Patterns of the Network of Cross-Border University Research Collaboration in the Guangdong-Hong Kong-Macau Greater Bay Area

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Abstract: This study analyzes the patterns of university co-authorship networks in the Guangdong-Hong Kong-Macau Greater Bay Area. It also examines the quality and subject distribution of co-authored articles within these networks. Social network analysis is used to outline the structure and evolution of the networks that have produced co-authored articles at universities in the Greater Bay Area from 2014 to 2018, at both regional and institutional levels. Field-weighted citation impact (FWCI) is used to analyze the quality and citation impact of co-authored articles in different subject fields. The findings of the study reveal that university co-authorship networks in the Greater Bay Area are still dispersed, and their disciplinary development is unbalanced. The study also finds that, while the research areas covered by high-quality co-authored articles fit the strategic needs of technological innovation and industrial distribution in the Greater Bay Area, high-quality research collaboration in the humanities and social sciences is insufficient.

Keywords: Guangdong-Hong Kong-Macau Greater Bay Area; cross-border research collaboration; university co-authorship network

1. Introduction

China’s 2017 government work report stated, “We will promote closer collaboration between the mainland and Hong Kong and Macau. We will draw up a plan for the development of a city cluster in the Guangdong-Hong Kong-Macau Greater Bay Area, give full play to the distinctive strengths of Hong Kong and Macau, and elevate their positions and roles in China’s economic development and opening up.” Since then, the construction of the Guangdong-Hong Kong-Macau Greater Bay Area (hereinafter referred to as “the Greater Bay Area”) has become a major national strategy [1]. The Greater Bay Area refers to the urban agglomeration formed in the Pearl River Estuary bay area by Guangzhou, Foshan, Zhaoqing, Shenzhen, Dongguan, Huizhou, Zhuhai, Zhongshan, and Jiangmen, along with the two special administrative regions of Hong Kong and Macau [2,3].

On 18 February 2019, the Development Plan for the Guangdong-Hong Kong-Macau Greater Bay Area was promulgated and proposed to “promote the cooperative development of education”, which set the tone for the integrated development of education in the Greater Bay Area [2,4]. On 5 July 2019, Guangdong Province officially issued “The Opinions on the Implementation of Outline Development Plan for the Guangdong-Hong Kong-Macao Greater Bay Area” (hereinafter referred to as the “Implementation Opinions”). The Implementation Opinions put forward the key objective of building an international science and technology innovation center in the Greater Bay Area. In addition,
a range of specific measures was proposed to create a research collaboration platform in the Greater Bay Area, including plans for joint research centers and laboratories in key areas [5]. The promulgation of the Implementation Opinions was an important measure undertaken by the government to further coordinate research collaboration among the three regions.

Research collaboration between universities in the Greater Bay Area has been long well established, and article co-authorship has been the most commonly adopted collaborative form [6,7]. Research collaboration has been proven to be at the kernel of science strategy for both individual scientists and institutions [8–10]. It is significant for the research productivity of scientists [8,10], the impact of publications [11,12], and the innovation of enterprises and universities [13–15]. Analyzing article co-authorship has become one of the standard methods of measuring research collaboration between institutions [16–19], given the advantages of its verifiability, data availability, stability over time and ease of measurement [20]. Even though article co-authorship has been regarded as no more than a partial indicator of collaboration [20] and can only indicate the achievement of informal research collaborations [21], it can be regarded as successful research collaboration between institutions as it can demonstrate substantive proliferation of knowledge and technology [21].

As policy incentives have been initiated to facilitate higher education regionalization in the Area, the regional flow of research resources has sped up. As a result, the scale of research collaboration between universities has expanded, and the quantity and quality of article co-authorship between universities has increased [22]. Meanwhile, in the era of globalization, the global flow of research resources has also sped up along with the development of information and communication technology [9,23]. One of the consequences is that research collaboration in the form of co-authored articles has become increasingly prevalent [9,24,25], and the global number of co-authored articles has grown exponentially [26–28].

This phenomenon is also emerging in China, where the exponentially growing number of co-authored articles that has arisen from research collaboration in China has been examined by a number of bibliometric studies [29–34]. In addition, a growing body of empirical literature has shown that China’s scientific knowledge creation has become increasingly dependent on international and cross-border research collaboration, and that co-authored publications have become the most adopted collaborative method [23,27,32,35–43]. It has also been proven that international and cross-border authorship increases China’s overall citation impact [34,37], which implies that international and cross-border co-authorship has improved the international academic community’s perception of Chinese publications [34].

