Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-023-02475-3 OPEN

The relationship between interdisciplinarity and citation impact—a novel perspective on citation accumulation

Xiaojing Cai[1], Xiaozan Lyu[2] & Ping Zhou[3]✉

Interdisciplinary research is of significance for creating breakthroughs and facilitating innovations and may achieve higher citation impact, although contrary results still exist. The current study looks into the relationship between interdisciplinarity and citation impact from a brand-new perspective—the process of citation accumulation—by exploring how interdisciplinarity, as measured by Rao-Stirling and DIV, affects the accumulating process of citations, based on scientific papers published by Chinese or US authors in 2009–2011 in Chemistry. Two metrics are used to measure how long it takes for a paper to reach its citation peak (PEAK_YEAR) and how sustainable the citation impact remains after the peak (SUS). The results show that compared with Rao-Stirling, DIV is more sensitive to the length of the citation window and more closely aligned with the nature of interdisciplinarity. In Chemistry, higher interdisciplinarity is more likely to encounter delayed recognition and greater citation sustainability, which may explain the inconsistency in the relationship between interdisciplinarity and citation impact. In conclusion, it is necessary to consider the length of the citation window when explaining the relationship between interdisciplinarity and citation impact. A longer citation window may be a better solution, as an alternative or supplement, in assessing the academic performance of interdisciplinary research.

[1] School of Business, Research Center for Government Governance and Public Policy, Yangzhou University, Yangzhou 225127, China. [2] School of Law, Department of Administrative Management, Hangzhou City University, Hangzhou 310015, China. [3] School of Public Affairs, Zhejiang University, Hangzhou 310058, China. ✉email: pingzhou@zju.edu.cn

Introduction

Given the fact that interdisciplinary research (IDR) enables combinations of complementary and diverse knowledge (Katz and Martin, 1997), thereby further fostering knowledge innovation (Gibbons et al. 1994), its importance in academia and funding agencies has gained increasing recognition. Moreover, addressing complex social issues, such as climate change and public health, requires joint efforts across disciplinary boundaries. Consequently, the evaluation of interdisciplinarity has become essential as a means to better understand and promote IDR.

Bibliometrics and bibliographic databases such as the Web of Science (WoS), Scopus, and Dimensions provide a powerful tool for quantitatively exploring interdisciplinarity. This is evidenced by the greater proportions of references to and citations from foreign disciplines, higher values of interdisciplinary metrics, and an increasing number of studies related to interdisciplinarity (Lariviere and Gingras, 2014; van Noorden, 2015; Weart, 2013; Zhou et al. 2022). In addition to the measurement, drivers, and obstacles of IDR, the relationship between interdisciplinarity and scientific success, typically operationalized as citation impact, has been extensively studied, although the results have been inconsistent (e.g., Larivière et al. 2015; Levitt and Thelwall, 2008; Wang et al. 2015). The reasons for it, however, have rarely been explored.

The study seeks to bridge the gap by exploring *how interdisciplinarity impacts the dynamic accumulation of citations of scientific papers*. To this end, the following research questions will be addressed: (1) What are the differences between Rao-Stirling diversity (RS) and Diversity (DIV) in measuring interdisciplinarity? (2) How does interdisciplinarity influence the citation accumulation process of papers in Chemistry? Through this investigation, we hope to enhance the understanding of the use of interdisciplinary measures in the realm of scientific evaluation, as well as to elucidate the relationship between interdisciplinarity and citation impact.

Related work

Numerous studies have undertaken investigations into the relationship between interdisciplinarity and citation impact. These inquiries have utilized a variety of indicators, encompassing datasets across varying time windows and research fields, in an effort to explore the association between cross-boundary combinations of ideas, knowledge, or skills and the emergence of ground-breaking research. For example, previous studies have illuminated that research characterized by higher interdisciplinarity often accrues a greater frequency of citations (Levitt and Thelwall, 2008; Okamura, 2019; Wang et al. 2015), and endeavors conducted by interdisciplinary teams tend to yield more substantial advancements than their non-interdisciplinary counterparts (Abramo et al. 2017). Furthermore, co-cited journal pairs originating from distinct research fields tend to exhibit higher citation impact when compared with those within a single field (Larivière et al. 2015). Highly cited papers often demonstrate a higher level of interdisciplinarity (Chen et al. 2015) or an elevated propensity for atypical linkages (Schilling and Green, 2011). Integrated interdisciplinarity indicators, such as the Rao-Stirling index and the Leinster–Cobbold Diversity Index, have been empirically linked to a positive influence on citation impact (Chen et al. 2022). In addition, interdisciplinarity has been associated with broader societal impact, with publications underscored by a higher degree of interdisciplinarity often displaying greater utilization (Zhang et al. 2021).

Despite the fact that IDR based on similar knowledge combinations displays greater impact and is more widely recognized than risky research based on dissimilar knowledge combinations (van Noorden, 2015; Yegros-Yegros et al. 2015), the relationship between interdisciplinarity and citation impact is not without nuances. In certain cases, no significant relationship, or even a negative correlation, between interdisciplinarity and citation impact has been observed. For instance, IDR originating from the UK has been associated with lower citation rates (Elsevier, 2015). According to Scopus data, mono-disciplinary publications in health sciences, life sciences, and physical sciences were found to receive twice as many citations as their multidisciplinary counterparts (Levitt and Thelwall, 2008). Notably, certain aspects of IDR, such as peer review (Lyall et al. 2013; Woelert and Millar, 2013) and project selection (Bromham et al. 2016; Nicholson and Ioannidis, 2012), have been identified as domains where interdisciplinarity faces disadvantages. A study by Sun et al. (2021) investigated the relationship between interdisciplinarity and citation impact at the individual level, concluding that grant recipients engaged in IDR initially exhibit lower citation impact than their specialized counterparts but ultimately achieve higher academic productivity and impact over the long run. Moreover, several studies have explored the effects of different dimensional features of interdisciplinarity on academic impact (Wang et al. 2015; Yegros-Yegros et al. 2015).

Intriguingly, the relationship between interdisciplinarity and research impact, as measured by citations, is influenced by a multitude of factors, with the choice of citation window emerging as a pivotal consideration. Several studies have explored this issue, with Chen and colleagues (2022) conducting a review of the use of citation windows in IDR. These studies have adopted citation windows ranging from 3 to 15 years, yet most have not furnished conclusive evidence concerning the impact of citation windows on interdisciplinary studies. Chen and colleagues further explored the duration of the citation window, discerning its contingent nature in relation to the selected interdisciplinary metrics. Van Noorden (2015) found that the relationship between interdisciplinarity and citations is controversial. Specifically, papers referencing diverse references tend to garner fewer citations over a 3-year period but experience an upsurge in citations over 13 years. Similarly, based on all journal articles indexed in WoS in 2001, Wang et al. (2015) explored the relationship between different dimensions of interdisciplinarity and short-term (3 years) and long-term (13 years) citations. They posited that publications with greater variety and disparity are more likely to experience citation delays, indicating a relatively lower short-term impact but an augmented long-term impact. Collectively, these investigations suggest that IDR may require an extended timeframe to garner citation advantages and, in all likelihood, to encounter delayed recognition.

In conclusion, the present study has sought to contribute to the existing literature on the relationship between interdisciplinarity and citation impact by offering insights into the dynamics of citation accumulation within the field of Chemistry over a 10-year period. Notably, amid the extensive scholarship on this topic, limited attention has been devoted to scrutinizing the facets of citation accumulation across research with varying levels of interdisciplinarity.

