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Does open access foster interdisciplinary citations? Decomposing open access citation advantage

Kai Nishikawa[1,2] · **Akiyoshi Murakami**[2]

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Abstract

The existence of an open access (OA) citation advantage—that is, whether OA increases citations—has been a topic of interest for many years. Although numerous studies have focused on whether OA increases citations, expectations for OA go beyond that. One such expectation is the promotion of knowledge transfer across various fields. This study aimed to clarify what effects OA, particularly gold OA, has on knowledge transfer across fields. Specifically, we measure the effect of OA on interdisciplinary and within-discipline citation counts by decomposing an existing OA citation advantage metric. OA increased both interdisciplinary and within-discipline citations in many fields studied, and only interdisciplinary citations in chemistry, computer science, and clinical medicine. In these three fields, clinical medicine showed a tendency toward interdisciplinary citations, independent of journal or paper. These findings suggest that OA fosters knowledge transfer across disciplines.

Keywords Open access citation advantage · Open access · Gold open access · Interdisciplinary citation · Knowledge transfer

Introduction

Since the release of the Budapest Open Access Initiative, the number of open access (OA) papers has grown steadily. With several countries' policies now mandating that publicly funded research outputs be made OA, the number of OA papers is expected to continue increasing in the future. A paper can be made OA in several ways. The most frequently selected method is gold OA, which entails publishing a paper in a fully OA journal in which all papers are published as OA (Heidbach et al., 2022). Gold OA requires authors to

✉ Kai Nishikawa
knishikawa@slis.tsukuba.ac.jp

1 Institute of Library, Information and Media Science, University of Tsukuba, 1-2, Kasuga, Tsukuba, Ibaraki 305-8550, Japan

2 National Institute of Science and Technology Policy (NISTEP), Ministry of Culture, Science and Sports (MEXT), 3-2-2, Kasumigaseki, Chiyoda-ku, Tokyo 100-0013, Japan

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pay the publisher a fee for OA, called the article processing charge (APC), and countries that mandate OA often subsidize the APC.[1]

In this policy context, the effects of OA are often evaluated through the lens of the OA citation advantage, which refers to the potential increase in the number of citations that OA publications receive compared to non-OA publications. Although research on this advantage has been ongoing since Lawrence (2001) proposed its existence, previous studies have produced differing results, and no generalizable finding has been established to indicate that the OA citation advantage exists consistently across all groups of papers (Langham-Putrow et al., 2021).

Additionally, most previous studies have focused on determining whether an OA citation advantage exists. Even when results suggest that OA increases citation counts, few studies have examined the types of citations in detail. However, expectations surrounding OA—and open science more broadly—should not be confined to boosting citation counts. One key expectation is that openness will foster knowledge transfer across fields and sectors (Organization for Economic Co-operation and Development [OECD], 2015).

Therefore, the question we address in this study is to clarify what effects OA, particularly gold OA, has on knowledge transfer across fields. Specifically, we decompose the traditional metric of the OA citation advantage by distinguishing between interdisciplinary and within-discipline citations and introduce a new metric to determine whether OA increases interdisciplinary citations. Based on this metric, we address the following specific research questions:

1. *Are papers across various natural science fields more likely to be cited in papers from other fields when published as OA?*
2. *If so, how do OA papers affect the fields where OA fosters interdisciplinary citation?*

Literature review

Open access citation advantage

Since Lawrence (2001) proposed the existence of the OA citation advantage in the field of computer science, numerous studies have sought to verify this phenomenon across various fields. Langham-Putrow et al. (2021) recently identified 134 relevant publications. However, it noted that researchers have yet to reach a consensus on whether an OA citation advantage exists. Although many previous studies encompassing multiple fields have reported evidence of an OA citation advantage in some fields, they concluded that a generalizable advantage is lacking (e.g., Dorta-Gonzalez & Santana-Jiménez, 2018; Dorta-Gonzalez et al., 2017). Langham-Putrow et al. (2021) attributed inconsistencies in the findings to several factors, including the different types of OA being examined and the absence of standardization in the definitions, metrics, and methodologies used to measure the OA citation advantage.

Early studies on the OA citation advantage proposed three postulates as mechanisms by which OA leads to more citations (Craig et al., 2007; Davis et al., 2008; Kurtz et al., 2005; Moed, 2007). The first is the *open access postulate*, which suggests that OA papers are read and cited more frequently because of their greater availability. The second is the *early*

[1] If diamond OA is considered a subtype of gold OA, then paying an APC is not always required for gold OA.

view postulate, which suggests that OA papers tend to have higher cumulative citation counts because they are made available online earlier than other publications. The third, the *selection bias postulate*, states that papers authored by reputable authors or those of higher quality are more likely to be made OA, leading to increased citation counts for OA papers.

It has been suggested that a pure OA citation advantage corresponds to the first postulate and that the influences of the second and third postulates should be controlled to ascertain whether an OA citation advantage exists (Dorta-Gonzalez et al., 2017; Gaulé & Maystre, 2011; Niyazov et al., 2016). To control for the *early view postulate*, researchers often assess the number of citations of a paper within a specific citation time window (e.g., three years post-publication; Dorta-Gonzalez et al., 2017; Sotudeh et al., 2015). Additionally, Sotudeh et al. (2015) mentioned this postulate as particularly relevant for green OA, possibly because preprints in green OA are often made available without embargoes, allowing earlier access compared to version of records. To address the *selection bias postulate*, a common approach involves comparing OA and non-OA papers by categorizing them based on their journal impact factor (JIF) quartiles in their respective fields (Niyazov et al., 2016).[2]

Many studies have employed the mean or median citations per paper as metrics to measure the OA citation advantage (Langham-Putrow et al., 2021). Additionally, various other metrics have been utilized depending on the research purpose and context. In particular, studies investigating the OA citation advantage across fields often use the ratio of the difference between the average citation count of OA papers and non-OA papers to the average citation count of non-OA papers (as described in the Methods section, this metric is called the OACA in the present study; Dorta-Gonzalez et al., 2017; Sotudeh et al., 2015). Moreover, most previous studies have calculated the OA citation advantage based on the number of citations without examining the attributes of each citation, such as its field of origin.

The social impact of OA

Studies on OA citation advantage have examined the scholarly impact of OA by focusing on citation relationships among scholarly publications. According to Cole et al. (2024), a review of studies on the social impact of open science, including OA, the primary focus in research on the social impact of OA is social engagement and use in policy-making.

With regard to social engagement, multiple studies have examined the OA altmetrics advantage, which explores whether OA publications contribute to higher altmetrics scores for individual papers. Although many studies have reported the existence of an OA altmetrics advantage (e.g., Cho, 2021a, 2021b; Nabavi, 2022), some have suggested that this advantage varies by field (Holmberg et al., 2020). In addition, some studies have examined the relationship between OA and altmetrics from perspectives other than the pure

[2] However, in the current landscape—characterized by the proliferation of e-journals and the implementation of policies mandating OA in some countries—it is no longer the case that only reputable authors choose to make their papers OA or that only high-quality papers are published as OA. It is also not unusual for a version of record to be made publicly available as "early access" shortly after acceptance of a manuscript. Consequently, the influence of the *early view* and *selection bias postulates* may differ between the 2000s, when these concepts were first proposed, and the present day. Notably, some recent studies have not explicitly addressed these postulates (e.g., Basson et al., 2021).