Several empirical studies published in the Chinese language have used social network analysis methods to reveal the features or evolution of the article co-authorship networks of Chinese universities in different geographic ranges: Li [44] drew an article co-authorship network map of 26 universities in the Beijing-Tianjin-Hebei region from 2008 to 2017; Zhang [45] paid close attention to 19 universities in Tianjin; and Wang and Ni [46] analyzed the status of article co-authorship in Fujian’s undergraduate-level universities.

Despite all the aforementioned empirical studies adopting article co-authorship as a key measurement indicator to analyze patterns of university research collaboration, we have not found any empirical attempts to explore the patterns of cross-border article co-authorship networks among universities of the Greater Bay Area. To address this research gap, this study analyzed the networks of co-authored articles in 34 research universities in the Greater Bay Area from 2014 to 2018. The social network analysis and the index of field-weighted citation impact (FWCI) were used to analyze and compare the quality of co-authored articles in different disciplines, and to outline the structure of the co-authored article network among universities in the Greater Bay Area at both regional and institutional levels.

On the practical front, since 2017, the construction of the Greater Bay Area has become a major national strategy. Study on the patterns of article co-authorship networks in the Area can provide policy implications on facilitating research collaborations among three regions in the Area. Furthermore,
university research collaborations are beneficial for talent flow within the Area; understanding the patterns of research collaborations is useful for policymakers to consider policy-making for talent cooperation and circulation within the Area. The institutional environment of the Greater Bay Area for talent flow is unique and more complicated than that in other international bay areas, as the Greater Bay Area steps across three customs zones involving different administrative and legal systems [2].

2. Materials and Methods

2.1. Research Methods

The essence of co-authorship network analysis is the application of social network analysis to the field of scientific measurement. Scientific papers are taken as the research object, by describing and analyzing the relationship between which the characteristics of knowledge creation activities are interpreted [47]. Firstly, this study used the method of “social network analysis” to describe the evolution of the article co-authorship network in the universities of the Greater Bay Area. Currently, social network analysis is divided into two research levels: regional network analysis and institutional network analysis. Regional network analysis studies the relationships and interaction between all individuals within an organization, pays attention to measuring the structural characteristics of the network, and generally uses indicators such as network density and central potential. Institutional network analysis mainly studies individual-centered networks or social relations, focusing on the analysis of individual network attributes, and indicators such as centrality and structural holes [48]. Starting from the subordinate units (universities) of the authors, this study explores the evolution of the overall network of article co-authorship in the Greater Bay Area. It mainly focuses on three indicators: network density, network centralization, and network cooperation frequency. Furthermore, this paper quantitatively analyzes the evolution of the characteristics of individual centrality and structural holes in the networks of research collaborations between universities in the Greater Bay Area. We adopt indicators from double-layer networks (“regional network” and “institutional network”) to make a more precise and distinct detection of the structure of research collaboration networks in the Greater Bay Area. The specific indicator description and calculation methods used are shown in Table 1.

In order to describe the evolution of the article co-authorship network of institutions in the Greater Bay Area more clearly and stereoscopically, this paper also explores the quality of co-authored articles in the networks. We applied the FWCI index to measure the quality of individually authored/co-authored articles from various institutions in the Greater Bay Area in 2014 and 2018, respectively, to identify the impact mode and change trend of scientific research cooperation among these institutions in terms of the quality of their papers.

Finally, this paper analyzes the hot research topics of high-quality papers co-authored at higher education research institutions in the Greater Bay Area. To account for the differences in disciplines, the processed data set was first divided into five major disciplines, i.e. economy/management, medicine, agronomy, engineering, and science. Based on the FWCI values, the top 30% of the papers in each major discipline were selected as analysis samples. VOSviewer software was used to analyze the keyword co-occurrence network of papers in the five disciplines, respectively, so as to obtain a list of the high-frequency research topics in the high-quality co-authored articles in each discipline.
Table 1. Meaning and calculation formula of network characteristic indexes analyzed in this paper.