Data and method

Data selection. The study examines the relationship between interdisciplinarity and citation impact across seven Chemistry disciplines indexed in Clarivate WoS: Chemistry, Analytical; Chemistry, Inorganic and Nuclear; Chemistry, Applied; Chemistry, Medicinal; Chemistry, Physics; Chemistry, Organic; Chemistry, Multidisciplinary. The choice of Chemistry as the

focal domain is underpinned by several reasons. Firstly, its data accessibility and data availability make it an ideal choice for this investigation. Chemistry, as a well-established fundamental discipline, primarily produces academic papers as its principal research output. Consequently, over 90% of references used in Chemistry articles emanate from scientific papers indexed in WoS. This abundance of pertinent data forms a robust data foundation for the calculation of interdisciplinary indicators. Secondly, Chemistry encompasses a broad spectrum of fields, spanning from traditional domains such as organic and inorganic chemistry to interdisciplinary realms like material chemistry and medicinal chemistry. This approach allows for comparisons between subfields characterized by varying degrees of interdisciplinarity. Thirdly, despite exhibiting a relatively lower interdisciplinary compared with other science fields, Chemistry has great potential for IDR. Its inherent connection to many other sciences and its growing interdisciplinary engagement render it a particularly apt subject for investigating the interplay between interdisciplinarity and citation dynamics. Therefore, the examination of the relationship between interdisciplinarity and citation dynamics, with Chemistry as a case study, serves as a useful benchmark for comprehending the relationship in diverse academic fields.

The dataset under study is limited to research papers published in 2009–2011, facilitating a sufficient citation window spanning 10 years, and exclusively includes document types of *Article* and *Review*. To ensure a representative sample, papers with at least one author from either China or the US are incorporated into the analysis. This selection criterion is informed by the fact that these two nations collectively contribute to over 40% of global research output and 37% of global Chemistry research[1]. The sources cited within the reference lists were extracted and subjected to rigorous matching procedures, including full journal names, abbreviations, and any alterations in titles, as indexed in Journal Citation Report (JCR). These matched sources were further classified into WoS Categories (WC). Papers with more than 20 authors or with matched references fewer than 10 were excluded from the dataset, and thus obtaining a final dataset of 148,123 papers with 79,954 (54.9%) from China and 71,768 (48.5%) from the US. Of the total references (6,074,052), 90.1% (5,509,673) were accurately matched with the WoS indexed journals and thus their corresponding WCs.

Identification of globally top-5% highly-cited papers within the same field and the same document type is facilitated by retrieving the citation percentile for each paper from Clarivate Incites. Annual citation data[2] is acquired from Clarivate WoS to enable the construction of citation curves and the comprehensive analysis of the relationship between interdisciplinary indicators and the process of citation accumulation. A detailed depiction of the process of data retrieval, data cleaning, and calculation of indicators is presented in Fig. 1.

Methods. Two comprehensive interdisciplinary indicators, Rao-Stirling diversity (RS) and Diversity (DIV), were computed based on the distributions of WoS categories within reference lists. These indicators were chosen to capture the cross-boundary combinations of knowledge and ideas, reflecting the multi-faceted nature of interdisciplinarity. The selection of both indicators was underpinned by their widespread acceptance and frequent utilization in academic research, thereby ensuring their relevance and recognition within the scholarly community. Applying both indicators can facilitate comprehensive comparisons concerning the relationship between interdisciplinarity and citation impact. Furthermore, if the same conclusion was reached using both indicators, this approach could substantiate a robust result concerning how interdisciplinarity influences the process of citation accumulation.

RS, also known as the Stirling Index, was proposed by Rao (1982) and Stirling (2007) and has gained substantial prominence in the realm of science & technology studies (Rafols and Meyer, 2010). This index possesses the capability to capture multiple dimensions of interdisciplinarity (Porter and Rafols, 2009; Stirling, 2007). However, it has been later proved insufficient in fully encapsulating the three dimensions of interdisciplinarity, namely variety, balance, and disparity (Leydesdorff, 2018). The computation of RS is expressed in Eq. (1), where p_i denotes the proportions of references belonging to each category i, and d_{ij} denotes the disparity between categories i and j. The disparity between WoS category pairs is determined by subtracting the co-citing similarity among all WoS category pairs from 1, drawing upon the 2015 WoS co-citation data[3].

$$Rao - Stirling = \sum_{i,j} d_{ij}(p_i p_j) \tag{1}$$

$$DIV = \frac{n}{N} * Gini * \left(\sum_{i,j} \frac{d_{ij}}{n * (n-1)}\right) \tag{2}$$

$$Gini = \frac{\sum_{i=1}^{n} (2i - n - 1)x_i}{n \sum_{i=1}^{n} x_i} \tag{3}$$

In contrast, DIV, conceptualized by Loet Leydesdorff, was devised to address the shortcomings of RS, particularly its failure to account for the dimension of balance hidden by variety (Leydesdorff, 2018). DIV endeavors to offer a more precise reflection of the integration of variety, balance, and disparity inherent in interdisciplinarity. The formulation of DIV encompasses the relative variety (n/N), as depicted in Eq. (2), wherein n represents the number of categories referenced by a single paper, and N denotes the total number of categories in the 2015 JCR. The Gini index, encapsulated in Eq. (3), involves x_i, denoting the observed number of references in category i.

Figure 2 visually illustrates that the RS and the square root of DIV for most chemistry papers under study range from 0.1 to 0.45 and from 0.06 to 0.16, respectively. To gain an intuitive understanding of how interdisciplinarity relates to the process of citation accumulation, all papers were categorized into 10 RS categories and 10 DIV categories based on these two indicators. The choice of 10 discrete categories ensures the creation of an ample number of distinct groups, guaranteeing that papers assigned to lower-interdisciplinarity groups exhibit noticeably lower interdisciplinarity in contrast to their counterparts in the high-interdisciplinarity categories. Specifically, all papers underwent initial sorting in ascending order by RS values, subsequently divided into 10 equal parts. The papers with the lowest 10% RS values were assigned to the *rs1* group, while those possessing the highest 10% RS values were classified into the *rs10* group. Using the same approach, papers were stratified into div1 to div10 groups using DIV values. Additionally, we calculated the 'hit' rate of a given dataset, denoting the percentage share of globally top-5% highly cited papers within each category, and subsequently visualized the hit rates across various citation windows, grounded in accumulated citations.

To examine the relationship between interdisciplinarity and citation accumulation, we have constructed two indicators to encapsulate the dynamic characteristics of citation accumulation, drawing upon the available dataset. The first indicator, denoted as PEAK_YEAR, signifies the year at which a paper reaches its maximum citation count, commonly referred to as the citation peak, within the span of 10 years since the publishing year. It is noteworthy to acknowledge that certain research papers may indeed require an extended timeframe for recognition, sometimes even surpassing the 10-year timeframe under consideration. The

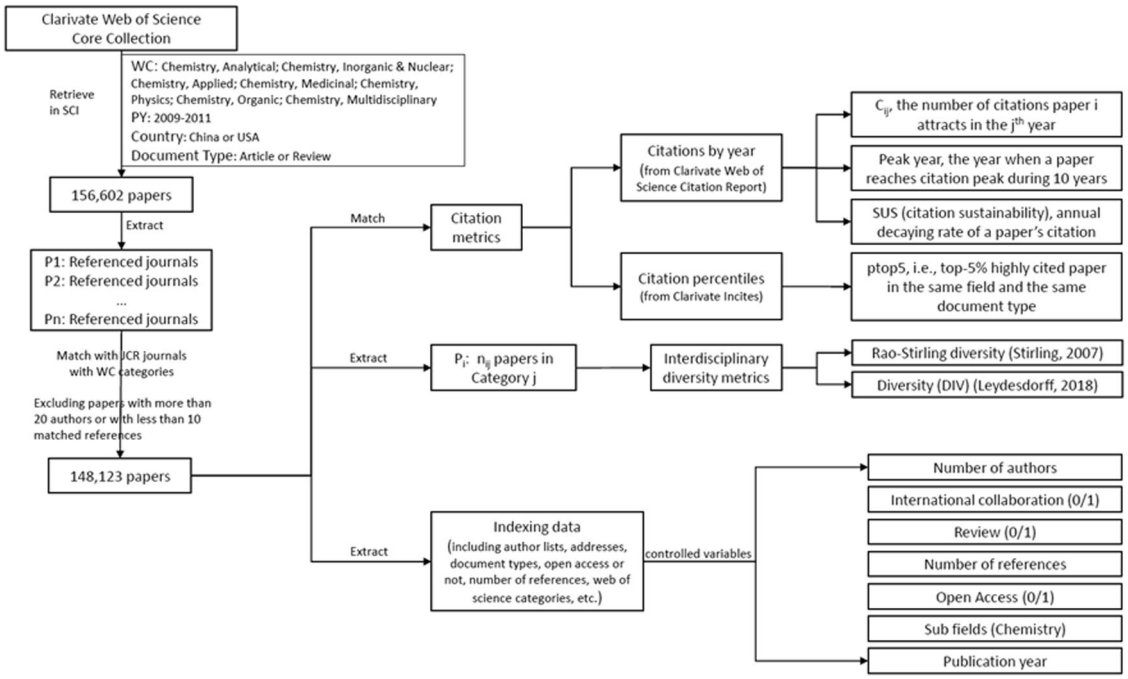

Fig. 1 Data processing. The figure describes the processes for obtaining and cleaning the data.

