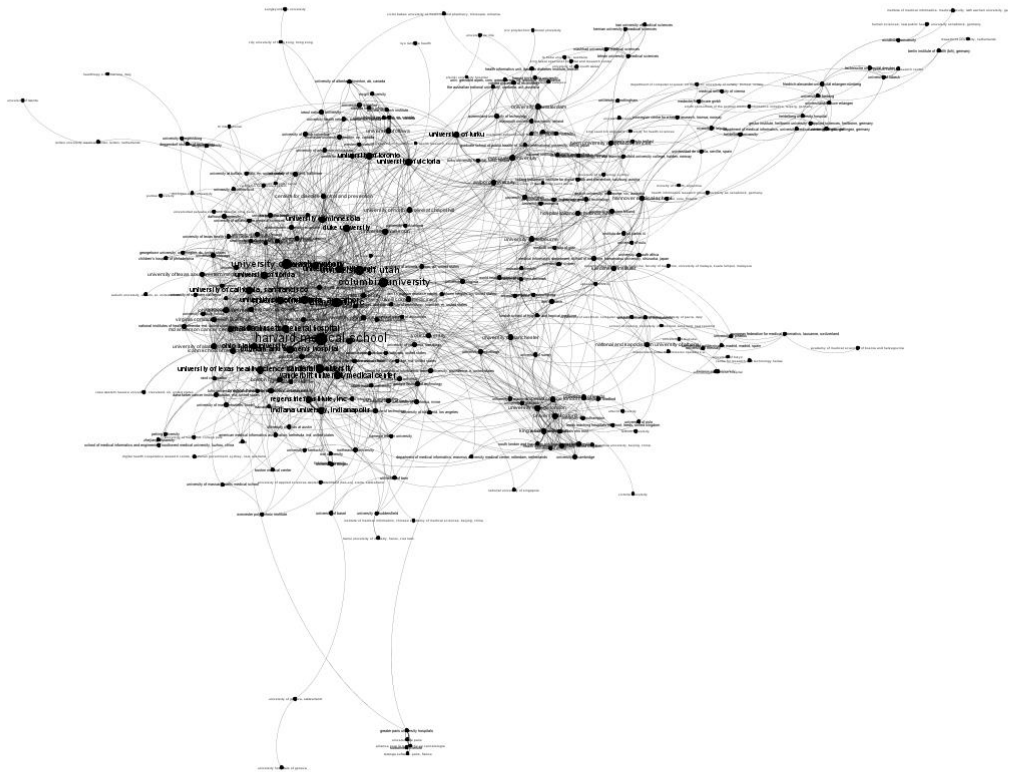

Figure 2. Institution collaboration map.

Harvard Medical School (betweenness centrality: 1754.79) also stands out as the most influential institution, a crucial node for connecting different network parts. Its strategic position allows it to act as a critical intermediary, facilitating collaborations that would not otherwise occur. Mayo Clinic (betweenness centrality: 1618.28) is also an influential actor within the network. The Karolinska Institutet (betweenness centrality: 778.57) stands out as an institution that connects different parts of the network, as do the Massachusetts General Hospital (betweenness centrality: 695.16) and the University of Michigan, Ann Arbor (betweenness centrality: 675.81). At the opposite extreme, institutions such as Vanderbilt University Medical Center (betweenness centrality: 28.65) are less able to act as intermediaries, indicating that while they may have direct connections, they are not essential to maintaining the overall cohesiveness of the network.

Country	Degree	Country	Betweenness	Country	Eigenvector
harvard medical school	96	harvard medical school	1754.788338	vanderbilt university	0.997187
mayo clinic	65	mayo clinic	1618.282147	vanderbilt university medical center	0.974829
university of washington	65	karolinska institutet	778.568867	university of utah	0.671366
columbia university	59	massachusetts general hospital	695.158723	yale university	0.605306
university of utah	56	university of michigan, ann arbor	675.813518	york university	0.501937
vanderbilt university	54	university of manchester	624.692266	university of wisconsin-madison	0.485388
university of michigan, ann arbor	50	university of utah	596.292555	university of pittsburgh	0.448671
vanderbilt university medical center	44	columbia university	549.271911	university of texas health science center at houston	0.445532
massachusetts general hospital	42	university college london	530.821827	virginia commonwealth university	0.408198
university of pennsylvania	40	university of amsterdam	530.797619	weill cornell medicine	0.401788
university of california, san francisco	40	university of california, san francisco	529.537235	university of pennsylvania	0.380098
duke university	40	university of florida	506.36896	university of victoria	0.363007
university of texas health science center at houston	39	university of missouri	454.868576	university of toronto	0.357942
brigham and women's hospital	39	hannover medical school	435.897222	university of michigan, ann arbor	0.355496
university of florida	38	university of toronto	427.261369	university of wisconsin-milwaukee	0.344762
university of pittsburgh	37	king's college london	415.538095	university of turku	0.262459
stanford university	37	university of pennsylvania	402.131674	university of minnesota	0.255669
university of victoria	34	macquarie university	394.55175	university of california, san francisco	0.24045
university of toronto	34	university of texas health science center at houston	388.016971	university of virginia	0.227555
university of minnesota	34	duke university	385.678003	university of florida	0.21002

Table 6. Institution centrality measures.