| Research Object | Index                | Index Meaning                                                                 | Index Calculation Method                                      |
|-----------------|----------------------|-------------------------------------------------------------------------------|----------------------------------------------------------------|
|                 | Network density (ρ)  | This index shows how close the inter-institution connections in Guangdong and  | In a network containing N institutions, the ratio of the actual   |
|                 |                      |                  and Hong Kong, Guangdong and Macau, Hong Kong and Macau, Guangdong      | number of connections L for institutions to the theoretical       |
|                 |                      |                  and Hong Kong, and Macau and other regions.                          | maximum possible value: ρ = L / [N(N-1)]                          |
|                 | Regional network     | This index reflects the gap between the influence of the universities with the |                                                                            |
|                 |                      |                  strongest influence and other institutions in Guangdong and Hong    |                                                                            |
|                 |                      |                  Kong, Guangdong and Macau, and Hong Kong and Macau.                  |                                                                            |
|                 |                      |                  The higher network centralization is, the more concentrated the    |                                                                            |
|                 |                      |                  article co-authorship in this region is, and the fewer institutions |                                                                            |
|                 |                      |                  co-authorship relies on [50].                                        |                                                                            |
|                 |                      | This index depicts the number and frequency of instances of paper cooperation | NetDraw software can directly count the number of instances of     |
|                 | Number of links (L)  |                  and exchange among institutions in Guangdong and Hong Kong,      | cooperation between institutions in the network.                 |
|                 |                      |                  Guangdong and Macau, and Hong Kong and Macau.                    |                                                                            |
|                 | Degree centrality (DC)| This index measures the importance of individual institutions in the network; | The normalized centrality index of institution i is the ratio of    |
|                 |                      |                  a high degree of centrality indicates that this institute has      | the number of other institutions connected to institution i in the |
|                 |                      |                  had more co-authored articles in the Greater Bay Area network [51].| network to the maximum possible degree k_i:                      |
|                 |                      |                  NetDraw software can directly count the number of instances of     | DC_i = df / L_max                                                  |
|                 | Structural hole (SH) | This index describes an institution that only has direct cooperative         | The structural hole index of institution i is the sum of the       |
|                 |                      |                  connections with some other institutions but is indirectly        | difference between the number of connections L_i and the          |
|                 |                      |                  connected or completely isolated from other institutions.         | network distance D_ijk between institution i and all neighboring   |
|                 |                      |                  A structural hole occupies the position between institutions     | institutions in the network V_i:                                 |
|                 |                      |                  without a cooperative relationship [52].                         | SH_i = ∑_{j∈E}(L_i,j - D_ijk)                                      |

2.2. Data Source

Using the Scopus database developed by Elsevier as the data source, and disciplines as the basis of their search, the researchers exported the title information of scientific papers published by higher education research institutions in the Guangdong-Hong Kong-Macau Greater Bay Area from 2014 to 2018 and obtained title information from 77 disciplines. However, since this study derived title information based on discipline division, and the same scientific paper might involve different disciplines, the title information for each interdisciplinary paper was merged into one piece of datum. Secondly, because this study focused on papers co-authored at higher education research institutions in the Greater Bay Area, subordinate units outside this Area were excluded. After the above operations, 241,926 scientific papers were finally obtained.

2.3. Data Coding

This study aimed to explore the overall network of scientific papers co-authored by researchers in Guangdong and Hong Kong, Guangdong and Macau, Hong Kong and Macau, and all three regions together, as well as the evolution of the location of individual higher education institution in the network from 2014 to 2018. The first step in the study involved processing and encoding the data. First of all, the title information for all co-authored articles was screened based on the location of the co-authors and categorized into one of the regional pairings (or the three-region category) listed above. Secondly, BibExcel software was used to calculate the frequency of co-authored articles co-occurring in each region in each year (i.e., the number of times that the same researchers co-authored together),
and the co-authorship network matrix was sorted to complete the transformation of relational data. Finally, Ucinet software was used to calculate the overall network characteristics, such as the number of times cooperation had occurred, the network density, and the potential network center for each article co-authorship network, as well as to calculate the individual network characteristics such as the centrality and structural holes of each university.