OA altmetrics advantage. For example, Shahraki Mohammadi et al. (2024) compared the altmetrics scores of OA and non-OA retracted papers, while other studies have combined OA citation advantage analysis with altmetrics data (e.g., Hadad & Aharony, 2023; Wang et al., 2015).

Furthermore, some studies focused on the OA altmetrics advantage in books rather than in papers. Taylor (2020) reports an OA altmetrics advantage, at least for OA books and chapters in the humanities and social sciences. Similarly, Wei and Chakoli (2020) compared the citation and altmetric advantages of OA books and found that OA books received more mentions on social media than non-OA books did. However, they noted that an OA citation advantage was not observed except in certain fields.

With respect to use in policy-making, Vilkins and Grant (2017), Tai and Robinson (2018), and Zong et al. (2023) found that OA increased the citations of papers in policy documents, although their analyses were limited to specific fields and countries. Taylor (2020) also found that OA books are cited in policy documents more frequently than non-OA books.

OA and citation diversity

Some studies have examined the scholarly impact of OA by adopting an approach different from that of OA citation advantage studies. Huang et al. (2024) analyzed a large number of papers published between 2010 and 2019. Rather than simply examining whether making a paper OA increases the number of citations, these scholars investigated the effect of OA on the diversity of fields, regions, and institutions among the citing parties. Their findings revealed a strong correlation between OA status and an increased diversity of attributes among citing papers. Similarly, Young and Brandes' (2020) analysis of two journals found that OA papers were more likely to receive diverse citations from various fields compared to non-OA papers. Relatedly, by comparing OA and non-OA books, Neylon et al. (2021) found that OA books were downloaded from a more diverse range of countries.

Knowledge gap and position of this study

While this study shares an interest in the diverse effects of OA with research on its social impact, it primarily focuses on the scholarly impact of OA articles, and is therefore positioned as a study on OA citation advantage. However, unlike many previous OA citation advantage studies, our focus was not on whether OA increases the total number of citations but rather on its effect on interdisciplinary citations. We were interested in the relationship between OA and interdisciplinary citations because, as mentioned earlier, this is one of the various effects that OA is anticipated to produce, and to the best of our knowledge, no study has explicitly focused on it.

In this regard, this study shares common ground with studies that investigated effects beyond the traditional OA citation advantage, especially Huang et al. (2024) and Young and Brandes (2020), both of whom examined citation diversity of papers. However, those scholars did not adopt a citation count-based metric and consequently did not provide a detailed analysis of the internal structure of disciplinary diversity, such as how many citations from which field result from making a paper in a certain field OA. Such knowledge is lacking in existing research but could be valuable to policymakers promoting OA and researchers deciding whether to make their papers OA.

This study builds on previous studies that analyzed the OA citation advantage across multiple disciplines; however, it also considered, perhaps novelly, the citing papers' disciplinary attributes. In this sense, this study falls somewhere between an OA citation advantage and an OA citation diversity study, making a novel contribution by filling the knowledge gaps found in these two types of studies.

Methods

Data collection and processing

Sampling method and definition of the population

This study used total population sampling to collect data. The data consisted of raw data from the Web of Science (WoS) core collection at the end of 2022, purchased by the National Institute of Science and Technology Policy (NISTEP). They included records from the Science Citation Index Expanded (SCIE), the Social Sciences Citation Index (SSCI), the Arts and Humanities Citation Index (AHCI), and the Conference Proceedings Citation Index (CPCI-S/CPCI-SSH), which represent the most recent available version of WoS metadata housed at NISTEP.

We first extracted as cited articles publications that appeared in SCIE, were published in 2017, and had a document type of article or review ($n = 1{,}528{,}868$). The gold OA and non-OA papers were selected according to the procedure described below. We then extracted papers that cited the cited papers, including those indexed in databases other than SCIE. Following Dorta-González et al. (2017) and Basson et al. (2021), who examined OA citation advantage across fields using WoS data, we selected a 6 year citation window. In other words, the total number of citations of papers published between 2017 and 2022 is used to calculate each metric. Measuring the number of citations based on a certain citation window helps to control the *early view postulate* (Dorta-Gonzalez et al., 2017). The year 2017 was selected as the publication year for the cited papers because it was the latest publication year available within the 6 year citation window.

OA type

Among the cited papers mentioned above, 299,419 were classified as gold OA by the WoS. However, information on OA type in WoS reflects the paper's current status (as of data creation) and does not necessarily indicate that the paper was originally published with that type of OA. We use data from the Directory of Open Access Journals (DOAJ) to identify cited papers definitively categorized as gold OA in 2017. Specifically, we matched cited papers with DOAJ data using the journal name, ISSN, and e-ISSN as keys and identified papers published in journals whose publication year was listed as 2016 or earlier in the DOAJ. Therefore, the OA type of the cited papers in this study was gold OA, excluding the hybrid OA. After applying this filter, we obtained 248,874 gold OA papers. In contrast, non-OA papers were not classified under any OA type in the WoS and were not listed as OA in the DOAJ ($n = 823{,}480$).

Field classification

Cited and citing papers were assigned field information based on the 22 major categories in the Essential Science Indicators (ESI). The ESI assigns each journal to one of 22 field categories on a mutually exclusive basis. In other words, only one field of information was assigned to each of the cited and citing papers based on their journal source.

Additionally, only 18 fields were used for the cited papers, excluding economics and business, social sciences—general, space science, and multidisciplinary, which were among the original 22 fields. These four fields were excluded for the following reasons. First, the cited papers in this study were limited to those included in SCIE, and the number of papers under economics and business and social sciences—general was insufficient to calculate the metrics used in the analysis. The number of gold OA papers in space science was also insufficient.[3] Moreover, the multidisciplinary field likely contains papers from various fields, whose inclusion would have rendered the interpretation of the analysis results challenging (Basson et al., 2021). However, all 22 fields were used for the citing papers. The numbers of gold OA and non-OA papers per field are presented in the next section (see Table 1).

JIF quartile

As mentioned in the Literature Review, the JIF is useful for controlling *selection bias* (Niyazov et al., 2016). To calculate the metrics by JIF quartiles for each of the 18 fields, we obtained the JIF data for all journals indexed in the SCIE as of 2017 (Journal Citation Reports [JCR] year 2017) from the JCR and assigned them to the cited papers by matching the journal titles.

Data analysis

Metrics

We used the proportion of the difference between the average citations of OA and non-OA papers relative to the latter as a metric of OA citation advantage, following the approach used in cross-disciplinary studies on OA citation advantage (Dorta-González et al., 2017; Sotudeh et al., 2015). This metric is defined as follows:

$$OACA_i = \frac{OAC_i - NOAC_i}{NOAC_i} \times 100$$

Here, OAC_i refers to the average citation count of OA papers in field i, and $NOAC_i$ refers to the average citation count of non-OA papers in field i. This metric, referred to as the OACA, represents $p\%$ more citations for OA papers than for non-OA papers; if p is negative, OA papers are cited $p\%$ less frequently.

