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From SARS to COVID –19: Is interdisciplinary research progressed in responding to another global pandemic?

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ABSTRACT

Interdisciplinary research (IDR) plays a vital role in tackling grand and complex challenges such as COVID-19, which has severe consequences for public health, economy, politics, and society. This study compares several facets of interdisciplinarity that occurred in the research relating to two serious global pandemics in this century, namely SARS and COVID-19, and provides a comprehensive summary of the performance and growth of pandemic-related interdisciplinary research. Generally, the scientific community gathers more multidisciplinary efforts to tackle COVID-19 in comparison to SARS. Firstly, COVID-19 related research from each major field has greater connections with their established expertise and research threads such that they are studying the impact of COVID-19 on their own existing research subjects, while the studies of SARS by different disciplines exhibit less discernable disciplinary characteristics. Secondly, as for the interdisciplinarity observed in the knowledge base of pandemic-related publications, we observe a greater presence of social science knowledge and a more dispersed distribution of knowledge from various disciplines comparing publications on COVID-19 with SARS. Thirdly, regarding interdisciplinarity in research collaboration, COVID-19 publications are on average produced by more interdisciplinary teams than SARS, as measured by the number and diversity of affiliated disciplines of authors. Our discovery on the growth of multidisciplinarity and interdisciplinarity in pandemic-related research signals positive achievement that the scientific community is responding to such a global challenge as a whole and is willing to break down existing disciplinary silos to facilitate the flow of knowledge and breed novelty.

KEYWORDS

SARS; COVID-19; Interdisciplinarity; Multidisciplinary collaboration; Response pattern

Introduction

First diagnosed on 31 December 2019, COVID-19 (also known as SARS-CoV-2) has now

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spread across the globe and has fundamentally disrupted almost all aspects of human society. The unprecedented outbreak has brought enduring threats to public health worldwide and caused tremendous challenges to the production and life of the world. By 23 June 2022, about 220 countries and regions had reported 539,119,771 confirmed cases, with 6,322,311 deaths globally[1].

This is not the first time that humanity has been challenged by a severe global pandemic, and it will not be the last. As early as 165 A.D., the Antonine Plague raged the Roman Empire and was estimated to cost 5-10 million lives, roughly 10% of the entire population of the empire[2]. Many contagious diseases continue to perplex human health, such as influenza, HIV/AIDS, SARS, Ebola, and COVID-19, just to name a few. Throughout history, the emergence and spread of various infectious diseases seem to constitute a regular fixture that resurfaces every few decades and causes a significant disturbance. Nonetheless, as the scientific enterprise grows exponentially and rapidly, more solutions are manufactured by the scientific community to tackle pandemics and other problems associated with them. In response to the COVID-19 pandemic, a large number of academic studies and case reports have emerged in major international scientific and medical journals, including tracking the evolution of coronavirus, investigating epidemiologic features and potential risk factors, and reporting clinical, laboratory, and imaging findings (Holshue et al., 2020; Thelwall & Thelwall, 2022)

Although still causing increasing infections and loss of lives, many countries are ready to move on to the "new normal" in the post-COVID-19 world and ease restrictions on various social activities while maintaining selected essential infrastructures built during COVID-19, such as vaccine development, PCR tests, quarantines for international travellers. It is time for a summary and reflection on the achievements and activities of the scientific community - How is science doing so far in responding to COVID-19? Has science progressed in responding to another global pandemic? What can be improved to prepare for the next outbreak?

To answer these questions, many researchers contribute their perspectives through quantitative science studies. Zhang et al. (2020) noted that historical patterns show that researchers have always responded quickly to public health emergencies with a sharp increase in the number of publications on the emergency topic. Bas and Yılmaz (2021) compared the scientific productivities of the three most famous outbreaks of beta-coronavirus genus: SARS, MERS, and COVID-19. Fry et al. (2020) found COVID-19 research had smaller teams and involved fewer nations by tracking the international collaboration patterns in coronavirus-related research. Aviv-Reuven and Rosenfeld (2021) also found that COVID-19 research papers were less likely to involve international collaboration than non-COVID-19 papers during the same period. Liu et al. (2021) observed that the "parachuting collaborations"-new connections not seen before the pandemic-which have dramatically increased during the pandemic. Ram and Nisha (2020) conducted a bibliometric analysis of the highly cited articles in "coronavirus" research. Cheng et al. (2020) presented the generic research themes of the coronavirus diseases: COVID-19, MERS, and SARS, by applying a text mining technique with a latent Dirichlet allocation procedure. Liu et al. (2021) found that COVID-19 research exhibits higher novelty than coronavirus research before the pandemic.

Another focal question that warrants discussion is how interdisciplinary research (IDR) was done on COVID-19 related topics. With ubiquitous impacts on every aspect of human soci-

1 https://covid19.who.int/ [23–06–2022]

2 https://en.wikipedia.org/wiki/Antonine_Plague

ety, the challenges that humankind faces during COVID-19 are too complex and multifactorial to be addressed within the traditional disciplinary boundaries. IDR is increasingly recognized as a central approach to solving such global challenges that researchers have never come up with before. The unprecedented outbreak of COVID-19 represents one of the most substantial global challenges of this century, which has severe consequences for public health, economics, politics, and society. Facing such a critical public health emergency, researchers from all disciplines are coming together to contribute their expertise (Homolak et al., 2020). For example, interdisciplinary collaboration between medical science and computer science contributes significantly to one of the most decisive infrastructures in reducing infection and death, the record-breaking fast development of vaccine and drug discovery. Computer scientists and data scientists were summoned to construct Artificial Intelligence (AI) models to identify the sequence of COVID-19 for drug discovery (Abubaker Bagabir et al., 2022), predict vaccine candidates using machine learning-based ML reverse vaccinology tools (Ong et al., 2020), and determine key locations for vaccine trial sites (Park, 2021). The involvement of AI tools provided cost-saving and greater agility, which is essential for a rapid response to the pandemic at an early stage. The importance of IDR during COVID-19 is discussed theoretically by many researchers from different lenses. Bontempi et al. (2020) stated that the pandemic's diffusion patterns are typically caused by a multiplicity of environmental, economic, and social factors. The understanding of contagion diffusion patterns should also rely on an interdisciplinary, multi-dimensional approach. In addition, the restrictions on mobility and closures of non-essential workplaces, recommendations regarding physical distancing and isolation, the virtualization of work and schooling, and the increased demand on essential health care services, etc., all the work is taking place under challenging conditions within and across multiple sectors with great efforts from researchers, professionals, organizations, etc. Meisner et al. (2020) also advocated the adoption of interdisciplinary approaches in response to COVID-19. The connections between and across disciplines can provide essential insights into the current crisis. Based on the review of the impact on the healthcare systems and the economy and society of the European second wave, Uttpal et al. (2021) strongly suggested the establishment of an international healthcare transdisciplinary workforce devoted to investigating, mitigating, and also controlling future virus outbreaks. White et al. (2021) described a case study of how an interdisciplinary institute for research on aging has managed the process of change during COVID-19 restrictions. However, relatively little effort goes into measuring and assessing interdisciplinarity in coronavirus-related literature empirically. Though Zhao et al. (2022) analyzed the interdisciplinarity and patterns of disciplinary co-occurrence in coronavirus-related research, different research contents and the interdisciplinary collaborations among various fields still remain uninvestigated.