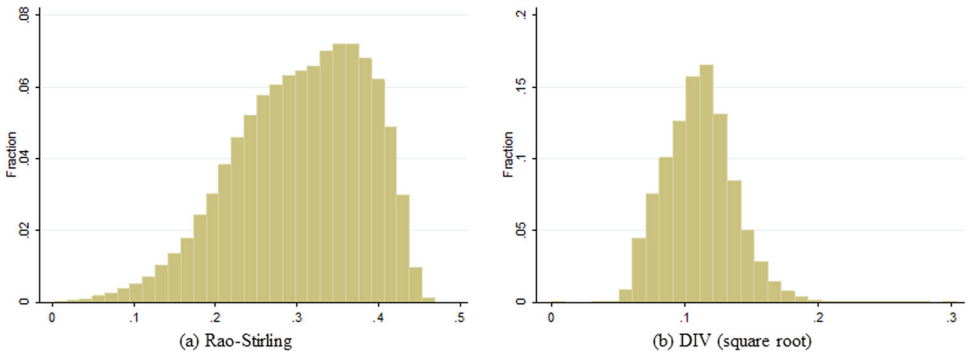

Fig. 2 Distribution of Rao-Stirling and (the square root of) DIV. The figure depicts the distributions of the interdisciplinary indicators, Rao-Stirling (**a**) and the square root of DIV (**b**).

operational definition of PEAK_YEAR, as employed in the current study, is designed to capture the temporal dimension related to the rate at which a paper attains its peak level of citations within the confines of data availability.

The second indicator, referred to as citation sustainability (SUS), quantifies the annual rate of citation decay following the citation peak and is calculated using Eq. (4):

$$SUS = \sqrt[10-PEAK\_YAER]{C_{10}/C_{peak}} \quad (4)$$

where C_{10} denotes the number of citations received by a paper in the 10th year following its publication, while C_{peak} represents the maximum annual citations achieved during the 10 years since the publication year. A higher SUS value indicates a lower decaying rate in citation impact after reaching the peak. For instance, consider papers A and B, both reaching the same citation peak of 20 in the 3rd and 5th year since publication, respectively, and each garnering 10 citations in the 10th year. Their indicators are computed as follows: $SUS_A = \sqrt[10-3]{10/20} = 0.906$, $SUS_B = \sqrt[10-5]{10/20} = 0.871$. This observation indicates that paper A exhibits a more enduring citation impact, characterized by a slower rate of decline after reaching the citation peak, in contrast to paper B. It is worth noting that certain papers may require extended time, approaching or even exceeding a 10-year horizon, to achieve their citation peaks. To account for this, we have implemented an exclusion criterion when performing regressions on SUS, specifically considering papers that attain their citation peaks within 6 years following publication, thereby ensuring a minimum of 4 years for the citation decline from the peak year to the 10th year.

To comprehensively investigate the relationship between interdisciplinarity and citation accumulation, we employ ordinary least squares (OLS) regression analysis, utilizing the two metrics (PEAK_YEAR and SUS) as dependent variables. The core independent variables encompass the two interdisciplinary metrics, RS and DIV, while control variables encompass factors such as whether the paper is a review, open access, internationally collaborated or not, number of authors, number of references, the publishing year, and sub-field categorizations. For each dependent variable, we initially perform the regression analysis on the entire dataset, followed by a regression analysis on the top 5% of highly cited papers on a global scale, aiming to assess the existence of this relationship within elite research samples.

Table 1 presents the descriptive statistics for the dataset consisting of 148,123 papers. On average, each paper contains 4.88 authors and cites 41.0 references. The average time taken to reach the citation peak is 4.43 years, with 60.5, 81.2, and 92.0% of papers attaining their citation peaks within 4, 6, and 8 years, respectively (Fig. S1). Furthermore, the average number of citations garnered in the 10th year stands at 3.96, slightly below half of the average citation peak value, which is 8.48. The mean value of the citation SUS is 0.548. Additionally, 9.6% of the papers are globally top 5% highly cited, 3.4% fall under the category of the *Review* type, 21.5% are the results of international collaborations, and 16.0% are published in open access mode.

Results

Descriptive analysis on interdisciplinarity and citation accumulation. Figure 3 presents a graphical representation of the annual average number of citations garnered by papers since publication, divided into RS categories (a) and DIV categories (b). Both citation curves demonstrate similar patterns across the categories. Specifically, papers with a higher degree of interdisciplinarity, regardless of whether RS or DIV is used, tend to garner more citations on average. This observation suggests a positive correlation between interdisciplinarity and citation impact. Additionally, in line with patterns frequently observed in the natural sciences, papers across various levels of interdisciplinarity tend to reach citation peaks in the third- or fourth-year following publication, followed by a notable decline in citations, referred to as citation decay.

Table 1 Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
PEAK_YEAR	144,629	4.43	2.27	1	10
C_{peak}	147,911	8.48	18.16	0	1602
C_{10}	147,911	3.96	15.20	0	1602
SUS	139099	0.548	0.406	0	1
RS	148,123	0.305	0.080	0.002	0.469
DIV (Square root)	148,123	0.111	0.025	0	0.304
Globally top-5% highly cited	146,675	0.096	0.295	0	1
Review	146,675	0.034	0.182	0	1
Number of authors	148,123	4.88	2.335	1	20
International collaboration	148,123	0.215	0.411	0	1
Open Access	148,123	0.160	0.367	0	1
Number of references	148,123	41.0	35.9	11	4783
Publication year	148,123	2010.1	0.819	2009	2011

Figure 3 also reveals distinctions in citation curves between the two categories. When papers are categorized using the RS index (Fig. 3a), it is evident that papers within the highest RS category (rs10) demonstrate later peak years than other groups. All groups exhibit nearly identical declining rates of citations, with the average citations in the 10th year amounting to approximately 75% of that in the 3rd year. This observation highlights that, in terms of how quickly citations accumulate and decline, the citation curves of papers in different RS categories exhibit a higher degree of similarity. However, it is the level of interdisciplinarity, as measured by RS, that significantly influences the magnitude of accumulated citations rather than the rate of citation accumulation.

Figure 3b demonstrates that papers characterized by higher DIV values (div7 and div10) experience a delayed citation peak in comparison with their lower DIV counterparts (div1 and div4). Additionally, these highly interdisciplinary papers exhibit a more gradual rate of citation decline and a flatter citation tail. For instance, in the 10th year following publication, the div10 group attracts an average of 5.76 citations per paper, equivalent to 95.7% of its citation peak in the 3rd year after publication. Conversely, the lowest-DIV group (div1) achieves an average of 2.73 citations per paper in the 10th year, representing only 50.7% of its 3rd-year citation count. These findings suggest that *papers with higher DIV values are more likely to attain greater and more sustained citation impact over the long term.*

We further compare the "hit" rates, which represent the percentage of globally top-5% highly cited papers, for each DIV category across varying citation windows ranging from 1 year to 10 years (Fig. 4). Our findings confirm the effectiveness of the commonly used 3-year citation window in capturing the long-term citation impact of papers at a macro level, regardless of their degree of interdisciplinarity. When assessing the impact of papers within specific DIV categories, however, a nuanced picture emerges. For groups with lower DIV (div1–div3), the 'hit' rates decrease as the citation window lengthens, indicating a distinct citation advantage for short-term impact as opposed to long-term impact. In contrast, the 'hit' rates of div4 and div5 groups remain stable when considering citation windows of 3–10 years. Intriguingly, groups with higher DIV values (div6–div10) generally exhibit an increasing trend in 'hit' rates as the citation window extends. This observation suggests that papers with higher levels of interdisciplinarity require more time to reach their full citation potential compared with those with lower interdisciplinarity levels.