We also decomposed the OACA to explore whether OA increases the number of interdisciplinary citations. Specifically, we distinguished between citations in other fields and citations in the same field and propose two metrics. The first is IOACA, which represents

[3] The number of gold OA and non-OA papers in these three fields is shown in the footnote of Table 1.

the proportion of the difference between the average interdisciplinary citations of OA papers and non-OA papers to that of the latter. Interdisciplinary citations refer to papers in field *i* that are cited by papers from outside field *i*. IOACA is defined as follows:

$$IOACA_i = \frac{IOAC_i - INOAC_i}{INOAC_i} \times 100$$

Here, IOAC*i* refers to the average interdisciplinary citation count of OA papers in field *i*, and INOAC*i* refers to the average interdisciplinary citation count of non-OA papers in field *i*. The interpretation of the IOACA values was the same as that of OACA.

The second metric is the WOACA, which represents the proportion of the difference between the average within-discipline citations of OA and non-OA papers to that of the latter. Within-discipline citations refer to papers in field *i* cited by others in the same field. WOACA is defined as follows:

$$WOACA_i = \frac{WOAC_i - WNOAC_i}{WNOAC_i} \times 100$$

Here, WOAC*i* refers to the average within-discipline citations of OA papers in field *i*, and WNOAC*i* refers to the average within-discipline citations of non-OA papers in field *i*. The interpretation of the WOACA values was the same as that of OACA and IOACA.

Specific examples are provided to help interpret the OACAs. For instance, if OACA, IOACA, and WOACA were 29.6%, 35.6%, and 17.2% in field A, respectively, then OA papers in field A were cited 29.6% more than non-OA papers, 35.6% more in papers from other fields, and 17.2% more in the same field.

Tools for analysis

MySQL was used to aggregate the data and each metric was calculated using Microsoft Excel. Unless otherwise noted, the tables presented in the following sections were created in Microsoft Excel, and the figures were created using R software and its ggrepel and tidyverse packages (R Core Team, 2024; Slowikowski, 2024; Wickham et al., 2019).

Results and Discussion

Basic information

Table 1 presents the number of gold OA papers, non-OA papers, and total number of papers per field. The gold OA rate varied across fields. For example, fields such as microbiology, immunology, and molecular biology exhibit high gold OA rates, whereas fields such as computer science, mathematics, and engineering showed lower rates. The gold OA rate varied according to JIF quartile.

OACAs by field

Figure 1 shows each metric calculated using the cumulative number of citations within a 6-year citation window for each field. At least one type of metric was positive in all fields except agriculture, engineering, environmental science, and materials science.

Table 1 Prevalence of gold OA by field

Field	Abbreviation for Field	No. of gold OA papers	No. of non OA papers	No. of total papers	Percentage of gold OA papers (%)				
					Q1	Q2	Q3	Q4	total
Agricultural science	AGR	7970	28,367	47,646	9.49	6.63	25.60	37.10	16.73
Biology and biochemistry	BIO	11,658	32,101	69,339	26.91	6.31	9.03	15.55	16.81
Chemistry	CHE	15,538	125,545	178,741	2.51	18.59	5.48	5.47	8.69
Clinical medicine	CLI	45,957	141,961	282,888	7.59	25.43	13.80	15.26	16.25
Computer science	COM	2078	28,940	43,201	4.30	6.15	3.05	2.22	4.81
Engineering	ENG	12,905	113,530	159,042	3.73	9.72	10.10	15.22	8.11
Environment/ecology	ENV	8444	35,296	59,057	4.24	33.01	6.93	8.25	14.30
Geosciences	GEO	7771	28,429	50,450	12.17	16.00	26.12	10.33	15.40
Immunology	IMM	6864	8228	24,378	37.98	27.75	8.39	25.55	28.16
Materials science	MATE	9345	79,610	105,884	1.88	13.10	20.14	16.45	8.83
Mathematics	MATH	2751	17,485	44,954	4.55	10.72	4.73	2.46	6.12
Microbiology	MIC	7461	5365	20,148	45.34	59.47	8.55	14.29	37.03
Molecular biology and genetics	MOL	10,654	11,760	47,612	36.75	18.36	19.54	16.94	22.38
Neuroscience and behavior	NEU	7581	21,779	48,994	8.69	17.51	22.75	7.38	15.47
Pharmacology	PHA	5732	24,749	43,293	16.47	8.88	14.39	9.73	13.24
Physics	PHY	13,302	51,813	102,638	24.65	7.58	3.37	5.92	12.96
Plant and animal Science	PLA	11,967	41,223	73,727	15.72	13.03	13.38	18.18	16.23
Psychiatry/psychology	PSY	1597	7995	16,069	7.24	17.35	2.44	6.82	9.94

The number of gold OA and non-OA papers in each of the three fields, excluded owing to an insufficient number of papers, was as follows: Economics & Business ($n=432$ / $n=29{,}844$), Social Sciences, General ($n=84{,}864$ / $n=155{,}038$), and Space Science ($n=1302$ / $n=27{,}975$)