This study aims to contribute to the literature with a comparative analysis of the pattern of IDR that emerged in SARS and COVID-19 and investigate whether IDR grows or improves after almost two decades (2003 to 2020) facing another global pandemic. The comparison is feasible and relevant in several aspects. Firstly, both SARS and COVID-19 are classed as species of SARS-related coronavirus, similar to SARS-CoV, and belong to the genus beta-coronavirus (Rodriguez-Morales et al., 2020). Several similarities and differences in the causative agents, pathogenesis and immune responses, epidemiology, diagnosis, treatment, and management of COVID-19 and SARS have been identified (Chen et al., 2020; Law et al., 2020). Secondly, both SARS and COVID-19 have caused vast transmission and deaths globally, which made them visible and relevant to a wide spectrum of researchers around the

world. Thirdly, the two both attacked the world in the new century when scholarly outputs are more traceable bibliographically via databases such as Scopus and Web of Science with better coverage and more comprehensive metadata, rendering a data-wise tangible comparison. Therefore, this study took SARS and COVID-19 as examples to assess the inter-/trans-disciplinary response of the scientific community to pandemics. We focus our analyses on three aspects of pandemic-related IDR, namely multidisciplinarity in scholarly outputs, interdisciplinarity in knowledge base, and interdisciplinarity in scientific collaboration. Below we introduce and discuss each.

Specifically, the research questions addressed in this paper are as follows:

1. Which disciplines are involved in the research on SARS and COVID-19? What are the differences in the topics of research outputs between SARS and COVID-19?

2. Which discipline contributes to the knowledge base of research on SARS and COVID-19, respectively? Is pandemic-related research becoming more interdisciplinary after almost two decades?

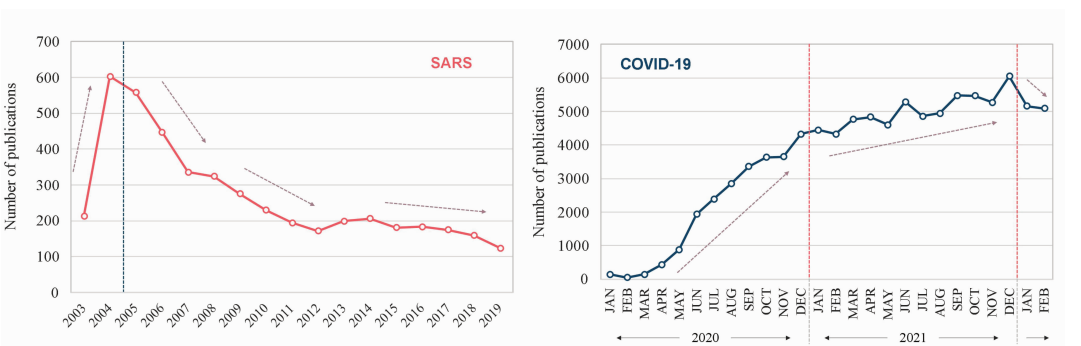
3. What are the patterns of interdisciplinary collaboration in the research of SARS and COVID-19? Is there any difference in different stages of pandemics?

Data and methods

Following our previous study on the analysis of response patterns scientific research reacts to international public health emergencies (Zhang et al., 2020), we obtained SARS and COVID-19 related publication records from Clarivate Analytics' Web of Science (WoS). Considering the publishing and citation differences among different document types, only original journal articles are included in our dataset. Three types of information are mainly obtained:

- Bibliographic information includes titles, journals, publication dates, categories, DOIs, etc.
- Bibliographic data for the references listed in the article; and
- Author address information for the focal publications.

All records were updated on 10 Mar 2022. Since the keywords "SARS(-CoV)" and "severe acute respiratory syndrome" for SARS also appeared in COVID-19 research due to the expression of "SARS-CoV-2" and "severe acute respiratory syndrome 2" on COVID-19, we manually cleaned the dataset for SARS firstly. After removing duplications and records without cited references or author addresses, 114,432 publications remained in our dataset. As shown in Figure 1, 6,332 publications cover both SARS and COVID-19 disease.



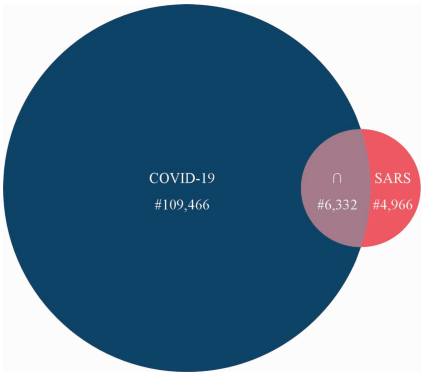


Figure 1 Overview of the dataset. Top panel: Temporal distributions of SARS (left) and COVID-19 (right) related publications. Vertical dashed lines denote different periods of SARS and COVID-19. Bottom panel: Venn Diagram comparing publications related to SARS and COVID-19.

Furthermore, the top panel of Figure 1 shows the temporal distribution of SARS and COVID-19 publications. Immediately following the outbreak of SARS in 2003, the number of publications related to this epidemic rose sharply, reaching a peak in 2004 and then declining gradually. It should be noted that both SARS and COVID-19 belong to the genus beta-coronavirus taxonomically (Rodriguez-Morales et al., 2020); with the outbreak of COVID-19 in late 2019, SARS-related research has also grown exponentially. To intuitively display the evolution of SARS-related publications, The x-axis was uniformly set from 2003 to 2019 in this research. As for the publication dynamics of COVID-19, there has been a sharp increase since April 2020. In 2021, publications continued to grow steadily. And it slightly decreased in the first two months of 2022.

To recognize the disciplinary attribution of different authors, we applied the method proposed by Zhang et al. (2018). i.e., assigning collaborators to appropriate disciplines through the disciplinary feature words that appeared in the name of secondary author affiliations.

To quantify the interdisciplinarity of publications in our dataset, two indicators are applied, namely, variety and integrated diversity.

Variety is defined as the number of non-empty categories assigned to system elements. In this study, the system elements were: 1) the WoS-indexed references, and 2) the affiliations in the bylines. Accordingly, the non-empty categories were: 1) the WoS subject categories of cited references; and 2) the disciplines recognized from the address information.