Eigenvector centrality considers both the number of direct connections and the quality of the connected institutions, highlighting the prestige and relevance of the entity within the network. The University of Washington (eigenvector centrality: 1,000) leads in this metric, showing that it not only has many connections but that these connections are with other highly influential institutions, giving it a high level of prestige. Vanderbilt University (Eigenvector centrality: 0.997) is another institution with high prestige, reflecting that it is very well connected to other equally relevant institutions. Vanderbilt University Medical Center (eigenvector centrality: 0.975) follows closely behind, consolidating the prestige associated with the Vanderbilt network. The University of Utah (eigenvector centrality: 0.671) and Yale University (eigenvector centrality: 0.605) also appear well-positioned, demonstrating strategic links with influential institutions.

From a regional perspective, North America dominates in all metrics, specifically the United States. In terms of importance, Harvard Medical School (USA) leads the way. Still, other United States institutions such as the University of Washington (centrality degree: 65), the Mayo Clinic (centrality degree: 65), and Columbia University (centrality degree: 59) are also among the most important, demonstrating that universities and research centers in this country are critical nodes in the international collaboration network. The University of Michigan, Ann Arbor, and the University of Utah continue this pattern. The same is true for the measures of influence and prestige, with institutions such as Harvard Medical School, Mayo Clinic, Massachusetts General Hospital, University of Washington, Vanderbilt University, and Yale University standing out.

On the other hand, some institutions have a significant influence in Europe. This is the case of the Karolinska Institutet (Sweden), an essential player with multiple connections, consolidating Sweden's position as a leader in the field. The same institution stands out for its influence (betwenness centrality: 778.57), connecting different regions and facilitating international collaboration. The University of Manchester (United Kingdom) also appears as a critical node in influence, facilitating European connections and partnerships. Others stand out, such as University College London, University of Amsterdam, King's College London, and the University of Oxford. This shows that British institutions still have a strong presence and influence at the global level. The Karolinska Institutet also leads in terms of prestige.

Asian, Latin American, African, and Australian institutions do not appear to be as frequent in the highest centrality metrics, which could indicate a lower level of global connectivity and prestige than their North American and European counterparts. However, the situation varies across subregions and countries.

4. CONCLUSION

The results of this study indicate that the United States and the United Kingdom are the countries that exhibit the most remarkable dominance in terms of both the number of publications and citation impact. However, it is notable that other countries have high productivity and citation ratios, including Switzerland, the Netherlands, Germany, and Canada. The centrality analysis, however, reveals a diverse picture of the health and medical informatics research network. The United States, the United Kingdom, Germany, Canada, and Switzerland are the most prominent countries, occupying critical roles as necessary, influential, and prestigious nodes. This analysis indicates that success in networking is contingent upon both the quantity and the quality of the connections established. It underscores the importance of strategic alliances for enhancing global influence and prestige.

The analysis of scientific collaboration in health and medical informatics demonstrates that North America and Europe are the preeminent regions, exhibiting dense and well-connected networks that facilitate the global integration of scientific knowledge. Asia, with key countries such as India and the United Arab Emirates, is emerging as an essential region, especially regarding intermediation and prestige. While Latin America and Africa are less represented, there is potential for these regions to increase their participation by expanding their collaborative networks, which is critical to improving the impact and visibility of their research. Finally, the Middle East is growing as an influential region.

Latin America and Africa collaborate at a comparatively lower level in the context of the health and medical informatics network. While some nations, such as Brazil, Argentina, South Africa, and Nigeria, have initiated the integration process, the overall level of collaboration could be much higher. Therefore, developing policies that encourage international research and collaboration would be advisable.

An analysis of scientific productivity by institution reveals that Harvard Medical School, Mayo Clinic, and the University of Washington are preeminent in the generation and impact of research in medical informatics and health. These institutions are distinguished not only by the number of papers they have produced but also by their high impact, as evidenced by citations, and by their capacity to integrate into extensive collaborative networks. Moreover, some institutions, including MIT and The

Alan Turing Institute, demonstrate high implications despite exhibiting lower production levels.

Concurrently, North America, particularly the United States, is the unquestionable frontrunner in all centrality metrics, exhibiting a pronounced distinction in degree, betweenness, and eigenvector. This is attributable to a robust research infrastructure, funding availability, and the capacity to attract high-quality international collaborations. Notable institutions such as Harvard Medical School, the University of Washington, and the Mayo Clinic are highly connected within the scientific community and facilitate connections between different parts of the world, ensuring the efficient flow of knowledge and innovation. In Europe, institutions such as Karolinska Institutet and the University of Manchester occupy pivotal positions, enabling them to serve as vital nodes for scientific collaboration within the region. The elevated intermediation centrality of Karolinska Institutet serves to reinforce Europe's role as a principal actor in the domain of medical sciences and biomedical research.

Further research could employ alternative metrics to investigate this phenomenon, offering a more nuanced perspective and potentially richer data.

Conflict of interests

The authors should declare potential conflicts of interest or not.

Contribution statement

Conceptualization, formal analysis, investigation, and methodology: Elsa Carmen Oscuvilca Tapia, Gladys Magdalena Aguinaga Mendoza, Hemerson Rostay Paredes Jiménez.

Methodology, software, validation, and visualization: Jhonny Javier Albitres Infantes, Hemerson Rostay Paredes Jiménez, Elia Clorinda Andrade Girón.

Writing - review & editing: Elsa Carmen Oscuvilca Tapia, Elia Clorinda Andrade Girón.

Statement of data consent

The data generated during the development of this study has been included in the manuscript.

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