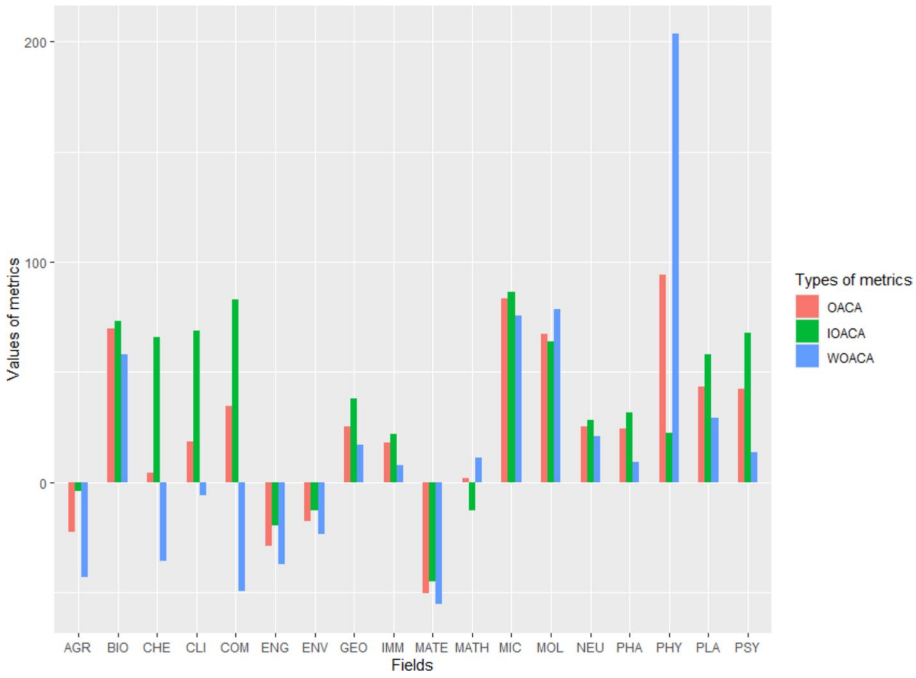

Fig. 1 Values of OACAs by field

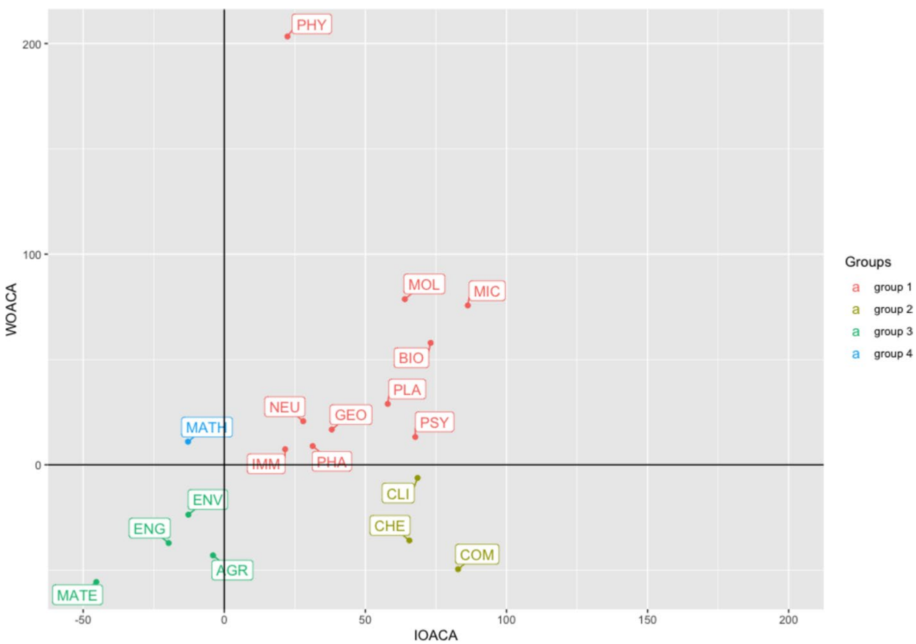

Fig. 2 Characteristics of each field in terms of the IOACA and WOACA

Direct comparison with prior OA citation advantage studies is challenging due to methodological diversity (Langham-Putrow et al., 2021). However, Dorta-González et al. (2017), who also used WoS data and the OACA metric to assess the impact of gold OA across disciplines, found positive OACA values in fields such as biology, chemistry, clinical medicine, immunology, and molecular biology. While strict comparisons between this study and Dorta-González et al. (2017) are limited owing to differences in publication years and field classification methods, the findings seem to align to some extent. However, in our study, distinguishing between IOACA and WOACA revealed field-specific characteristics that were not captured in previous studies.

Figure 2 plots each field with the IOACA and WOACA on the axes. The fields were divided into four groups. For Group 1 (upper right; inclusive of biology and biochemistry, geosciences, immunology, microbiology, molecular biology and genetics, neuroscience and behavior, pharmacology and toxicology, physics, plant and animal science, and psychiatry/psychology), both IOACA and WOACA were positive. Group 2 (lower right) fields had a positive IOACA but a negative WOACA, such as chemistry, clinical medicine, and computer science. Group 3 (lower left) fields had a negative IOACA and WOACA, such as agricultural science, engineering, environment/ecology, and materials science. For Group 4 (upper left; mathematics), the WOACA was positive, but the IOACA was negative.

Both Groups 1 and 2 encompass fields in which the OA citation advantage of interdisciplinary citations is evident. Group 2 is notable for the fact that this OA citation advantage is observed solely for interdisciplinary citations.

Figures 1 and 2 are based on calculating each metric by summing the number of citations over a 6 year citation window. However, if a field experienced an unusually high number of citations in a specific year, the values of these metrics may be skewed. Therefore, it is important to verify whether the characteristics of each field have been consistent when calculating the metrics annually. As shown in Fig. 3, some fields exhibited negative

Fig. 3 OACAs by field and year

OACAs only in the year when the cited paper was published (2017). Nonetheless, the same general trends previously dicussed were consistent when OACAs were calculated annually. For this reason, the remainder of this section focuses on OACAs calculated by summing citations over a 6 year window.

Table 1 shows that the gold OA rate varies across JIF quartiles by field. Because journals in higher JIF quartiles generally receive more citations per paper, the OACAs for each field shown in Figs. 1 and 2 may have been influenced by the proportion of gold OA journals in higher JIF quartiles within a field. Figure 4 shows the results of calculating OACAs using the JIF quartile for each field. Considering Table 1, Fig. 4 suggests that the relationship between the gold OA rate and OACAs is not as straightforward; the higher the gold OA rate in Q1 journals, the higher the OACAs in each field.

However, in some cases, a high gold OA rate in a specific quartile along with a high value of a specific metric in the same quartile may drive a higher value of the specific metric for the field as a whole. Specifically, in physics, the high gold OA rate and WOACA in Q1 resulted in a high WOACA for the entire field. Similarly, among the fields in Group 2, chemistry exhibited a high gold OA rate and IOACA in Q2 journals, resulting in a high IOACA for chemistry overall. In computer science, although no single quartile had an exceptionally high gold OA rate, the IOACA of Q1 journals was notably high, shaping an overall high IOACA in the field. Therefore, fields that exhibit a high OACA in a particular quartile may have been significantly influenced by specific journals in that quartile.

Although some fields, such as biology, biochemistry, and clinical medicine, have high gold OA rates in specific quartiles, the OACA trends are similar across all quartiles in some fields. In these cases, the characteristics of each metric may reflect the nature of knowledge in the field rather than being driven by a specific journal.