3. Results

Figure 1 presents the structure of the comprehensive collaboration network in the Greater Bay Area from 2014 to 2018, with 35 nodes and 1552 links. In this network, each node represents a university, the color of a node demonstrates the location of a university, the size of a node represents the degree of centrality of a university, and the width of the link indicates the number of papers co-authored between two universities. Clearly, the number of papers co-authored between universities and regions varied greatly: there were more collaborations between universities located in Guangdong and Hong Kong, such as Sun Yat-Sen University, Shenzhen University, the University of Hong Kong, and the Chinese University of Hong Kong. However, universities located in Macau generally had fewer collaborations with universities in Hong Kong and Guangdong.

Figure 1. Structure of university collaboration networks in the Greater Bay Area, 2014–2018.

3.1. Analysis of Overall Network Evolution

3.1.1. Evolution of Network Connections and Network Density

Figures 2 and 3 reflect the evolution of the overall level of the article co-authorship network in the Greater Bay Area, based on the change trend in the number of network connections and the network density. With the overall stability of the higher education institutions (network nodes) participating in the article co-authorship network, the number of co-authorship network connections between any two regions (and among all three regions) in the Greater Bay Area increased significantly from 2015 to 2016. The number of co-authorship connections among Guangdong, Macau, and Hong Kong increased by 54, between Guangdong and Macau increased from 372 to 426, and between Guangdong and Hong Kong increased from 596 to 650. The network density increased accordingly. This shows that higher education institutions in the Greater Bay Area expanded their regional cooperation on papers that year. From 2016
to 2017, there was no obvious change in the co-authorship connections between the three regions. The overall number of connections among Guangdong, Hong Kong, and Macau remained unchanged. The number of connections between Guangdong and Hong Kong decreased from 650 to 628, but the network density maintained growth, from 0.17 to 0.20, with a growth rate of 17.65%. This shows that, although the number of connections decreased, the intensity of cooperation between higher education institutions in Guangdong and Hong Kong continuously increased, and the scientific research cooperation relationship between these higher education institutions became increasingly close.

![Figure 2](image-url)  
**Figure 2.** Evolution of the number of papers co-authored within the network of higher education institutions in the Greater Bay Area, from 2014 to 2018.

![Figure 3](image-url)  
**Figure 3.** Evolution of the network density of article co-authorship among the universities in the Greater Bay Area, from 2014 to 2018.

After steady growth in the previous year, 2017 marked the start of considerable year-by-year increases in the number of network connections among Guangdong, Hong Kong, and Macau and between any two of these regions. The number of connections between Guangdong and Macau increased from 430 to 476, and that between Guangdong and Hong Kong soared from 628 to 710—a considerable increase. The number of connections between Hong Kong and Macau also increased from 110 to 114, while the connections in the overall network among Guangdong, Hong Kong, and Macau increased by 86. The network density also increased in varying degrees. The value added to the overall density of the network among Guangdong, Hong Kong, and Macau was 0.04, with a growth rate of 25%. The value added to the density of the network between Guangdong and Hong Kong was 0.05,
with a growth rate of 25%. The value added to the density of the network between Guangdong and Macau was 0.04, with a growth rate of 30.77%. The least significant increase was 0.02 in the density of the network between Hong Kong and Macau, which lagged relatively behind with a growth rate of 6.45%.

If we look at the node strength of the co-authored articles in the Greater Bay Area from 2014 to 2018, we can see that the number of papers co-authored among the higher education institutions in the three regions continuously increased. The increase in the number and density of network connections from 2017 to 2018 is particularly notable, and the growth rate in that year was significantly higher than that in previous years.

3.1.2. Evolution of Degree of Centralization

As can be seen from Figure 4, the centralization of the overall network of article co-authorship among universities in the Greater Bay Area experienced a significant decline from 2014 to 2015 and from 2015 to 2016, and then showed a steady and slight upward trend until 2018. If we look at the overall network centralization amongst Guangdong, Hong Kong, and Macau, we can see that the centralization of the co-authorship network between Guangdong and Macau dropped from 0.26 to 0.21 in 2015, but remained higher than that of the Guangdong-Hong Kong network and that of the overall network between the three regions; the network between Hong Kong and Macau matched its degree of centralization at 0.21 in 2015. However, it can be seen from the figure that, by 2018, the centralization of the network between Guangdong and Hong Kong had surpassed the centralization of the Hong Kong-Macau co-authorship network and reached 0.22, alongside the Guangdong-Macau network, which shows that Guangdong’s higher education institutions have been increasing their influence in the overall co-authorship network in the Greater Bay Area.