Integrated diversity comprises three "traditional" components, namely variety, balance, and disparity, as has been outlined by Stirling (2007). For the specific measure, the "true" diversity (TD) proposed by Zhang et al. (2016) is used:

$$TD = \frac{1}{\sum_{i \neq j} p_i p_j \left(1 - d_{ij}\right)} \tag{1}$$

Where $p_i = x_i/X$, $X = \Sigma x_i$, d_{ij} is the disparity between the subject categories (SCs in WoS) *i* and *j*. When calculating the disparity in a reference list, *sij* was based on a cross-citation similarity matrix of the WoS subject classifications during the period 2009-2018[3]. When calculating the disparity of affiliations, *sij* was derived from a cross-citation similarity matrix of the 13 affiliation disciplines, which is aggregated from the WoS subject cross-citation matrix according to the hierarchical structure of ECOOM classification (Glänzel & Schubert, 2003).

3 The cross-citation matrix of all SCs (2009-2018) was constructed based on an in-house database of the Centre for R&D Monitoring (ECOOM), Belgium.

Results

Multidisciplinarity in scholarly outputs

We firstly generated the science overlay maps in VOSviewer (Waltman et al., 2010) to visualize the subject distribution of focal publications related to SARS and COVID-19. The results are shown in figure 2.

Compared with the concentrated distribution of SARS-related publications in the medical and biomedical fields, more categories are involved in response to COVID-19. Except for the growth in medical-related disciplines like Psychology and Healthcare, the number of publications in Social Science, Computer Sciences and Engineering, Management, and other clusters also increased significantly. On the other hand, Infectious Diseases, Clinical Medicine, Biomedicine, and Other Medicine four clusters have a high number of publications in both SARS and COVID-19 related research.

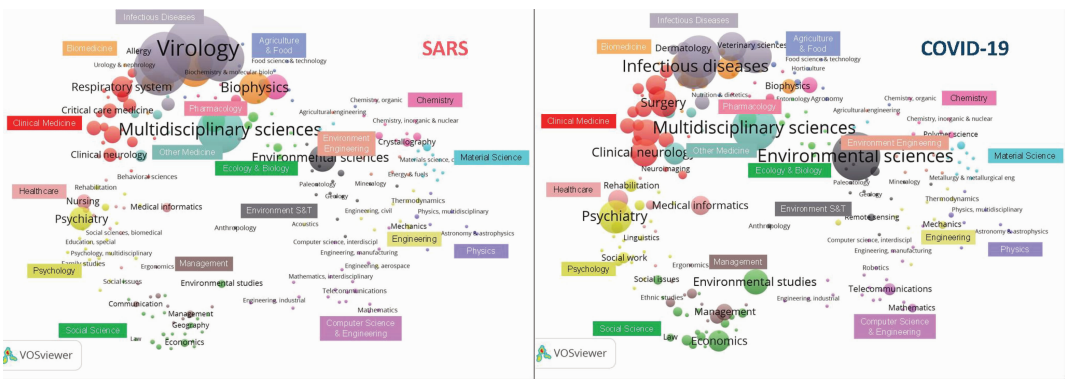


Figure 2 19 clusters of publications related to SARS and COVID-19. Each node represents a WoS subject category, and the size of the node indicates the number of publications. Different colours represent the clusters generated using the approach introduced by Carley et al. (2017).

Note: The base map was developed from a WoS category matrix of 227× 227 cells. The matrix was generated from citation counts and normalized with a cosine function (Carley et al., 2017).

After mapping WoS subject categories to ECOOM 16 major disciplines, we further present the temporal evolution of publications in different disciplines during the first 24 months since the outbreak of SARS and COVID-19, respectively. The results are shown in Figure 3. Considering that both SARS and COVID-19 broke out in December 2002 and 2019, respectively, we chose January of the following years as the starting year for this analysis.

What can be seen from Figure 3 is that facing the COVID-19 epidemic, academia has shown a more rapid multidisciplinary response. Although Clinical and Experimental Medicine (I & II) contributed the most publications in the first two years of the outbreak of both SARS and COVID-19, only two fields, Biology (Organismic & Supraorganismic level) and Biosciences (General, Cellular & Subcellular Biology, Genetics), account for a large proportion of SARS related publications. Only sporadic research can be found for other fields and even no publications in Arts & Humanities in the first two years SARS outbreak. On the other hand, for COVID-19 related research, all fields have exhibited a persistent contribution of scholarly

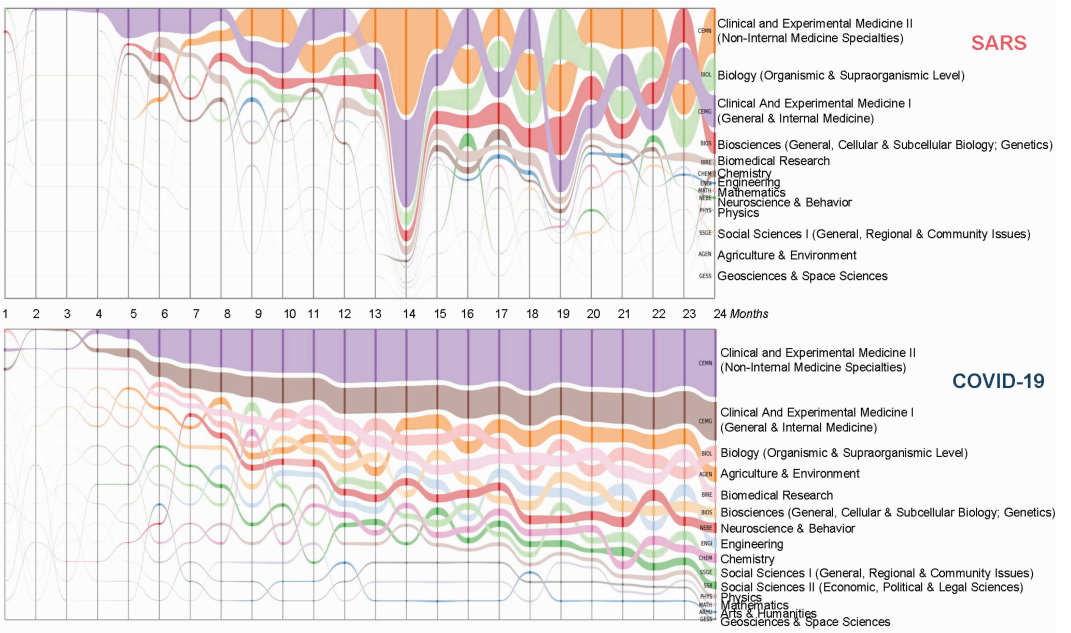


Figure 3 Temporal evolution of SARS and COVID-19 related research from different fields. The first month of SARS-related publications is January 2003, and for COVID-19 is January 2020

publications since the third month. Agriculture & Environment, Engineering, Social Sciences (I & II), and other fields all published a nonnegligible share of publications. Overall, the scientific community responded to COVID-19 in a more widely-engaged and relatively-focused model in which medical fields constitute the core while other fields are also rapidly and actively engaged.