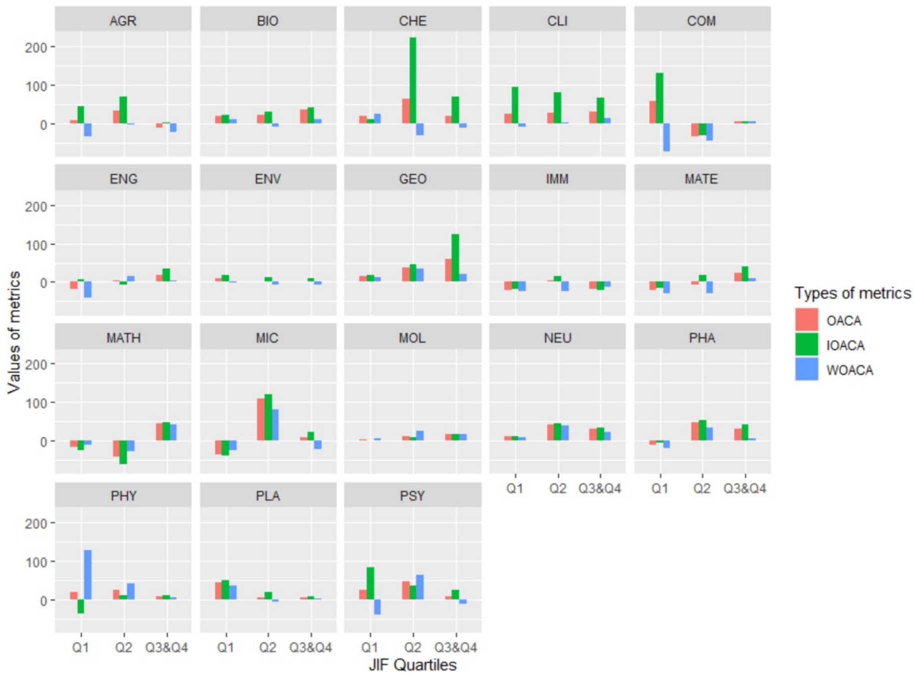

Fig. 4 OACAs by field and JIF quartile

Table 2 Distribution of interdisciplinary citations by Q2 gold OA journal in chemistry

Journal title	No. of interdisciplinary citations	%
International journal of molecular sciences	78,633	36.22
Sensors	56,047	25.82
Molecules	43,406	20.00
Arabian journal of chemistry	13,847	6.38
Catalysts	8514	3.92
Beilstein journal of organic chemistry	3555	1.64
Journal of Saudi chemical society	3181	1.47
Frontiers in chemistry	2901	1.34
Chemistry central journal	2170	1.00
Excli journal	1441	0.66
International journal of polymer science	1324	0.61
Chemistryopen	1175	0.54
Green chemistry letters and reviews	886	0.41
Total	217,080	100.00

Table 3 Distribution of interdisciplinary citations by Q1 gold OA journal in computer science

Journal title	No. of interdisciplinary citations	%
Journal of statistical software	17,109	53.06
BMC bioinformatics	12,662	39.27
Journal of cheminformatics	2476	7.68
Total	32,247	100.00

Based on our analysis, we provide an answer to the first research question stated in the Introduction. Our results show that gold OA papers are more likely to be cited than non-OA ones in a majority of fields. Among these fields, Group 1 demonstrates the impact of OA on both interdisciplinary and within-discipline citations, whereas Group 2 exhibits an effect of OA exclusively on interdisciplinary citations. In the following sections, we address the second research question—*how OA papers affect fields where OA fosters interdisciplinary citation*—with a particular focus on Group 2 fields: chemistry, computer science, and clinical medicine.

Distribution of interdisciplinary citations by journal

As discussed in the previous section, Fig. 4 suggests that in chemistry and computer science, a higher IOACA for the entire field may be driven by certain journals in Q2 and Q1, respectively, leading to interdisciplinary citations. Therefore, we first examined the number of interdisciplinary citations per journal.

Table 2 presents the number of interdisciplinary citations for papers published in Q2 gold OA chemistry journals, segmented by journal, and the corresponding percentages. The *International Journal of Molecular Sciences*, *Sensors*, and *Molecules* stand out with high percentages of interdisciplinary citations, suggesting their influence on the IOACA

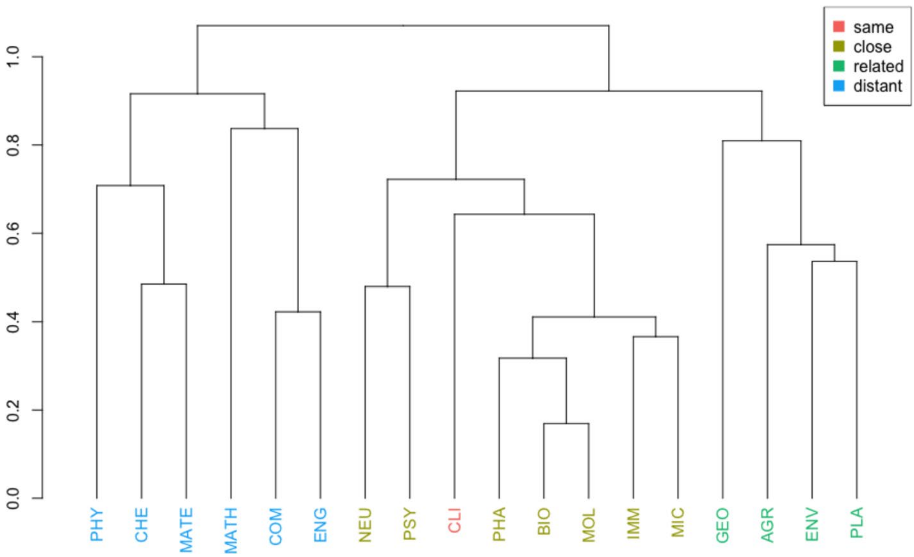

Fig. 5 The proximity of each field to clinical medicine

in chemistry. The JCR categorizes the *International Journal of Molecular Sciences* and *Molecules* under "Biochemistry & Molecular Biology" and "Chemistry, Multidisciplinary," and *Sensors* under "Chemistry, Analytical" and "Engineering, Electrical & Electronic" categories, highlighting the interdisciplinary nature of these chemistry journals.

Similar to Table 2, Table 3 presents the number of interdisciplinary citations of papers published in Q1 gold OA journals in computer science, segmented by journal, and the corresponding percentages. The *Journal of Statistical Software* and *BMC Bioinformatics* account for a large share of interdisciplinary citations, indicating that they have contributed significantly to the high IOACA in computer science. According to the JCR, the former is listed under the "Computer Science, Interdisciplinary Applications" and "Statistics & Probability" categories, whereas the latter is under the "Biochemical Research Methods", "Biotechnology & Applied Microbiology," and "Mathematical & Computational Biology" categories. These classifications emphasize the interdisciplinary nature of journals. Additionally, both journals have published papers that have received an exceptionally high number of citations, as shown in Figs. 7 and 8 (see Appendix), suggesting that the high IOACA in computer science is strongly influenced by papers that have been highly cited in other fields.

These results suggest that the high IOACA observed in group 2 was largely driven by journals or papers in chemistry and computer science. In contrast, a high IOACA in clinical medicine appears to be a characteristic of the entire field. In the next section, we focus on clinical medicine and examine how OA affects this field in greater detail.