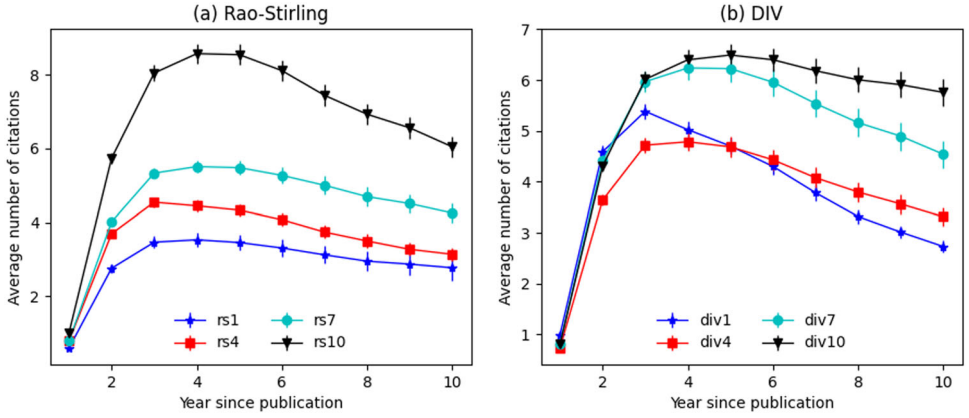

Fig. 3 Citation curves with 95% CI by interdisciplinarity categories. The figure represents the average number of citations by both Rao-Stirling (**a**) and DIV (**b**) categories. Error bars represent the upper and lower bounds of 95% confidence intervals.

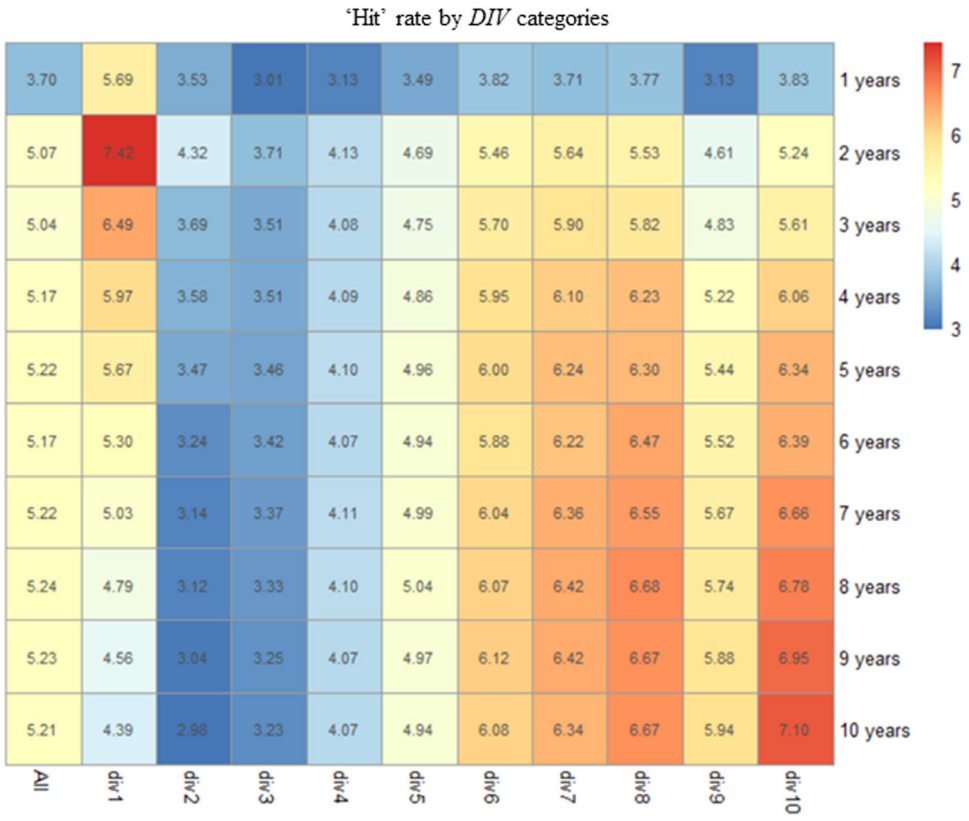

Fig. 4 Heatmap of 'hit' rate by DIV categories and citation windows. The number in each cell represents the 'hit' rate of the corresponding DIV category (*x*-axis) using accumulated citations in certain years (*y*-axis) since the publishing year. The 'hit' rate is the percentage of global top-5% highly cited papers in a given set. This figure signifies the 'hit' rate associated with papers falling within the highest DIV category (div10) using 10-year citations.

Moreover, our results highlight a positive relationship between interdisciplinarity and citation impact, with papers characterized by higher DIV values consistently achieving higher 'hit' rates on average, regardless of the length of the citation window, except for the lowest DIV group. The heatmap visualization underscores the significance of citation windows in scientific evaluation. 'Younger' papers, those published more recently, appear to face a disadvantage compared with 'older' ones when varying citation windows are employed. Furthermore, the choice of citation window can influence the relationship between interdisciplinarity and citation impact, potentially elucidating the inconsistencies observed in prior studies. For instance, the use of 3-year citations reveals an inverted U-shaped relationship between DIV and citation impact, whereas a more linear relationship emerges when considering 10-year citations.

Similar outcomes emerge when considering RS categories (Fig. 5). These results affirm that concerning RS, a 3-year citation window suffices for promptly capturing citation impact, thus substantiating the suitability of using shorter windows for calculating journal impact factors. However, this contrasts significantly with the situation for DIV, where 'hit' rates increase either as RS values rise or as the length of the citation window extends. Datasets within higher RS categories consistently exhibit elevated 'hit' rates using fixed citation windows, and longer citation windows correspondingly result in increased 'hit' rates across all RS categories. These observations indicate that RS levels exert minimal influence on citation accumulation, as 'hit' rates continue to rise irrespective of the RS category.

Statistical analysis on interdisciplinarity and citation dynamics. Table 2 presents the results of the regression analysis examining the relationship between Rao-Stirling & DIV and the peak year for papers published between 2009 and 2011. Column 1 in Table 2 and Fig. 6 demonstrate a U-shaped relationship between RS and the peak year. Specifically, when Rao-Stirling values fall below 0.286 (calculated as $-(-4.720)/8.266$), a negative correlation exists with the year of citation peak. Conversely, there is a positive correlation when values exceed this threshold. This finding implies that papers characterized by both low and high RS values need more time to achieve their citation peaks, while those with medium RS values reach the milestone more swiftly. In contrast, as demonstrated in Column 2 of Table 2, DIV exhibits a positive correlation with the peak year. In essence, higher DIV values are associated with later citation peaks, suggesting that a more extended citation window is necessary to examine the citation impact of papers with high DIV scores. These results are consistent with the patterns observed in the citation curves presented in Fig. 3 and provide further confirmation of the distinct characteristics of these two indicators in the context of interdisciplinarity.

When focusing on globally top-5% highly cited papers, as depicted in Columns 3–4 of Table 2 and Fig. 7, a discernible positive relationship emerges between DIV and the peak year[4]. This finding indicates that highly cited papers with higher DIV values also need more time to achieve their highest citation impact. Conversely, RS exhibits a statistically significant negative association with the peak year. This observation suggests that, in the case of highly cited papers, greater interdisciplinarity, as measured by RS, is linked to a lower peak year.

Several control variables also demonstrate statistically significant associations with the peak year. For instance, reviews and internationally collaborated papers tend to reach their peak citations in later years. Open access is positively linked to a higher peak year in all papers, although this relationship lacks significance for globally highly cited papers. Additionally, papers with larger teams and more references generally reach their citation peak sooner.