![Figure 4. Evolution of network centralization of article co-authorship among universities in the Greater Bay Area, from 2014 to 2018.](image)

3.2. Analysis of the Evolution of the Role and Position of Individual Universities in the Network

3.2.1. Evolution of the Degree of Centrality Ranking

The top 10 higher education institutions in terms of node degree of centrality from 2014 to 2018 are shown in Table 2. High degrees of centrality indicate that those higher education institutions had more co-authored articles in the Greater Bay Area network. During that period, the number of Hong Kong higher education institutions among the top ten dropped from six to five, and their centrality ranking showed a downward trend. The centrality ranking of higher education institutions in Guangdong changed to varying degrees (except for that of Sun Yat-Sen University, which always maintained the first place): for example, South China University of Technology rose from 4th in 2014 to 2nd in 2018;
Shenzhen University rose from 12th in 2014 to 7th in 2018; Guangzhou Medical University replaced Southern Medical University to enter the top 10 in 2017 and rose to 8th in 2018. In the past five years, Macau’s higher education institutions have not been found in the top 10, but the centrality rankings of the University of Macau and the Macau University of Science and Technology have slightly improved, rising from 15th and 22nd in 2014 to 13th and 21st in 2018, respectively, reflecting the increasing trend in the number of papers co-authored in Macau’s higher education institutions.

**Table 2.** Top 10 higher education institutions by degree of centrality, from 2014 to 2018.

| Year | 2014          | 2015          | 2016          | 2017          | 2018          |
|------|---------------|---------------|---------------|---------------|---------------|
| 1    | Sun Yat-Sen University | Sun Yat-Sen University | Sun Yat-Sen University | Sun Yat-Sen University | Sun Yat-Sen University |
| 2    | Chinese University of Hong Kong | University of Hong Kong | University of Hong Kong | University of Hong Kong | South China University of Technology |
| 3    | University of Hong Kong | Chinese University of Hong Kong | Chinese University of Hong Kong | Chinese University of Hong Kong | Chinese University of Hong Kong |
| 4    | South China University of Technology | South China University of Technology | South China University of Technology | South China University of Technology | University of Hong Kong |
| 5    | Hong Kong Polytechnic University | Hong Kong Polytechnic University | Hong Kong Polytechnic University | Hong Kong Polytechnic University | Hong Kong Polytechnic University |
| 6    | City University of Hong Kong | City University of Science and Technology | Hong Kong University of Science and Technology | Jinan University | Jinan University |
| 7    | Jinan University | Jinan University | Jinan University | Shenzhen University | Shenzhen University |
| 8    | Hong Kong University of Science and Technology | City University of Hong Kong | City University of Hong Kong | Hong Kong University of Science and Technology | Guangzhou Medical University |
| 9    | Southern Medical University | Shenzhen University | Shenzhen University | City University of Hong Kong | Hong Kong University of Science and Technology |
| 10   | Hong Kong Baptist University | Southern Medical University | Southern Medical University | Guangzhou Medical University | City University of Hong Kong |

Figure 5 further shows the change ratio of the centrality of each university in 2018 compared with 2014. Higher education institutions are arranged from left to right according to their degree of centrality in 2018. Among them, the higher education institutions with a growth rate of more than 10% in their degree centrality included Shenzhen University, Guangdong University of Technology, the University of Macau, Southern University of Science and Technology, the Foshan Institute of Science and Technology, Guangdong Medical University, Wuyi University, and Macau University of San Norse. Higher education institutions with a drop of more than 10% included City University of Hong Kong, Hong Kong Baptist University, Guangdong Pharmaceutical University, Guangdong University of Foreign Studies, Hong Kong Lingnan University, and Guangdong Ocean University. If we look at the types of higher education institutions within this figure, we can see that the degree of centrality of higher
education institutions specializing in science and engineering increased significantly, while that of higher education institutions specializing in the humanities and social sciences, agriculture, and normal education decreased. This change trend shows that scientific research cooperation between higher education institutions in the Greater Bay Area was mostly concentrated in the fields of engineering, science, and medicine from 2014 to 2018.

![Figure 5](image-url)

**Figure 5.** Changes in the degree of network centrality of higher education institutions (note: the data related to co-authored articles at the City University of Macau were missing in 2014.).