Case study of clinical medicine

To better understand the effects of OA in clinical medicine, we examined OA and non-OA papers regarding the fields in which they were cited and the topics on which they were

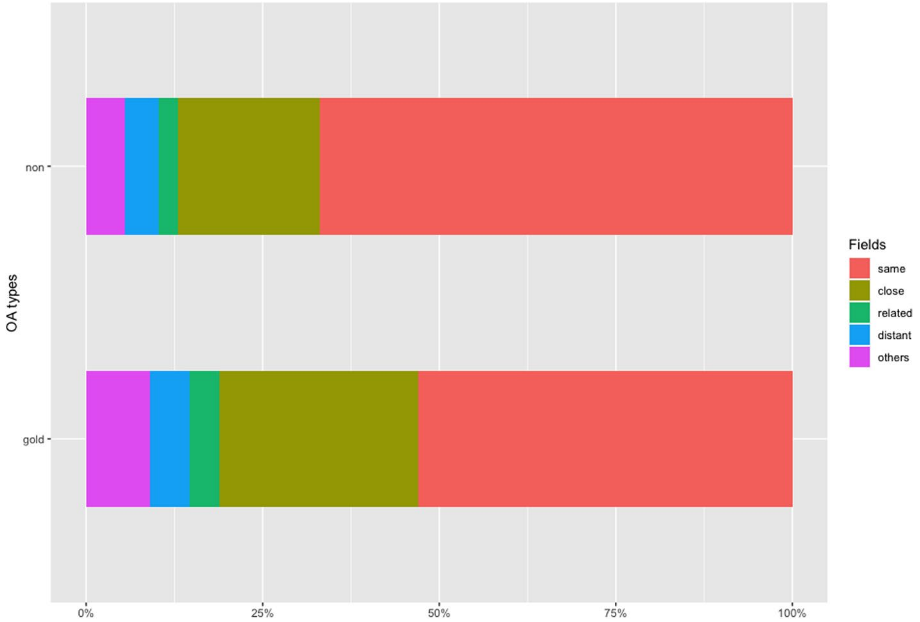

Fig. 6 Percentages of citing papers in clinical medicine by field. "Others" included citing papers in the four fields deemed to be outside the scope of this study's analysis, as described in the Methods section, or citing papers not assigned to the ESI category

cited. As mentioned previously, this study focused on 18 natural science fields. To facilitate clearer interpretation, these fields were grouped into several categories based on their proximity to clinical medicine. Specifically, we used hierarchical clustering following Ward's method to analyze the proximity of each of the 18 fields based on the number of citations from all fields, including those excluded from the present study. The stats package in R was used to perform analyses (R Core team, 2024). Figure 5 shows the clustering results. Fields in the same cluster as those in clinical medicine were considered *close* fields, those in adjacent clusters were classified as *related* fields, and those in other clusters were labeled *distant* fields. Clinical medicine is expressed as being in the *same* field.

To analyze the topics of each paper, we used the *citation topics* provided by WoS. These topics were determined through clustering based on the citation relationships among the papers, with one topic exclusively assigned to each paper.[4] To assess whether there were differences in topics between OA and non-OA papers, we used the similarity of citation topics between the groups of papers as a metric. Given the variation in the number of gold OA and non-OA papers, we employed cosine similarity, which is independent of the sample size and allows for a comparison between the two datasets. The cosine similarity values in this study ranged from 1 to 0, with values closer to 1 indicating greater similarity and those closer to 0 indicating no relationship between the topics of the two groups of papers. These values were calculated using the lsa package in R (Wild, 2022).

[4] Citation topics were divided into macro, meso, and micro levels. We used the meso-level citation topics for the analysis.

Table 4 Similarities among citation topics

	oa_all	non_all	oa_same	non_same	oa_inter	non_inter	oa_close	non_close	oa_related	non_related	oa_distant	non_distant
oa_all*	1.00	***0.89***	0.97	0.82	0.96	0.93	0.90	0.89	0.70	0.67	0.82	0.67
non_all	–	1.00	0.93	0.98	0.77	0.91	0.70	0.84	0.56	0.63	0.73	0.78
oa_same	–	–	1.00	***0.90***	0.86	0.89	0.79	0.83	0.63	0.63	0.74	0.66
non_same	–	–	–	1.00	0.66	0.82	0.59	0.74	0.49	0.56	0.64	0.73
oa_inter	–	–	–	–	1.00	***0.91***	0.96	0.89	0.73	0.67	0.85	0.63
non_inter	–	–	–	–	–	1.00	0.88	0.96	0.66	0.71	0.84	0.80
oa_close	–	–	–	–	–	–	1.00	***0.93***	0.57	0.52	0.84	0.59
non_close	–	–	–	–	–	–	–	1.00	0.55	0.58	0.82	0.71
oa_related	–	–	–	–	–	–	–	–	1.00	***0.93***	0.53	0.38
non_related	–	–	–	–	–	–	–	–	–	1.00	0.49	0.45
oa_distant	–	–	–	–	–	–	–	–	–	–	1.00	***0.82***
non_distant	–	–	–	–	–	–	–	–	–	–	–	1.00

*oa_all indicates all the clinical medicine OA papers included in this study without distinguishing the fields of the papers citing them. Similarly, non_all refers to all non-OA papers published in clinical medicine

Bold highlights the cosine similarity between subsets of papers that differ in OA status but share the same field in the citing papers

Figure 6 summarizes the percentage of papers that cited clinical medicine papers by field. Table 4 shows the OA and non-OA papers divided into several subsets according to the fields of the citing papers and presents the cosine similarity of the citation topics between each subset.

Figure 6 shows that in clinical medicine, gold OA papers had a lower percentage of within-discipline citations (same) than non-OA papers, and instead had more citations from closely related fields (i.e., biology and biochemistry, immunology, microbiology, molecular biology and genetics, neuroscience and behavior, pharmacology and toxicology, and psychiatry/psychology). In this regard, Table 4 reveals that the cosine similarity between the citation topics of both OA and non-OA papers cited from close fields (i.e., between oa_close and non_close in Table 4) was as high as 0.93. This indicates that clinical medicine papers cited from close fields tend to have similar topics regardless of OA status. Furthermore, as shown in Table 4, the cosine similarity between OA and non-OA papers tended to be high when the citing paper field was consistent between the two (e.g., oa_same and no_same) and not only between oa_close and non_close papers. These findings suggest that clinical medicine OA papers were more frequently cited across different fields, not because they covered different topics than non-OA papers, but because OA has improved the availability of these papers.

Table 5 (see Appendix) lists the top 20 most-cited topics by citing paper fields for both OA and non-OA papers. The topics found exclusively in citing papers in different fields included neurodegenerative diseases, phytochemicals, and inflammatory bowel diseases and infections. These three topics also appeared in both OA and non-OA papers cited in close fields but were absent in papers cited within the same field. Given that OA increased the number of citations in close fields, we can infer that papers addressing these topics are in high demand across fields and cited more frequently because of the availability OA provides.

Topics common to both OA and non-OA papers that have within-discipline citations but not to those with interdisciplinary citations included cardiology—general, liver and colon cancer, and assisted ventilation. The high rankings of these topics in within-discipline citations may be attributed to their specialized nature in clinical medicine, which limits their citations in other fields even when papers are available as OA.

These findings are consistent with those of previous studies. For example, Chen et al. (2015) explored the interdisciplinary development of biochemistry and molecular biology (BMB) over the past 100 years using WoS data and found that BMB frequently cited papers in the field of clinical medicine. Consistent with the findings of Chen et al. (2015), we observed, as depicted in Figs. 4 and 5, that BMB is closely related to clinical medicine, with clinical medicine receiving more citations from close fields because of OA.