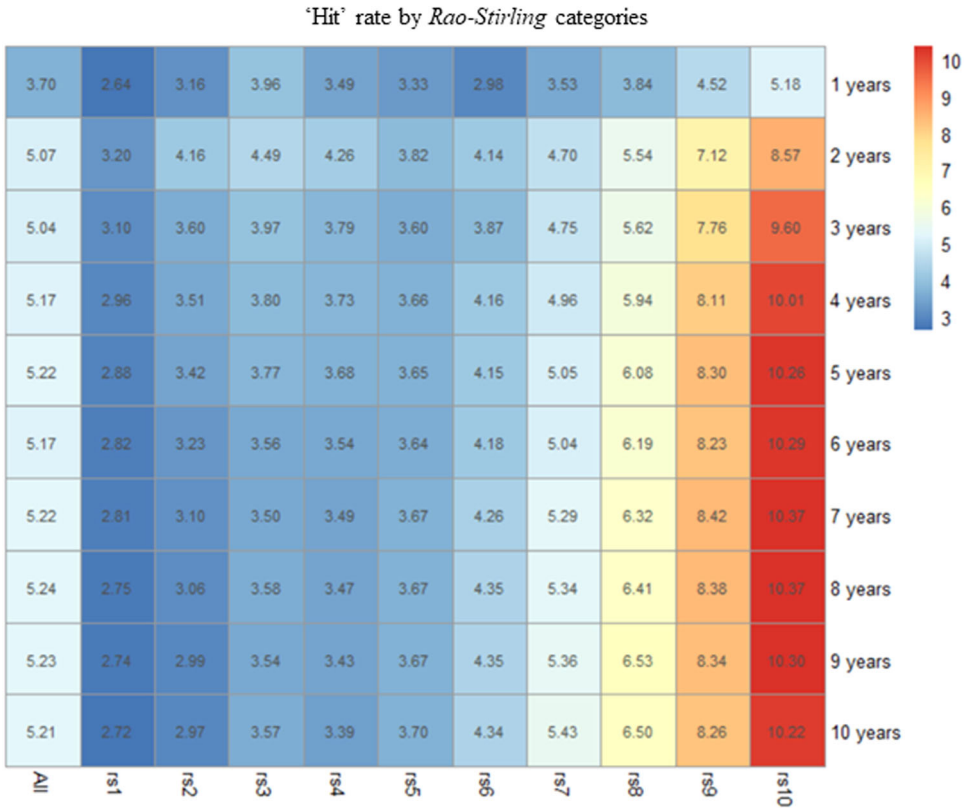

Fig. 5 Heatmap of 'hit' rate by RS categories and citation windows. The numbers represent the 'hit' rates of the corresponding Rao-Stirling category (*x*-axis) using accumulated citations (*y*-axis) after publication. The 'hit' rate is the percentage of global top-5% highly cited papers in a given set.

Table 2 OLS regression analysis of the relationship between Rao-Stirling & DIV and peak year.

	(1)	(2)	(3)	(4)
DV: PEAK_YEAR				
RS	−4.720*** (0.464)		−0.762*** (0.275)	
RS^2	8.266*** (0.794)			
DIV		11.937*** (1.546)		36.039*** (4.784)
DIV^2		−14.527** (6.672)		−82.436*** (20.122)
review	0.551*** (0.037)	0.510*** (0.037)	1.729*** (0.123)	1.512*** (0.120)
Ln (number of authors)	0.029** (0.013)	−0.002 (0.013)	−0.250*** (0.041)	−0.337*** (0.040)
International collaboration	0.079*** (0.015)	0.061*** (0.015)	0.093** (0.045)	0.069 (0.045)
Open access	0.096*** (0.017)	0.058*** (0.017)	0.017 (0.051)	−0.061 (0.051)
Ln (number of references)	−0.013 (0.013)	−0.079*** (0.013)	−0.492*** (0.042)	−0.546*** (0.042)
Year dummy	Yes	Yes	Yes	Yes
Subfield dummy	Yes	Yes	Yes	Yes
_cons	5.001*** (0.081)	3.603*** (0.101)	8.364*** (0.202)	5.715*** (0.338)
N	143,261	143,261	14,118	14,118
Sample description	All papers		Top 5% of highly cited papers	
R^2	0.016	0.023	0.079	0.107

Standard robust errors in parentheses.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 3 presents the results of the regression analysis, focusing on the relationship between interdisciplinarity indicators and citation SUS for papers reaching their citation peak within the first 6 years following publications. To provide a visual representation of the results, Figs. 8 and 9 illustrate the predictive margins of SUS based on the regression results.

Based on the entire dataset, a statistically positive association between RS and citation SUS is reported, indicating that as RS increases, the citation SUS also rises. More specifically, when RS is low, the citation SUS of papers increases at a slower pace, but as RS grows, the citation SUS of papers accelerates. Importantly, this positive relationship between RS and citation SUS holds true even among the globally top-5% of highly cited papers. These results suggest that, despite the U-shaped or negative relationship with PEAK_YEAR mentioned earlier, papers with higher RS tend to exhibit a more sustainable and enduring impact after reaching the citation peaks.

As for DIV, it is evident that DIV has a statistically positive impact on citation SUS in both groups[5], revealing that papers with higher DIV experience a slower rate of citation decline and

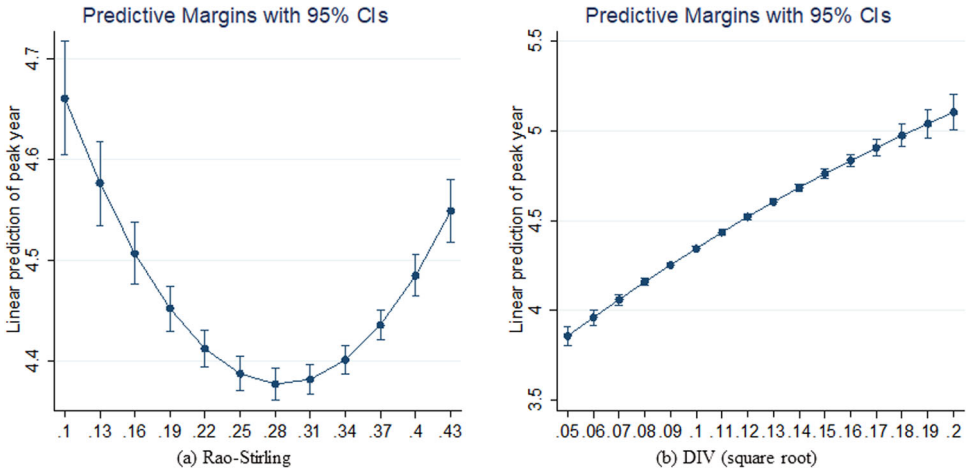

Fig. 6 Predictive margins for PEAK_YEAR by Rao-Stirling & DIV, all papers in 2009–2011. The figure shows the predicted dependent variable (i.e., peak year) based on values of Rao-Stirling (**a**) and square root of DIV (**b**), when all other covariates are set to their means. Error bars represent the upper and lower bounds of 95% confidence intervals.

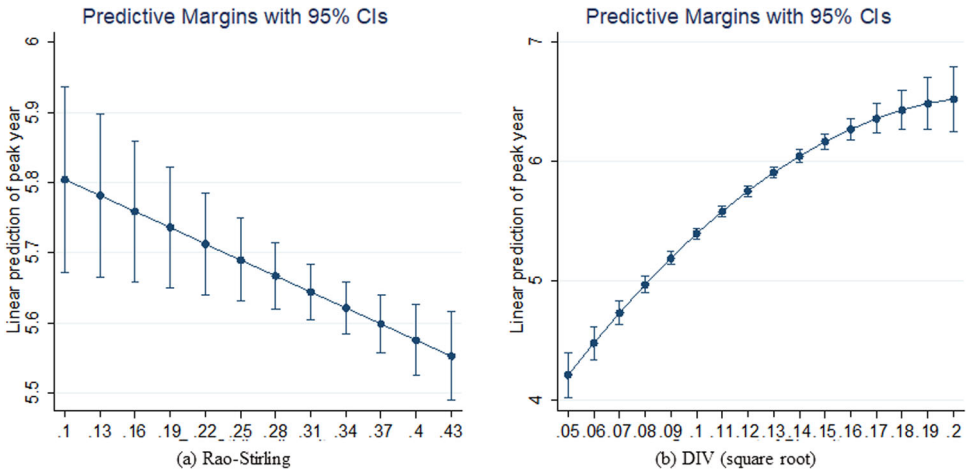

Fig. 7 Predictive margins for PEAK_YEAR by Rao-Stirling & DIV, top-5% highly cited papers in 2009–2011. The figure shows the predicted dependent variable (i.e., peak year) based on values of Rao-Stirling (**a**) and square root of DIV (**b**), when all other covariates are set to their means. Error bars represent the upper and lower bounds of 95% confidence intervals.