Furthermore, we tried to take a granular look at the differences in research topics in different fields of publications on SARS and COVID-19. To present the results in a simplified way, here we took the six major fields in OECD revised field of science and technology (FOS) as the basis for subject classification. After mapping WoS subject categories to the OECD FOS fields based on the mapping correspondence provided by InCites-Help[4], we created the keywords co-occurrence maps for each OECD FOS field using VOSviewer. Additionally, we manually labelled the topics of each cluster by reviewing the keywords that occurred. The results are presented in Figure 4.

As Figure 4 shows, increasing and more diverse collections of research topics can be found in the COVID-19 related publications in the compassion of that of SARS, especially for non-medical and non-biological branches of science, such as Agricultural Sciences, Social Science, and Arts & Humanities. In addition, the COVID-19 related research from each major field has more intensive connections with their established expertise and research threads such that they are studying the impact of COVID-19 on their own existing research subjects. However, as for responding to SARS, fields with less relevance to the epidemic are merely providing their insights as "external experts" and contributing publications with less discernable disciplinary characteristics. Next, we summarize the topics in SARS and COVID-19 relat-

4 https://incites.help.clarivate.com/Content/Research–Areas/oecd–category–schema.htm

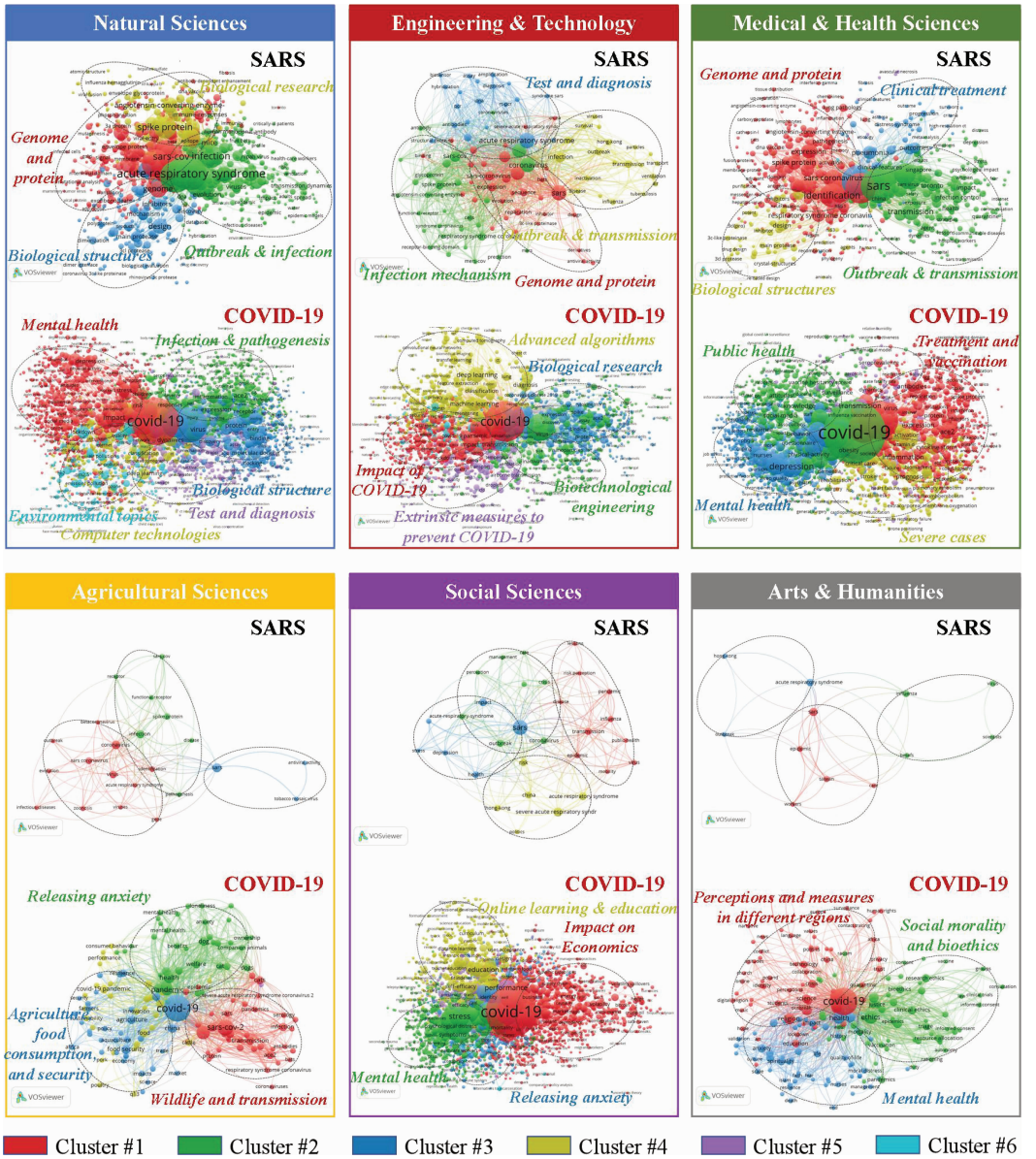


Figure 4 keywords co-occurrence of SARS and COVID-19 related publications in six major fields

ed publications across different major fields.

In *Natural Sciences*, all four clusters generated by SARS related publications are mainly focusing on the outbreak and identification of SARS from biomedical perspective, including cluster #1 (red) about the expression of genome and protein; cluster #2 (green) about the outbreak and evolution of SARS; cluster #3 (blue) about the structures of SARS virus; and cluster #4 (yellow) about the animal experiments on SARS. While in COVID-19 related publications, except for the two clusters similar to SARS, i.e., cluster #2 (green) with keywords like "ACE2", "infection", "pathogenesis", etc., which are mainly related to the research on

COVID-19 itself, and cluster #3 (blue) with keywords like "protein", "molecular docking", "receptor-binding domain", and other biological keywords, which are of great significance in the structure identification of the COVID-19 virus. There are other four new clusters in COVID-19 related publications: cluster #1 (red) with mental health related keywords like "stress", "depression", "physical activity", "depressive symptoms", etc., which mainly result from the lockdown and quarantine environment in facing COVID-19; cluster #4 (yellow) with keywords like "epidemiology", "deep learning", "optimization", "artificial intelligence", and so on, which mainly focuses on the computer technologies applied in the study of COVID-19; cluster #5 (purple) with keywords like "diagnosis", "PCR", and "antibody" etc., is mainly about the test of COVID-19; and cluster #6 is environmental-related topics under the lockdown circumstance.

In *Engineering and Technology*, the four clusters based on SARS related publications are still focusing on SARS from the biomedical perspective similar to clusters generated in Natural Sciences. While in COVID-19 related research, five distinctive clusters can be seen: cluster #1 (red) is about the impact of COVID-19 with keywords like "lockdown", "sustainability", "demand", etc.; cluster #2 (green) is about biotechnological engineering research with keywords like "biosensors", "nanoparticles", "immunoassay", etc.; cluster #3 (blue) is biological research with keywords like "spike protein", "ACE2", "expression", etc.; cluster #4 (yellow) is about advanced algorithms used in the diagnosis and treatment of COVID-19 with keywords like "deep learning", "convolutional neural networks", "feature extraction", etc.; and cluster #5 (purple) is mainly on extrinsic measures to prevent COVID-19 with keywords like "ventilation", "temperature", "aerosol" and so on.