However, according to Van Noorden (2015), who examined the interdisciplinarity of each field using WoS data, clinical medicine has received relatively few citations from other disciplines. Although our study did not focus on measuring interdisciplinarity, OA may increase the interdisciplinarity of clinical medicine given that the number of OA papers has increased since Van Noorden (2015), as our finding of a high IOACA in clinical medicine indicates.

Implications and limitations

By decomposing the OACA metric, which indicates whether OA increases the overall number of citations, this study introduced a new metric, IOACA, to measure the effect of OA on knowledge transfer across fields. Using the IOACA, we found that OA has been shown to foster knowledge transfer in many fields. Although previous research, such as that of the OECD (2015), suggests that OA promotes knowledge transfer across fields, our study explicitly demonstrates this effect. In this respect, this study contributes novel insights into OA citation advantage studies that focus on citation count. Furthermore, the findings will provide policymakers, research funders, academic libraries, and individual researchers with a rationale for promoting OA.

Specifically, IOACA is a citation count-based metric that measures the scholarly impact of OA, with a focus on interdisciplinary citations. It quantifies the extent to which OA papers in each field are more likely to be cited by papers from other fields compared to non-OA papers, expressed as a percentage. By normalizing the differences in the number of papers published in each field, this metric allows for cross-field comparisons. Positive values indicate an OA citation advantage in terms of interdisciplinary citations, while negative values indicate disadvantages.

The IOACA measures the scholarly impact of OA from a perspective different from the traditional OA citation advantage. In this respect, it is similar to the citation diversity indices proposed by Huang et al. (2024). However, unlike Huang et al. (2024), whose indices do not depend on citation counts, thereby omitting information on how frequently OA papers in a given field are cited by other fields, IOACA provides a clearer and more detailed representation of influence of OA on cross-disciplinary citation relationships. Therefore, our study explored Huang et al.'s (2024) findings in a more specific and focused manner, particularly regarding the field and yielded insights that complemented those of Huang et al. (2024).

Additionally, our results, focusing on clinical medicine, suggested no significant differences in topics between OA and non-OA papers. This implies that, in clinical medicine, the increased accessibility provided by OA encourages citations from other fields. However, the difference in some topics between papers cited in other fields and those cited in the same field suggests that certain topics are in high demand in other fields and that OA promotes interdisciplinary citations of papers covering those topics. These findings may offer valuable insights to clinical medicine researchers when deciding where and how to submit their work.

However, this study had several limitations. First, because the data were collected using total population sampling, our findings may not be generalizable to papers included in other databases, such as Scopus. Second, it relied on the ESI classification system, which is mutually exclusive and has a relatively small number of categories for focusing on knowledge transfers between disciplines. Although this was necessary to ensure sufficient data to calculate each metric for each field, previous studies on the OACA using WoS often used a more granular classification system called the subject category, making direct comparisons between this study and previous studies challenging. Third, because this study limited the fields of cited papers to those within the natural sciences, we were unable to capture trends in the humanities and social sciences; the effect of OA on interdisciplinary citations may also be observable in these fields. Fourth, this study focused exclusively on gold OA without considering other forms, such as green OA; consequently, the findings may not necessarily extend to papers made available through other types of OA.

Conclusion

This study clarified what effects OA, particularly gold OA, has on knowledge transfer across fields, by introducing IOACA, a measure of OA's impact on cross-disciplinary citations. The analysis revealed that OA fostered interdisciplinary citations in 13 out of the 18 natural science fields examined. Furthermore, OA has solely increased the number of interdisciplinary citations, especially in clinical medicine.

Regarding possible future research directions, firstly, the robustness of our findings could be confirmed by conducting a similar analysis using a different field classification system or dataset. Investigating whether similar results can be obtained using Scopus or OpenAlex is particularly important given that journal coverage varies across databases. Additionally, future research could examine the effect of OA on the interdisciplinary citation of papers made of OA using methods other than gold OA. In particular, with green OA, in which repositories and preprint servers serve as publication channels, researchers' behavior may differ from that associated with gold OA.

Appendix

See Figs. 7, 8 and Table 5,

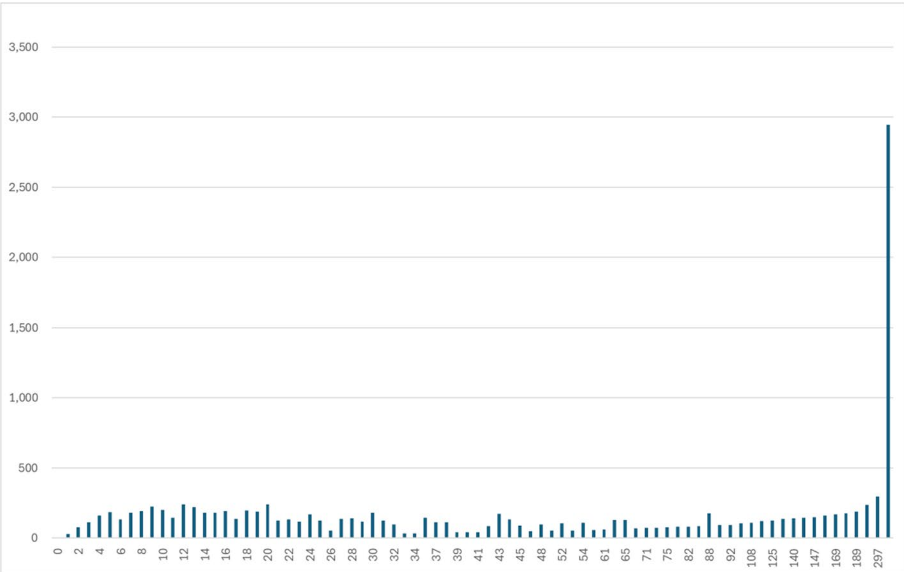

Fig. 7 The citation counts of papers published in *BMC Bioinformatics*. The x-axis shows the range of citations each paper has received, and the y-axis shows the value of each citation multiplied by the number of papers with that value. This figure was created using Microsoft Excel

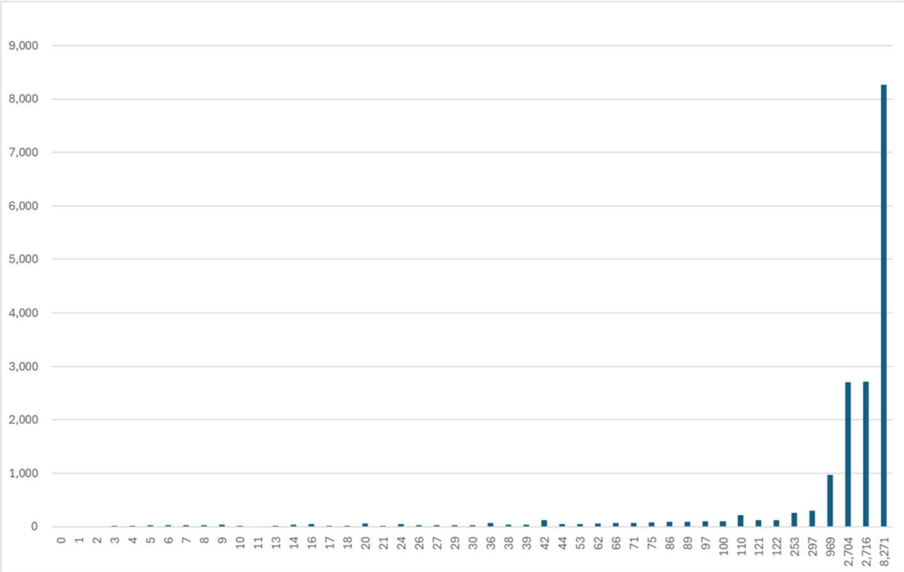

Fig. 8 The citation counts of papers published in the *Journal of Statistical Software*. The x-axis shows the range of citations each paper has received, and the y-axis shows the value of each citation multiplied by the number of papers with that value. This figure was created using Microsoft Excel