Table 3 OLS regression analysis of the relationship between Rao-Stirling & DIV and citation sustainability (SUS).

	(1)	(2)	(3)	(4)
DV: SUS				
RS	−0.129 (0.091)		0.101*** (0.017)	
RS^2	0.777*** (0.155)			
DIV		0.360*** (0.050)		1.247*** (0.250)
DIV^2				−2.241** (0.979)
Review	0.022*** (0.006)	0.022*** (0.006)	0.071*** (0.006)	0.065*** (0.005)
Ln (number of authors)	0.034*** (0.003)	0.039*** (0.003)	−0.014*** (0.002)	−0.016*** (0.002)
International collaboration	0.039*** (0.003)	0.036*** (0.003)	0.009*** (0.003)	0.007*** (0.003)
Open access	0.053*** (0.003)	0.054*** (0.003)	0.020*** (0.003)	0.016*** (0.002)
Ln (number of references)	0.139*** (0.002)	0.138*** (0.002)	−0.013*** (0.002)	−0.017*** (0.003)
Year dummy	Yes	Yes	Yes	Yes
Subfield dummy	Yes	Yes	Yes	Yes
Peak year dummy	Yes	Yes	Yes	Yes
_cons	−0.329*** (0.018)	−0.349*** (0.013)	0.888*** (0.047)	0.833*** (0.048)
N	116,353	116,353	9450	9450
Sample description	All papers		Globally top-5% highly cited papers	
R^2	0.077	0.074	0.043	0.062

Standard robust errors in parentheses.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

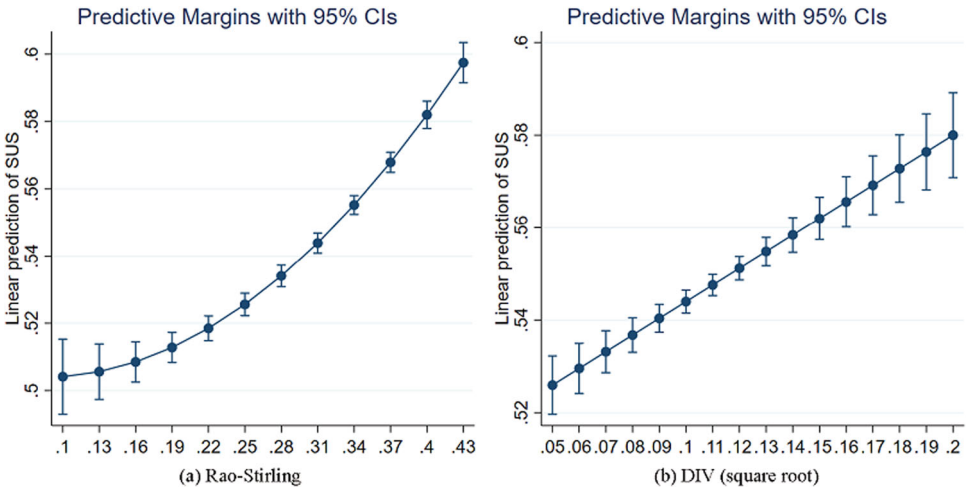

Fig. 8 Predictive margins for SUS by Rao-Stirling & DIV, all papers in 2009–2011. The figure shows the predicted dependent variable (i.e., SUS) based on values of Rao-Stirling (**a**) and square root of DIV (**b**), when all other covariates are set to their means. Error bars represent the upper and lower bounds of 95% confidence intervals.

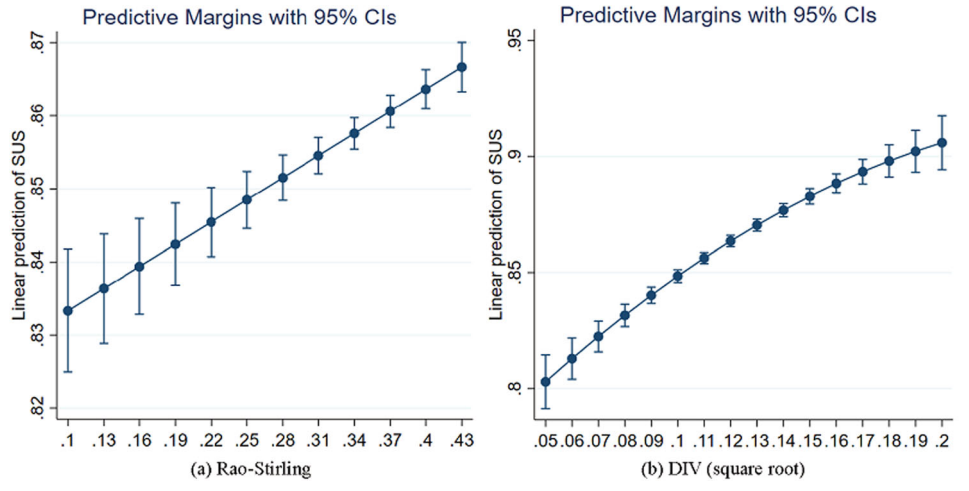

Fig. 9 Predictive margins for SUS by Rao-Stirling & DIV, globally top-5% highly cited papers in 2009–2011. The figure shows the predicted dependent variable (i.e., SUS) based on values of Rao-Stirling (**a**) and square root of DIV (**b**), when all other covariates are set to their means. Error bars represent the upper and lower bounds of 95% confidence intervals.

possesses a more enduring citation impact following their citation peak. This finding is further substantiated by the relationship between DIV and the peak year, indicating that papers with higher DIV are associated with delayed recognition and a more lasting impact, characterized by a later peak year and higher citation SUS. In conclusion, higher interdisciplinarity, as measured by both RS and DIV, is consistently associated with greater citation SUS.

To ensure the robustness of the findings, a series of multiple regression analyses are conducted based on papers attaining their citation peaks within the same year, ranging from the 3rd to 8th year subsequent to publication, respectively (Fig. S2). This stratified approach ensures that the observation period for measuring citation decline is of equal length, substantially reducing the potential influence of citation delay on SUS calculation. These supplementary analyses serve to reinforce and corroborate the previously outlined findings, confirming that higher interdisciplinarity, whether measured as RS or DIV, consistently associates with greater citation SUS.

In terms of the control variables, it is observed that reviews, internationally-collaborated papers, and openly-accessed papers demonstrate higher citation SUS. This finding indicates that these types of papers experience a lower rate of citation decay over time. Additionally, the coefficients for team size (measured by the number of authors) and the length of references are statistically positive in all papers but statistically negative in globally highly cited papers. This phenomenon could be explained by an inverted-U relationship between team size as well as the length of references and citation SUS. In all papers, those with larger team sizes and longer references tend to display higher SUS in their citations. However, among highly-cited papers with larger team sizes and longer reference lists on average, these attributes are typically associated with lower citation SUS.

Conclusion and discussions

The present study investigates the relationship between interdisciplinarity and citation accumulation based on papers in the field of Chemistry published between 2009 and 2011. It compares the citation impact of papers with varying levels of interdisciplinarity and examines how interdisciplinarity correlates

statistically with the accumulation of citations using regression models. Several conclusions can be drawn from the results.