As the backbone in responding to COVID-19, clusters generated based on SARS and COVID-19 related publications in Medical and Health Sciences show great significance. In the SARS co-occurrence network, the four main clusters are also focusing on the transmission, treatment, and biological structures of SARS. While in the COVID-19 network, except for research on the treatment and vaccination of COVID-19 (cluster #1, red), and severe cases related topics with keywords like "pulmonary embolism", "extracorporeal membrane oxygenation", "ECMO", etc. (cluster #4, yellow), public health (cluster #2, green) and psychological issues (cluster #3, blue) are also important research topics in Medical and Health Sciences.

In the other three fields, i.e., Agricultural Sciences, Social Sciences and Arts and Humanities, there are few SARS related publications, and the keywords co-occurrence networks are quite sparse. While in COVID-19 related publications, there are still distinctive clusters in the above three fields:

In *Agricultural Sciences* research, there are four main clusters as follows: cluster #1 (red) is mainly about abductive research related to wildlife and the transmission mechanism; cluster #2 (green) is about pets as an important accompany to release anxiety; cluster #3(blue) and cluster #4 (yellow) are about agriculture, food consumption and security related research under COVID-19.

In *Social Sciences*, the four main clusters are: cluster #1 (red), the impact of COVID-19 on economics, related keywords are "market", "trade", "supply chain", etc.; cluster #2 (green), mental health-related research; cluster #3 (blue), positive approaches related research to help release stress, for example, "communication", "trust", "beliefs", and so on; and cluster #4 (yellow), the emerging of online learning and education.

In *Arts and Humanities*, though publications in this field are relatively few, three main clusters are generated. Cluster #1 (red) is about different perceptions of COVID-19 and related measures undertaken in different regions/countries; cluster #2 (green) is about social morali-

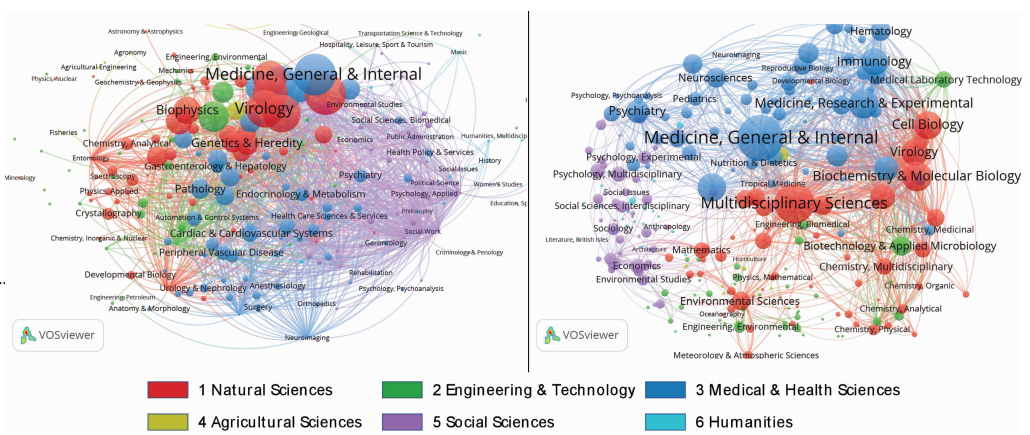
ty and bioethics related issues; and cluster #3 (blue) is about mental health-related studies.

In general, facing the SARS epidemic, relevant studies are mainly concentrated in *Medical and Health Sciences*, *Natural Sciences*, and *Engineering and Technology*, and the research topics are around the diagnosis and treatment of SARS, biological structures of SARS virus, and the transmission mechanisms. While in the study of COVID-19, researchers *from Agricultural Sciences, Social Sciences*, and *Arts & Humanities* also have made significant contributions to defeating the COVID-19 epidemic based on their professionals. More participation from social sciences, humanities and art, and agronomy is observed. At the same time, in addition to medical and biological topics such as diagnosis and treatment of COVID-19, studies on mental health have gained widespread attention from *Medical and Health Sciences, Agricultural Sciences, Social Sciences,* and *Arts and Humanities.*

Interdisciplinarity in the knowledge base

Knowledge base, i.e., references, in the academic literature are an important installation to indicate and acknowledge existing knowledge on which the article builds. Analyzing the disciplinary distributions of references in research articles can detect the sources of referred information and identify the contributions of different disciplines. Emerging from this perspective, reference analysis is probably the most discussed and utilized analytical approach for measuring the interdisciplinarity of different research objectives (Porter et al., 2007; Zhang et al., 2016; Zhang et al., 2018).

After mapping the WoS subject categories of references cited in SARS and COVID-19 publications to the OECD FOS fields, Figure 5 presents the field co-occurrence networks of SARS (Figure 5a) and COVID-19 (Figure 5b) studies, respectively.



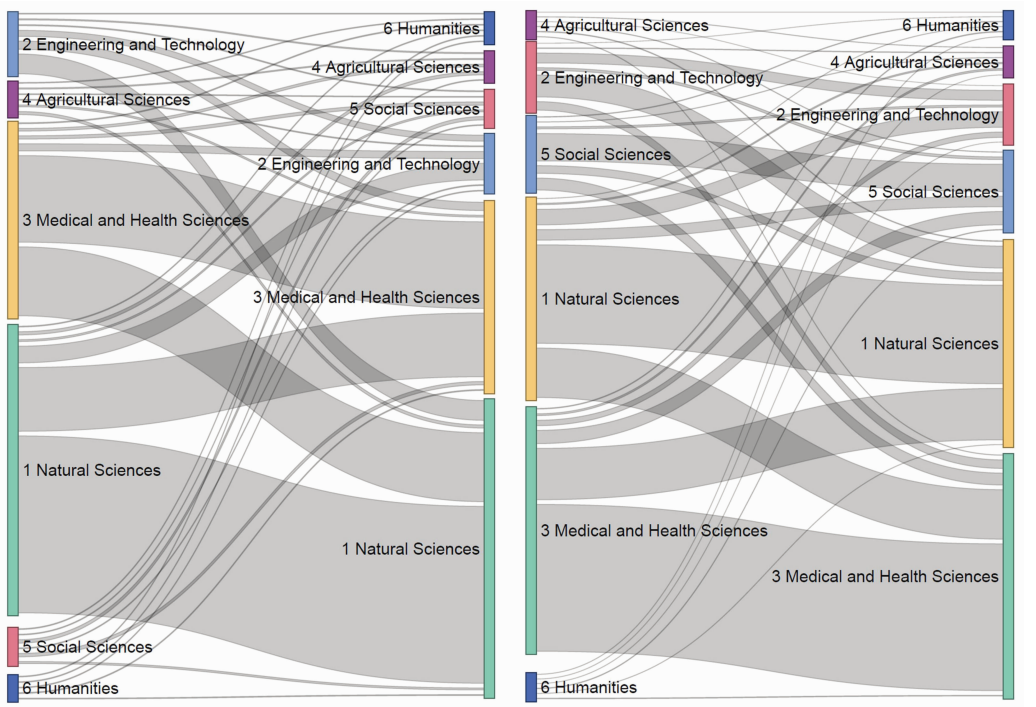
a. SARS b. COVID-19

Figure 5 Field co-occurrence network of references cited by SARS and COVID-19 publications. The networks are generated using VOSviewer with pre-organized pajek files. The size of the nodes indicates the number of cited references, the different colours indicate the OECD FOS major fields, and the lines indicate the co-citation strength of different OECD FOS minor fields.