3.2.2. Evolution of the Structural Hole Ranking

The top 10 higher education institutions ranked in terms of the structural holes in the network that were related to these institutions from 2014 to 2018 are shown in Table 3. The ranking and regional distribution of these top 10 higher education institutions are different from those in the degree of centrality ranking. A high degree of centrality indicates that nodes had more co-authored articles in the network, while a high structural hole ranking indicates that node’s ability to act as the medium for a non-repetitive relationship within the network. In other words, the higher an institution’s ranking for structural holes, the more irreplaceable the school was in the network of co-authored articles: scientific research cooperation between other higher education institutions needed to be formed through that school. According to Table 3, with the exception of Sun Yat-Sen University and South China University of Technology, which were firmly in the top two spots for five years, the rankings of other higher education institutions fluctuated and evolved in varying ways. If we look at the types of higher education institutions with high structural hole rankings, we find that comprehensive higher education institutions and science and engineering higher education institutions had higher rankings, while professional higher education institutions had lower rankings. Among the institutions, the rankings of the University of Macau and Shenzhen University rose most prominently, from 12th and 15th in 2014 to 3rd and 4th, respectively, in 2018. On the other hand, if we look at the regional distribution of higher education institutions, we can see that the top 10 higher education institutions in 2014 were distributed in Guangzhou and Hong Kong, while in 2018 such higher education institutions were distributed in Guangzhou, Macau, Hong Kong, Shenzhen, and Shantou, and the distribution of the higher education institutions in all regions was more balanced.
Table 3. Top 10 higher education institutions related to structural holes, from 2014 to 2018.

| Year | 2014              | 2015              | 2016              | 2017              | 2018              |
|------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Ranking | Institution                                             | Institution                                             | Institution                                             | Institution                                             | Institution                                             |
| 1     | Sun Yat-Sen University                                   | Sun Yat-Sen University                                   | Sun Yat-Sen University                                   | Sun Yat-Sen University                                   | Sun Yat-Sen University                                   |
| 2     | South China University of Technology                      | South China University of Technology                      | South China University of Technology                      | South China University of Technology                      | South China University of Technology                      |
| 3     | Chinese University of Hong Kong                          | South China Normal University                             | Jinan University                                          | University of Macau                                         | University of Macau                                         |
| 4     | Jinan University                                           | Jinan University                                           | South China Normal University                             | Jinan University                                          | Shenzhen University                                       |
| 5     | University of Hong Kong                                   | University of Hong Kong                                   | Guangdong University of Technology                        | Shenzhen University                                       | Guangdong University of Technology                        |
| 6     | Hong Kong University of Science and Technology             | Chinese University of Hong Kong                           | University of Macau                                         | Guangdong University of Technology                        | Jinan University                                           |
| 7     | Hong Kong Polytechnic University                          | Macau University of Science and Technology                | Hong Kong Polytechnic University                         | South China Normal University                             | Macau University of Science and Technology                |
| 8     | Hong Kong Polytechnic University                          | Hong Kong Polytechnic University                          | Shenzhen University                                       | University of Hong Kong                                    | South China Normal University                             |
| 9     | Guangdong University of Technology                        | University of Macau                                         | Hong Kong Baptist University                              | Macau University of Science and Technology                | Hong Kong Polytechnic University                          |
| 10    | South China Normal University                             | Guangdong University of Technology                        | Macau University of Science and Technology                | Chinese University of Hong Kong                           | Shantou University                                         |

3.3. Quality and Subject Distribution of Co-Authored Articles

This section mainly uses the FWCI index to analyze the quality and influence of the papers co-authored at higher education institutions in the Greater Bay Area. FWCI divides the actual citation frequency of a paper by the average citation frequency of all papers of the same discipline, the same document type, and the same publishing year, overcoming some of the challenges brought about by the lag between input and output, differences between publications, and differences in citation frequency between disciplines. This index defines the global average baseline as 1.0, which facilitates horizontal comparison [47].