Despite some similarities, DIV demonstrates greater sensitivity to the length of the citation window and better reflects novelty compared with RS. Generally, both RS and DIV show a positive relationship with cumulative citations, indicating that papers with higher indicators tend to attract more citations and are cited more frequently. This finding is consistent with previous studies (Abramo et al. 2017; Chen et al. 2022). Both indicators also exhibit a positive relationship with citation SUS after reaching the citation peaks, indicating that higher interdisciplinarity leads to longer-lasting impact. However, Rao-Stirling and DIV differ in two aspects. *Regarding citation impact, DIV is more sensitive to the length of the citation window*. Analysis of the average citation impact of papers with different levels of interdisciplinarity across citation windows reveals that papers with higher DIV scores experience later peak years and a longer-lasting impact on average. The relationship between DIV categories and hit rates varies depending on the citation window. In contrast, the citation curves for different RS categories do not exhibit significant differences, except for variations in citation peaks. The hit rates for all RS categories increase with the length of the citation window. *Concerning citation accumulation, DIV aligns more closely with the concept of novelty, providing a better illustration of interdisciplinarity's nature*. Regression analysis shows that higher DIV is associated with both later peak years and greater citation SUS, which partially explains the higher research impact of highly-novel research (Stephan et al. 2017; Uzzi et al. 2013) and the associated delayed recognition (Min et al. 2021; Wang et al. 2017). While RS exhibits a statistically positive relationship with citation SUS, it demonstrates a U-shaped relationship with peak year.

DIV was proposed due to the recognition that there is a lack of consideration for the dimension of balance in the calculation of RS within the concept of interdisciplinarity. Subsequently, several studies have examined the distinctions between DIV and RS, with a primary focus on DIV's higher degree of monotonicity as emphasized by Rousseau (2018), reduced propensity for perplexing or counterintuitive characteristics, and enhanced capacity for distinguishing units of greater diversity (Leydesdorff et al. 2013, 2019). With regard to the correlation between these metrics and citation impact, Chen et al. (2022) have considered both metrics in conjunction with others. Their findings underscore the necessity of employing an extended citation window when assessing scientific impact related to interdisciplinarity, whether relying on RS or DIV. However, explicit disparities in this regard have yet to be reported.

By focusing on the process of citation accumulation, the current study affirms DIV's higher resolving power, offering a clearer representation of its novelty and greater sensitivity to variations of the citation window duration. Consequently, this results in a more pronounced divergence in the average citation impact between papers with low and high DIV scores as the citation window expands. Nevertheless, whether these disparities between DIV and RS contribute to this sensitivity to the citation window duration deserves further exploration.

Furthermore, interdisciplinarity is positively associated with delayed recognition and greater citation SUS. From the perspective of the citation accumulation process, DIV shows a positive relationship with both peak years and citation SUS. This finding indicates that papers with higher DIV take longer to reach their maximum citation potential and exhibit a slower rate of citation impact aging. In contrast, papers with higher RS also reach peak years later and demonstrate more sustainable citation impact in general, although the statistical relationship between RS and peak year follows a U-shaped pattern. In summary, papers with higher interdisciplinarity not only have a greater citation impact on average but also require more time to attract academic recognition. These papers tend to have a more lasting and sustainable citation impact, characterized by a slow rate of aging. This is akin to the nature of novelty or breakthrough research (Min et al. 2021; Wang et al. 2017). The observed characteristic of greater citation SUS associated with interdisciplinarity, as elucidated in the current study, contributes significantly to our understanding of delayed recognition within the realm of IDR. From another perspective, research with higher interdisciplinarity takes longer to reach its citation peak but ultimately achieves a greater and more lasting citation impact. This is especially true when considering a longer citation window. Consequently, research with lower interdisciplinarity is more advantageous in the short term, while research with higher interdisciplinarity demonstrates a greater academic performance when using a longer citation window, as evidenced in other studies (Larivière et al. 2015; Wang et al. 2015). This could explain why the relationship between interdisciplinarity and citation impact is often inconsistent, as papers with higher interdisciplinarity may take longer to be recognized, thus displaying lower citation impact in earlier periods due to delayed recognition.

According to the results, there are several recommendations. Firstly, it is suggested that when evaluating research performance, particularly when assessing the relationship between interdisciplinarity and citation impact, careful consideration should be given to the length of the citation window, as it significantly affects the assessment of citation impact. Neglecting this factor may lead to underestimation or overestimation of the impact of certain papers, as illustrated in Figs. 4 and 5. Moreover, when examining interdisciplinarity, such as DIV in this study, the choice of citation window becomes more crucial, as the relationship between DIV and citation impact can differ depending on the length of the citation window. In existing research evaluations, both fixed and variable citation windows are commonly used. However, with a fixed but short-term citation window (e.g., 3 years), higher-DIV papers face a disadvantage while lower-DIV papers enjoy an advantage in terms of citations. On the other hand, when using a variable citation window, the window's effect cannot be considered when estimating the relationship between interdisciplinarity and citation impact. To ensure accuracy, it is recommended that the citation window be carefully chosen when selecting citation indicators, particularly when evaluating the interplay between interdisciplinarity and citation impact.

Secondly, we suggest that a longer citation window should be considered as an alternative indicator or supplement to short-term impact evaluations for high-interdisciplinary papers, research centers, and interdisciplinary projects. This is due to the delayed recognition of interdisciplinary relevance, which requires a longer citation window for a more accurate and robust evaluation.

The study makes several important contributions. Firstly, it shifts the focus from static citation impact metrics, such as number of citations, normalized citation indicators, or being highly cited or not, to the dynamic process of citation accumulation. It considers not only the *speed* at which a paper achieves its citation peak but also the *sustainability* of citation impact after reaching the peak. Secondly, the study provides a novel perspective by comparing the annual and cumulative citation impacts of publications under different conditions, highlighting both the commonalities and disparities between existing interdisciplinary indicators. Thirdly, the study not only confirms the association between interdisciplinarity and delayed recognition but also extends the analysis to underscore a higher degree of citation SUS subsequent to the citation peak. This expanded perspective offers a more robust explanation for the delayed recognition of IDR. Moreover, this

finding helps to explain the conflicting results of previous studies regarding the relationship between interdisciplinarity and citation impact, underscoring the importance to affording interdisciplinary programs and novel research more time and flexibility.

Limitations and future expectations. Some limitations exist in the current study. Firstly, it's important to note that the scope of the present study is limited to two of the largest producing countries, namely China and the US, within the field of Chemistry. Although expanding the study to include more countries could provide a more comprehensive insight, it's worth highlighting that papers published by Chinese or US authors collectively represent a substantial proportion of global research output—accounting for 40% across all fields and 37% in Chemistry. This substantial representation is the rationale behind our selection of these two countries as the primary subjects of investigation. In future studies, we do intend to broaden the scope by incorporating samples from more countries, thus providing a more holistic overview of the dynamics within the global publication system. Moreover, it's crucial to acknowledge that Chemistry, as a mature and well-established discipline, may exhibit distinct characteristics in terms of references to and citations from external disciplines (van Noorden, 2015). Therefore, the findings based on papers within the Chemistry domain may not be applicable to other disciplines, particularly characterized by higher interdisciplinarity. Future work encompassing other diverse disciplines will enable further validation and more flexible comparisons.

Secondly, there are considerations regarding the use of integrated interdisciplinary metrics (i.e., Rao-Stirling and DIV). Specifically, both DIV and RS rely on the distance between fields within a specific field classification system, such as WoS Categories. It is essential to recognize that any alteration made to the granularity or the underlying structure of the classification system can inevitably lead to variations in the results.

Thirdly, for the sake of computational efficiency, the current study primarily focuses on peak year and citation SUS as descriptors of the citation accumulation process. However, we recognize the potential value in exploring other indicators related to the accumulation of citations. These indicators could encompass 'residual citations', representing the citations kept after a long time period after the publication year (Bouabid, 2011), 'citation bursts' signifying rapid surges in the number of citations received by papers (Eom and Fortunato, 2011), 'citation speed' measuring how quickly a paper accumulates its citations (Wang, 2013), and consequently, 'citation decay' (Wang et al. 2015). While the current study employs a 10-year citation window to facilitate explorations into both short- and long-term citation impact, there may be merit in extending the length of the citation window. We remain open to the possibility of revisiting the research with extended citation windows in the future.

Data availability

The datasets generated during and/or analyzed during the current study are available in the Figshare repository, https://figshare.com/s/7b9c5d2be39549e0efc0.