As shown in Figure 5, except for the clustered distribution in *Natural Sciences* and *Medical & Health Sciences* in terms of references of SARS and COVID-19 publications, *Social Sciences* also play more important roles in the field co-occurrence network of references cited in

COVID-19 publications. Although the links between *Social Sciences* and other fields are very intensive in the network of references cited in SARS publications, the nodes themselves are pretty small. However, in the COVID-19 network, the sizes of *Social Sciences* nodes have increased significantly, which means more Social Sciences papers are cited by COVID-19 related publications.

Next, we demonstrate the inter/intra- disciplinary knowledge flow across different fields, from cited references to focal publications involved in SARS and COVID-19 publications in Figure 6.



a. SARS b. COVID-19

Figure 6 Sankey diagrams of fields from cited references to focal publications (SARS & COVID-19)

Compared with the knowledge flow in the research on SARS, the participation of *Social Sciences* in COVID-19 has increased significantly in both citing and cited directions. On the other hand, both *Natural Sciences* and *Medical & Health Sciences* share large proportions in terms of cited references and focal publications related to SARS and COVID-19. The above two fields have the highest self-citation ratio, and other fields also have a considerable amount of knowledge flowing into the two fields. At the same time, for publications in other fields, references from *Natural Sciences* and *Medical & Health Sciences* also occupy a considerable proportion.

We further calculated two IDR indicators, namely, variety (the number of disciplines) and integrated diversity (using the TD indicator), to quantify the interdisciplinarity in the knowledge base. Considering the differences in terms of publication, citation, collaboration, etc. across different fields, we present the IDR values and their temporal evolution of different OECD FOS fields in Figure 7. For SARS related publications with an extended period, the re-

sults are shown by year on the left, while COVID-19 results are presented by month on the right.

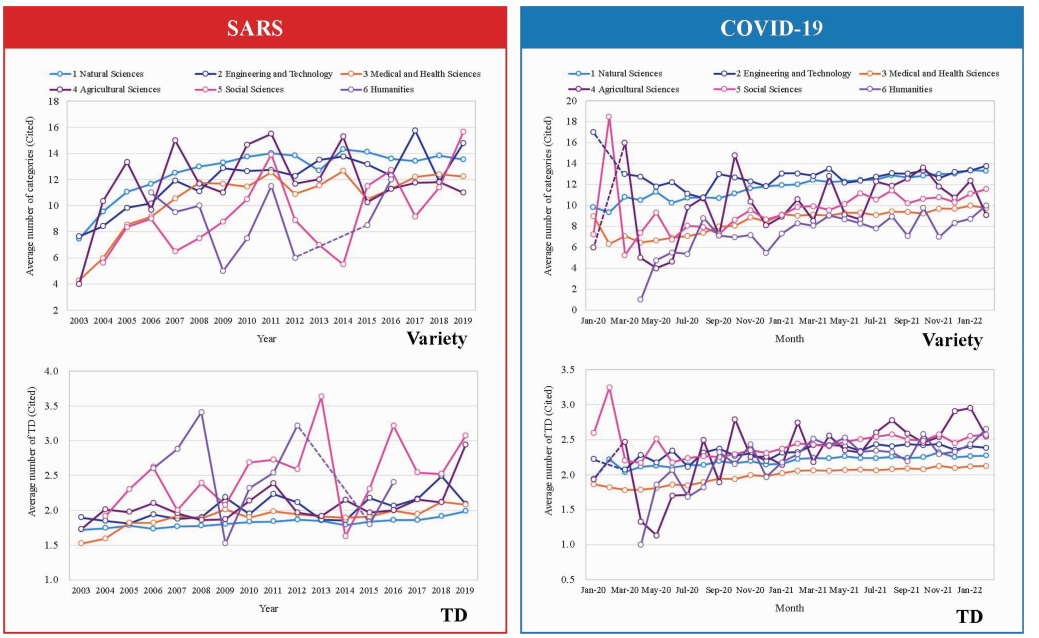


Figure 7 Dynamic IDR indicators of SARS and COVID-19 publications (reference perspective). Dashed lines indicate that there is no publication in the year or month between the two nodes in the corresponding field.

Firstly, the interdisciplinarity of COVID-19 publications in terms of cited references is significantly higher than that of SARS. In the early stage of the SARS pandemic, the number of subjects (disciplines) involved in the references of SARS publications is less than 8 on average, while in COVID-19 research, most of the cited references are from more than 10 disciplines on average. In addition, the integrated diversity of SARS publications is less than 2 in the first two years, while they are almost above 2 in COVID-19 research.

On the other hand, regardless of SARS and COVID-19, both *variety* and the integrated diversity TD show an increasing trend in general. It should be noted that the significant fluctuation of IDR values in the fields of *Agricultural Sciences, Social Sciences, and Humanities* is mainly because of the small sample size of these fields. Therefore, when taking the mean as a representation of such a group, it can be easily affected by extreme values.

Another interesting point is that the number of cited categories in *Natural Sciences* is relatively higher than that in other fields. Still, the average value of the integrated diversity TD is at a lower level among the six OECD FOS fields. The main reason is that, on the one hand, the subject categories of cited references in *Natural Sciences* are neighbouring categories with relatively close distances; on the other hand, whether the distribution of different cited categories is even or not also affects the integrated diversity, i.e., balance (Nijssen et al., 1998) and disparity (Zhang et al., 2018).

Interdisciplinarity in research collaborations

Figure 8 presents several aspects of research collaborations in publications on SARS and

COVID-19 such as the number of authors, the number of affiliations, and the number of countries over time.