3.3.1. Overall Quality of Co-Authored Articles in Regional Higher Education Institutions

By comparing the quality distribution of co-authored/individually authored articles in higher education institutions in the Greater Bay Area in 2014 and 2018 (Figure 6), it can be seen that: (1) the average FWCI of individually authored articles in higher education institutions in the Greater Bay Area in 2014 was 1.02 and that of co-authored articles was 1.24; in 2018, the values were 1.27 and 1.57, respectively. On the whole, the quality of co-authored articles was higher than that of
individually authored articles, and the quality of co-authored articles improved more obviously during those five years. (2) In 2014, only four Hong Kong higher education institutions had higher quality co-authored articles than individually authored articles. The number of such higher education institutions in Hong Kong increased to seven in 2018, which was the result of the continuous expansion of scientific research cooperation in the Greater Bay Area over those five years. (3) The quality of co-authored/individually authored articles in Greater Bay Area higher education institutions generally showed an upward trend, with the number of higher education institutions in the third quadrant (low in both co-authored and individually authored articles) decreasing from 11 in 2014 to 2 in 2018, while the number of higher education institutions in the first quadrant (high in both co-authored and individually authored articles) increased from 13 in 2014 (including 4 in Guangdong, 8 in Hong Kong, and 1 in Macau) to 24 in 2018 (including 14 in Guangdong, 8 in Hong Kong, and 2 in Macau), which shows that the scientific research level of higher education institutions in the Greater Bay Area improved over those five years. (4) Hong Kong higher education institutions maintained overall advantages in the quality of individually authored and co-authored articles, but Guangdong higher education institutions had the most obvious improvement in the quality of their papers, with the number of Guangdong higher education institutions in the first quadrant increasing from 4 in 2014 to 14 in 2018.

![Figure 6](image-url) Figure 6. Comparison of quality distribution of co-authored/individually authored articles in higher education institutions in the Guangdong-Hong Kong-Macau Greater Bay Area in 2014 and 2018. Quadrant I: High quality in both co-authored and individually authored articles. Quadrant II: High quality in co-authored and low in individually authored articles. Quadrant III: Low quality in both co-authored and individually authored articles. Quadrant IV: High quality in individually authored and low in co-authored articles. Part A: Quality of co-authored articles are higher than that of individually authored articles. Part B: Quality of individually authored articles are higher than that of co-authored articles. The size of the bubbles indicates the number of co-authored articles of each university in the Guangdong-Hong Kong-Macau Greater Bay Area.

3.3.2. Comparison of the Quality of Co-Authored Articles in Various Disciplines

Through the previous analysis, it can be seen that the changes in the rankings of the degree of centrality of different types of higher education institutions reflected differences in the growth of the number of papers co-authored in different disciplines, while the differences in quality that lie behind the growth in quantity can be revealed by comparing the FWCI scores of the co-authored articles in various disciplines. Figure 7 shows the distribution of the FWCI scores of the five papers with the highest quality co-authored between higher education institutions in the Guangdong-Hong Kong-Macau Greater Bay Area.
Greater Bay Area in each discipline from 2014 to 2018. Among them, the quality of co-authored articles in the medical field was the highest (average value was 68.3), followed by science and engineering (average values were 32.1 and 28.1, respectively), while the quality of co-authored articles in the fields of economics/management (average value was 19.2), the humanities/social science (average value was 11.4), and agronomy (average value was 6.2) was relatively low. This shows that the distribution of the quality of scientific research cooperation in different disciplines in higher education institutions in the Greater Bay Area was uneven over this five-year period. There was a prominent performance in the medical field, followed by science and engineering, but the cooperation in the humanities/social sciences and agronomy obviously showed poor quality. However, it should be noted that, according to Waltman and van Eck [53], citation bias across disciplines and fields does exist in scientific publishing systems, as articles and journals in medicine and physiology tend to receive relatively higher citations and impact factors, which may lead to some single articles in medicine receiving a higher FWCI score than other fields.

![Figure 7](image.png)

**Figure 7.** Field-weighted citation impact (FWCI) value distribution of high-quality papers in various disciplines co-authored between higher education institutions in the Guangdong-Hong Kong-Macau Greater Bay Area, from 2014 to 2018.