Received: 23 March 2023; Accepted: 28 November 2023;
Published online: 13 December 2023

Notes

1 Data from Clarivate Web of Science Core Collection.
2 Indexing data, including authors, addresses, subjects, etc. was obtained in October 2017, and citation-related data were obtained in June 2022.
3 Accessed from http://www.leydesdorff.net/wc15/.
4 Although the relationship between DIV and peak year is the inverted-U shape, the DIV value corresponding to the peak point is 0.219, which is higher than more than 99% of papers, thus DIV is still positively related to peak year.
5 Although in highly cited papers, the results mean an inverted-U shape between DIV and SUS, the (square root of) DIV of over 99% of the samples located in the increasing side (i.e., less than 0.252).

References

Abramo G, D'Angelo CA, Di Costa F (2017) Do interdisciplinary research teams deliver higher gains to science? Scientometrics 111(1):317–336. https://doi.org/10.1007/s11192-017-2253-x
Bouabid H (2011) Revisiting citation aging: a model for citation distribution and life-cycle prediction. Scientometrics 88(1):199–211. https://doi.org/10.1007/s11192-011-0370-5
Bromham L, Dinnage R, Hua X (2016) Interdisciplinary research has consistently lower funding success. Nature 534(7609):684–687. https://doi.org/10.1038/nature18315
Chen S, Arsenault C, Larivière V (2015) Are top-cited papers more interdisciplinary? J Informetr 9(4):1034–1046. https://doi.org/10.1016/j.joi.2015.09.003
Chen S, Song Y, Shu F et al. (2022) Interdisciplinarity and impact: the effects of the citation time window. Scientometrics 127:2621–2642. https://doi.org/10.1007/s11192-022-04338-1
Elsevier (2015) A Review of the UK's Interdisciplinary Research Using a Citation-Based Approach
Eom YH, Fortunato S (2011) Characterizing and modeling citation dynamics. Plos ONE 6(9):e24926. https://doi.org/10.1371/journal.pone.0024926
Gibbons M, Limoges C, Nowotny H et al. (1994) The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. Sage, London
Katz JS, Martin BR (1997) What is research collaboration? Res Policy 26(1):1–18
Lariviere V, Gingras Y (2014) Measuring interdisciplinary. In: Cronin B, Sugimoto CR (ed) Beyond Bibliometrics: Harnessing Multidimensional Indicators of Scholarly Impact. The MIT Press, Cambridge, p 187–200
Larivière V, Haustein S, Börner K (2015) Long-distance interdisciplinarity leads to higher scientific impact. PLoS One 10(3):e0122565. https://doi.org/10.1371/journal.pone.0122565
Levitt JM, Thelwall M (2008) Is multidisciplinary research more highly cited? A macrolevel study. J Am Soc Inf Sci 59(12):1973–1984. https://doi.org/10.1002/asi.20914
Leydesdorff L (2018) Diversity and interdisciplinarity: how can one distinguish and recombine disparity, variety, and balance? Scientometrics 116(3):2113–2121. https://doi.org/10.1007/s11192-018-2810-y
Leydesdorff L, Wagner CS, Bornmann L (2019) Interdisciplinarity as diversity in citation patterns among journals: Rao-Stirling diversity, relative variety, and the Gini coefficient. J Informetr 13(1):255–269. https://doi.org/10.1016/j.joi.2018.12.006
Leydesdorff L, Zhou P, Bornmann L (2013) How can journal impact factors be normalized across fields of science? An assessment in terms of percentile ranks and fractional counts. J Am Soc Inf Sci 64(1):96–107. https://doi.org/10.1002/asi.22765
Lyall C, Bruce A, Marsden W et al. (2013) The role of funding agencies in creating interdisciplinary knowledge. Sci Public Policy 40(1):62–71. https://doi.org/10.1093/scipol/scs121
Min C, Bu Y, Wu D et al. (2021) Identifying citation patterns of scientific breakthroughs: A perspective of dynamic citation process. Inf Process Manag 58(1):102428. https://doi.org/10.1016/j.ipm.2020.102428
Nicholson JM, Ioannidis JPA (2012) Conform and be funded. Nature 492(7427):34–36. https://doi.org/10.1038/492034a
Okamura K (2019) Interdisciplinarity revisited: evidence for research impact and dynamism. Palgrave Commun 5(1):1–9. https://doi.org/10.1057/s41599-019-0352-4
Porter AL, Rafols I (2009) Is science becoming more interdisciplinary? Measuring and mapping six research fields over time. Scientometrics 81(3):719–745. https://doi.org/10.1007/s11192-008-2197-2
Rafols I, Meyer M (2010) Diversity and network coherence as indicators of interdisciplinarity: Case studies in bionanoscience. Scientometrics 82(2):263–287. https://doi.org/10.1007/s11192-009-0041-y
Rao CR (1982) Diversity: Its measurement, decomposition, apportionment and analysis. Sankhyā Indian J Stat 44(1):1–22
Rousseau R (2018) The repeat rate: from Hirschman to Stirling. Scientometrics 116(1):645–653. https://doi.org/10.1007/s11192-018-2724-8
Schilling MA, Green E (2011) Recombinant search and breakthrough idea generation: An analysis of high impact papers in the social sciences. Res Policy 40(10):1321–1331. https://doi.org/10.1016/j.respol.2011.06.009
Stephan P, Veugelers R, Wang J (2017) Reviewers are blinkered by bibliometrics. Nature 544(7651):411–412. https://doi.org/10.1038/544411a
Stirling A (2007) A general framework for analysing diversity in science, technology and society. J R Soc Interface 4(15):707–719. https://doi.org/10.1098/rsif.2007.0213

Sun Y, Livan G, Ma A et al. (2021) Interdisciplinary researchers attain better long-term funding performance. Commun Phys 4(1):263. https://doi.org/10.1038/s42005-021-00769-z
Uzzi B, Mukherjee S, Stringer M et al. (2013) Atypical combinations and scientific impact. Science 342(6157):468–472. https://doi.org/10.1126/science.1240474
van Noorden R (2015) Interdisciplinary research by the numbers. Nature 525:306–307. https://doi.org/10.1038/525306a
Wang J (2013) Citation time window choice for research impact evaluation. Scientometrics 94(3):851–872. https://doi.org/10.1007/s11192-012-0775-9
Wang J, Thijs B, Glänzel W (2015) Interdisciplinarity and impact: distinct effects of variety, balance, and disparity. PLoS One 10(5):e0127298. https://doi.org/10.1371/journal.pone.0127298
Wang J, Veugelers R, Stephan P (2017) Bias against novelty in science: a cautionary tale for users of bibliometric indicators. Res Policy 46:1416–1436. https://doi.org/10.1016/j.respol.2017.06.006
Weart S (2013) Rise of interdisciplinary research on climate. Proc Natl Acad Sci 110(Supplement_1):3657–3664. https://doi.org/10.1073/pnas.1107482109
Woelert P, Millar V (2013) The "paradox of interdisciplinarity" in Australian research governance. High Educ 66:755–767. 10.1007.252Fs10734-013-9634-8
Yegros-Yegros A, Rafols I, D'Este P (2015) Does interdisciplinary research lead to higher citation impact? the different effect of proximal and distal interdisciplinarity. PLoS ONE 10(8):e0135095. https://doi.org/10.1371/journal.pone.0135095
Zhang L, Sun B, Jiang L et al. (2021) On the relationship between interdisciplinarity and impact: distinct effects on academic and broader impact. Res Eval 30(3):256–268. https://doi.org/10.1093/reseval/rvab007
Zhou H, Guns R, Engels TCE (2022) Are social sciences becoming more interdisciplinary? Evidence from publications 1960–2014. J Am Soc Inf Sci 73(9):1201–1221. https://doi.org/10.1002/asi.24627

Acknowledgements

This work was supported by the National Natural Science Foundation of China [71843012], Jiangsu Provincial Double-Innovation Doctoral Program [JSSCBS20221304], Humanities and Social Science Funds of Yangzhou University [xj2023-23], and Zhejiang Soft Science Program [2023C35102].

Author contributions

Research design: XC, XL, and PZ. Data collection and analysis: XC. Writing and editing: XC, XL, and PZ.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

Informed consent was not required as the study did not involve human participants.

Competing interests

The author(s) declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-023-02475-3.

Correspondence and requests for materials should be addressed to Ping Zhou.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.