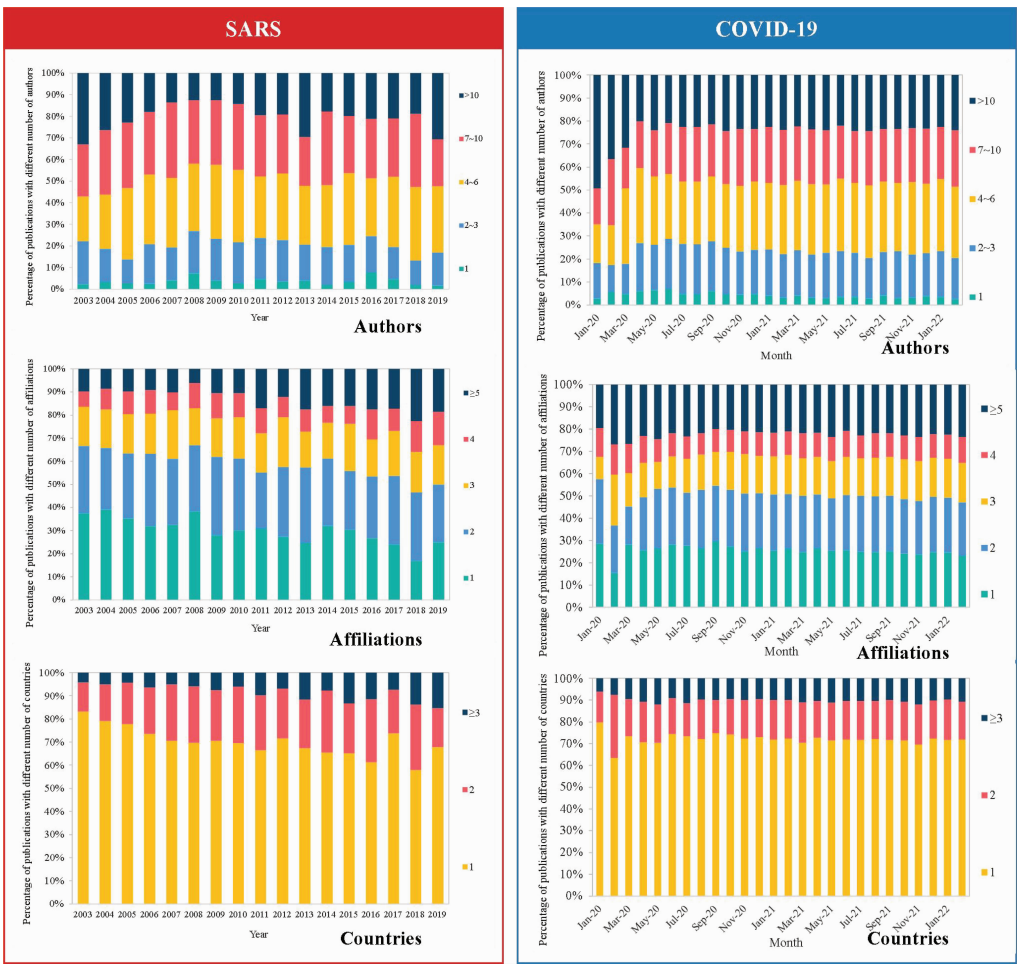
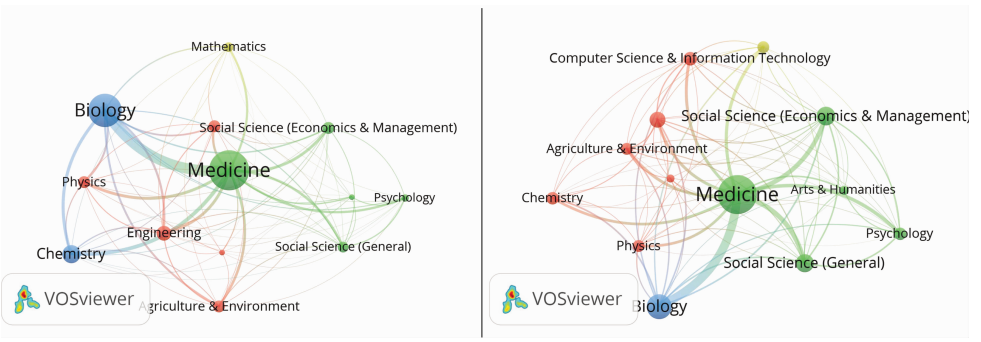


Figure 8 The distribution of individual publications according to the number of authors, the number of affiliations and the number of countries over time

What can be seen first is that the proportion of single-authored publications is the lowest both on SARS and COVID-19. Then, the proportion of large-scale collaborative publications (more than 10 authors) shows a clear declining trend as the epidemic evolves. Throughout the research of SARS over 18 years, we can observe decreasing trends in the proportions of large-scale collaborative publications in terms of the number of affiliations and countries. Based on the above conclusions, we argue that in the early stage of the different pandemics, academia usually builds large-scale teams (i.e., the number of authors) within their familiar environment (the proportion of publications affiliated to the same affiliation). As time went on, the epidemic was relatively contained, and related research is gradually matured, the number of authors in each publication decreases. At the same time, researchers have more energy to conduct in-depth research with collaborators from other affiliations and even other countries. As shown in Figure 8, the proportions of multi-affiliation collaborative publications and international collaborative publications increase gradually.

Based on the disciplines extracted from the author's affiliations, we present the cross-disciplinary collaboration networks of SARS and COVID-19 publications in Figure 9. Compared to SARS, the cross-disciplinary collaboration network of COVID-19 publications is much more intensive. Firstly, *Biology* and *Medicine* play critical roles in SARS and COVID-19 collaboration networks, and the two disciplines show the closest collaboration. At the same time, the status of *Social Sciences* (*General and Economics & Management*), *Computer Science & Information Technology*, and *Arts & Humanities* in the collaboration network have substantially improved. This phenomenon was also observed in Fry et al. (2020): research publications produced in the first months of the COVID-19 pandemic show that COVID-19 research involved fewer nations than pre-COVID-19 coronavirus research.



a. SARS b. COVID-19

Figure 9 The network visualization of authors' affiliation disciplines (SARS & COVID-19)

Furthermore, we also calculate the IDR indicators, i.e., *variety* and the integrated indicator *TD*, based on the disciplines extracted from author affiliations. The results are presented in Figure 10 in terms of different OECD FOS fields over time.