Table 5 The top 20 most cited topics by citing paper field for both OA and non-OA papers

(a) Citation topics in papers cited from different fields*

Gold OA				Non OA		
Rank	Citation topics	Citations	%	Citation topics	Citations	%
1	Micro and long Noncoding RNA	16,932	4.96	Immunology	24,586	3.96
2	Nutrition and dietetics	13,572	3.97	Micro and long noncoding RNA	22,051	3.55
3	Immunology	12,076	3.54	Nutrition and dietetics	18,284	2.94
4	Diabetes	10,476	3.07	Dentistry and oral medicine	17,589	2.83
5	Molecular and cell biology—cancer, Autophagy and apoptosis	9223	2.70	Diabetes	15,961	2.57
6	Ophthalmology	8781	2.57	Inflammatory bowel diseases and infections	14,419	2.32
7	Neurodegenerative diseases	7822	2.29	Molecular and cell biology—cancer, autophagy and apoptosis	13,689	2.20
8	Phytochemicals	7797	2.28	Hepatitis	11,885	1.91
9	Nursing	7163	2.10	Orthopedics	11,689	1.88
10	Molecular and cell biology—cancer and development	6652	1.95	Nursing	11,597	1.87
11	Allergy	6404	1.88	Rheumatology	11,214	1.81
12	Inflammatory bowel diseases and infections	5858	1.72	Obstetrics and gynecology	11,156	1.80
13	Healthcare policy	5773	1.69	Ophthalmology	10,559	1.70
14	Urology and nephrology—general	5376	1.57	Bone diseases	9767	1.57
15	Parasitology—malaria, toxoplasmosis and coccidiosis	5195	1.52	Stem cell research	9545	1.54
16	Obstetrics and gynecology	5173	1.52	Neurodegenerative diseases	9127	1.47
17	Antibiotics and antimicrobials	5146	1.51	Sports science	8729	1.41
18	Stem cell research	5034	1.47	Allergy	8411	1.35
19	Medical ethics	4887	1.43	Urology and nephrology—general	8364	1.35
20	Psychiatry	4791	1.40	Lung cancer	8214	1.32

Table 5 (continued)

(b) Citation topics in papers cited in the same field

Gold OA				Non OA		
Rank	Citation topics	Citations	%	Citation topics	Citations	%
1	Ophthalmology	17,109	4.43	Orthopedics	69,016	5.43
2	Nutrition and dietetics	13,960	3.61	Dentistry and oral medicine	42,269	3.33
3	Orthopedics	13,686	3.54	Cardiology—general	41,188	3.24
4	Diabetes	12,325	3.19	Ophthalmology	39,923	3.14
5	Immunology	11,522	2.98	Liver and colon cancer	39,123	3.08
6	Micro and long noncoding RNA	11,470	2.97	Immunology	31,929	2.51
7	Urology and nephrology—general	10,331	2.67	Nutrition and dietetics	31,891	2.51
8	Allergy	10,008	2.59	Nursing	29,029	2.28
9	Cardiology—general	9620	2.49	Prostate cancer	27,940	2.20
10	Nursing	9573	2.48	Obstetrics and gynecology	27,670	2.18
11	Rheumatology	9118	2.36	Gastrointestinal and esophageal diseases	25,090	1.97
12	Obstetrics and gynecology	8334	2.16	Rheumatology	23,414	1.84
13	Liver and colon cancer	7454	1.93	Assisted ventilation	22,911	1.80
14	Assisted ventilation	7252	1.88	Pancreas and gall bladder disorders	22,757	1.79
15	Dentistry and oral medicine	7109	1.84	Diabetes	22,578	1.78
16	Breast cancer scanning	6515	1.69	Breast cancer scanning	21,987	1.73
17	Medical ethics	5812	1.50	Blood clotting	21,935	1.73
18	Palliative care	5764	1.49	Lung cancer	21,808	1.72
19	Cardiology—circulation	5654	1.46	Cardiology—circulation	21,757	1.71
20	Molecular and cell biology—cancer, autophagy and apoptosis	5556	1.44	Anesthesiology	21,507	1.69

Table 5 (continued)

(c) Citation topics in papers cited in close fields

Gold OA				Non OA		
Rank	Citation topics	Citations	%	Citation topics	Citations	%
1	Micro and long noncoding RNA	13,764	6.73	Immunology	19,624	5.21
2	Immunology	9353	4.57	Micro and long noncoding RNA	18,197	4.83
3	Molecular and cell biology—cancer, autophagy and apoptosis	6991	3.42	Diabetes	10,353	2.75
4	Diabetes	6382	3.12	Molecular and cell biology—cancer, autophagy and apoptosis	10,304	2.74
5	Neurodegenerative diseases	6105	2.98	Inflammatory bowel diseases and infections	9527	2.53
6	Ophthalmology	4944	2.42	Rheumatology	8860	2.35
7	Molecular and cell biology—cancer and development	4873	2.38	Hepatitis	8685	2.31
8	Nutrition and dietetics	4733	2.31	Neurodegenerative diseases	7140	1.90
9	Allergy	4344	2.12	Stem cell research	6653	1.77
10	Phytochemicals	4092	2.00	Nutrition and dietetics	6579	1.75
11	Antibiotics and antimicrobials	3789	1.85	Allergy	6300	1.67
12	Inflammatory bowel diseases and infections	3581	1.75	Dentistry and oral medicine	5803	1.54
13	Stem cell research	3560	1.74	Bone diseases	5792	1.54
14	Rheumatology	3551	1.74	Strokes	5666	1.50
15	Psychiatry	3521	1.72	Orthopedics	5547	1.47
16	Parasitology—malaria, toxoplasmosis and coccidiosis	3022	1.48	Obstetrics and gynecology	5547	1.47
17	Urology and nephrology—general	3016	1.47	Brain imaging	5516	1.46
18	Molecular and cell biology—genetics	2745	1.34	Ophthalmology	5450	1.45
19	HIV	2513	1.23	Lung cancer	5297	1.41
20	Neuroscanning	2445	1.19	Back pain	5139	1.36

* "Different fields" here refer to fields other than the same field

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