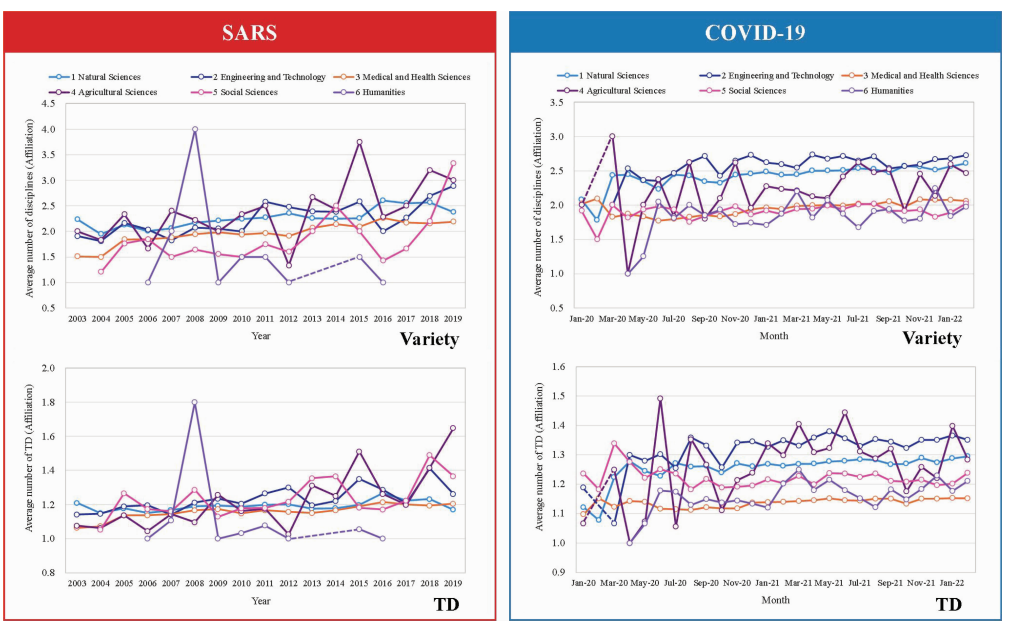


Figure 10 The interdisciplinarity in research collaboration measured by two IDR indicators using author affiliation information

Similar to the results in the interdisciplinarity of knowledge base, the interdisciplinarity of COVID-19 publications in terms of affiliation information is also relatively higher than that of SARS in the first two years of the two pandemics. Furthermore, a general increasing trend is also observed for variety and the integrated diversity TD with SARS and COVID-19 publications over time. The differences in interdisciplinarity among each field are in line with that shown in Figure 8. However, what can be seen is that the value of each IDR indicator calculated based on the disciplines of author affiliations is much lower than the same indicator calculated based on the subject categories of cited references. It is mainly caused by the different granularity of two classification schemes, i.e., 254 subject categories of cited references and 13 disciplines recognized from the address information.

Conclusion and discussion

Interdisciplinary research plays a vital role in tackling grand and complex challenges such as COVID-19 that have severe consequences for public health, economy, politics, and society. Multidisciplinary efforts and interdisciplinary collaborations provide the scientific society with the necessary intellectual synergy and novelty to contribute rapid solutions to address urgent needs. However, it remains unknown whether IDR has grown or improved in facing another global pandemic. This study compares several facets of interdisciplinarity that occurred in the research relating to two serious global pandemics in this century, namely SARS and COVID-19, and provides a comprehensive summary of the performance and growth of pandemic-related interdisciplinary research. We focus on three aspects of interdisciplinarity in pandemic-related publications: multidisciplinarity in scholarly outputs, interdisciplinarity in knowledge base, and interdisciplinarity in scientific collaboration.

Our analyses show that the scientific community gathers more multidisciplinary efforts to tackle COVID-19 in comparison to SARS, marked by greater and faster participation from non-medical disciplines such as *Social Science, Computer Sciences and Engineering, Management, Agriculture & Environment,* etc. In addition, COVID-19 related research from each major field has greater connections with their established expertise and research threads such that they are studying the impact of COVID-19 on their own existing research subjects, while the studies of SARS by different disciplines exhibit less discernable disciplinary characteristics. As for the interdisciplinarity observed in the knowledge base of pandemic-related publications, we observe a greater presence of social science knowledge and a more dispersed distribution of knowledge from various disciplines comparing publications on COVID-19 with SARS. In addition, the interdisciplinarity in knowledge base for COVID-19 publications is higher than that of SARS on average for most disciplines. In the early stage of the pandemic, COVID-19 related publications cite knowledge from 10 disciplines on average, while that of SARS is 8. Regarding interdisciplinarity in research collaboration, COVID-19 publications are, on average, produced by a relatively more interdisciplinary team than SARS, as measured by the number and diversity of affiliated disciplines of authors. A common characteristic that applies on the research collaboration for both COVID-19 and SARS is that academia usually builds large-scale teams (i.e., the number of authors) within their familiar environment (the proportion of publications affiliated to the same affiliation) at the early stage of pandemics. The size of collaborations decreased over time as the epidemic was relatively contained and related research gradually matured.

Our discovery of the growth of multidisciplinarity and interdisciplinarity in pandemic-related research signals positive achievement that the scientific community make in responding

to such a global challenge as a whole and is willing to break down existing disciplinary silos to facilitate the flow of knowledge and breed novelty. However, we should also keep in mind that IDR has become increasingly central to both academic interest and government science policies. Larivière and Gingras (2014) reported that since the mid-1980s, research papers have increasingly cited work outside their own disciplines. Discourse about IDR is also increasing dramatically. Various national and international programmes, focusing especially on promoting IDR, have been launched and developed in many countries through specialized research funding and grants or through staff allocations (Okamura, 2019).

On the other hand, medicine has a long history of drawing on other disciplines to make significant advances in clinical care (Smye & Frangi, 2021). Examples of clinical advances driven by disciplines other than medicine abound. For example, many techniques and technologies which underpin modern clinical imaging originated in the physics laboratory. The impressive advances in microscopy, which have been central to our understanding of biology, were driven in part by advances in physics and the demands of materials scientists.

The COVID-19 pandemic has caused millions of people to be ill and led to millions of deaths worldwide. This public health emergency has affected everyone's life and well-being. Through the suffering, however, there is one silver lining: for the first time in many decades, the COVID-19 pandemic has also provided motivation for varied disciplines and professions to come together and put up a united front against this crisis. Gibney (2020) reported that thousands of researchers have quickly jumped into studying coronavirus. Governments also alter their funding patterns as a result of the pandemic. Cohut (2021) summarized the interdisciplinary approaches established and fostered throughout the pandemic from the perspective of vaccine development, clinical settings, and the addressing of COVID-19's social 'side effects' – mental health resulted from numerous lockdowns and travel restrictions across the world.

Therefore, it is not just the medical sector alone that will carry us through COVID-19 and beyond, but the integration of the sociological, environmental, psychological, and political insights as well. Nonetheless, a vital question lingers: whether or not the progress in establishing and fostering interdisciplinary approaches that researchers and healthcare workers have made throughout the pandemic will persist beyond this public health crisis. We would argue there is still a long way to go. For example, although collaborative research has been intensifying during the pandemic, it also happens that they pull and push in different directions which will result in unnecessary tensions and clashes. Furthermore, IDR is known to suffer from greater communication costs, greater ambiguity in quality standards and wider epistemic gaps. With the outline of what the coexistence of disciplinary paradigms amounts to in the case of COVID-19, Mol and Hardon (2020) illustrated that interdisciplinarity should not be treated as a matter of adding the pieces of a puzzle together, but rather as a mediation process in which no discipline has to submit to either object definitions or criteria for good research of any other. Such barriers could slow down the production, evaluation, and dissemination of IDR and impede the early intervention of pandemic outbreaks.

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