Table 4 further lists the distribution of the top five research topics of co-authored articles with high FWCI values in various disciplines. It can be seen that, in the five-year period being studied, the research direction of papers co-authored between higher education institutions in the Greater Bay Area tended to focus on scientific and technological innovation fields such as biomedicine, information technology, high-end equipment manufacturing, new materials, etc. This research trend, based on regional traditional scientific research advantages and high-tech industries, conforms to the strategic positioning and functional layout of China’s policy departments in their promotion of the construction of the Greater Bay Area, which has focused on “accelerating the development of the advanced manufacturing industry” and “cultivating and strengthening strategic emerging industries” [54].

| Medicine     | Science          | Engineering       | Economics/Management | Humanities/Social Sciences | Agronomy       |
|--------------|------------------|-------------------|----------------------|----------------------------|----------------|
| Neoplasms    | MOEAs            | Solar cells       | Manufacture          | Social networking          | Polysaccharide |
| MicroRNAs    | Phosphorescence  | Energy harvesting | Supply chains        | Adolescent                 | Pectins        |
| Carcinoma    | Genes            | Electro catalysts | Industry             | Migrant                    | Antioxidants   |
| Cells        | Antioxidants     | photolysis        | Contracts            | Dyslexia                   | Citrus         |
| RNA          |                  | Capacitance       | Evolutionary algorithms | Student                   | miRNAs        |
4. Conclusions and Implications

Based on the above analysis of the patterns and evolution of the article co-authorship networks among universities in the Guangdong-Hong Kong-Macau Greater Bay Area from 2014 to 2018, the researchers came to a number of conclusions, as follows. Firstly, as can be seen from the analysis of the evolution of the overall network, in the past five years, the growth rate and speed of the densification of the networks for Guangdong-Hong Kong and Guangdong-Macau co-authored articles were higher than those of the Hong Kong-Macau co-authorship network. The growth rate and speed of the co-authorship network densification among the three regions from 2017 to 2018 were significantly higher than those of previous years. We can reasonably infer that China’s elevation of the construction of the Greater Bay Area into a major national strategy in 2017, and the strengthening of the connectivity of the 9 + 2 urban agglomeration in the Greater Bay Area, provided unprecedented historical opportunities for deepening and expanding research collaboration among higher education institutions in this area. From the evolution trend of the degree of centrality, it can be seen that, during the five years studied, the central potential of the Guangdong-Hong Kong co-authorship network increased rapidly. The fact that by 2018 it was on a par with that of Guangdong-Macau indicates that the influence of Guangdong’s higher education institutions in research collaboration in the Greater Bay Area was increasing year by year. However, the network central potential of the three regions was relatively low, indicating that research collaboration among the higher education institutions of the three regions was still scattered.

Secondly, if we look at the two indexes of the degree centrality and the structural holes related to individual university networks, we can see that Sun Yat-Sen University was consistently ranked first in terms of centrality. We can also see that the number of papers co-authored between Guangdong higher education institutions and other institutions in the Greater Bay Area network steadily surpassed those of Hong Kong in the five years studied. The degree of centrality of higher education institutions specializing in science and engineering increased significantly, while that of higher education institutions specializing in agriculture, the humanities or social sciences and that of normal universities decreased. This change indicates that the research collaboration between higher education institutions in the Greater Bay Area was mostly concentrated in the fields of engineering, science, and medicine over the five years studied. As can be seen from the rankings related to structural holes, comprehensive universities and science and engineering universities had higher structural hole rankings. Sun Yat-Sen University and the South China University of Technology held the top two places in the structural hole rankings for five years, showing their irreplaceable position in the Greater Bay Area’s research collaboration network. If we look at the regional distribution of the structural holes, we can see that the top ten universities expanded from being located in Guangzhou and Hong Kong in 2014 to locations in Guangzhou, Macau, Hong Kong, Shenzhen, and Shantou in 2018.

Thirdly, by comparing and analyzing the changes in the quality of individually authored and co-authored articles in universities in the Greater Bay Area in 2014 and 2018 using the FWCI index, the researchers showed that the quality of university research in all three regions in the Greater Bay Area improved over the five years studied. Although higher education institutions in Hong Kong maintained their overall advantages, Guangdong institutions showed a clear tendency to catch up with and surpass them. The articles co-authored with partners in the Greater Bay Area improved the research quality of Guangdong institutions. If we look at the quality of co-authored articles in sub-discipline fields, the quality of such articles in the medicine, science, and engineering fields in the Greater Bay Area was relatively high, especially in the field of medicine. By looking at the distribution of high-frequency subject words in high-quality co-authored articles in various disciplines, the researchers concluded that the outstanding cooperative research directions of higher education institutions in the Greater Bay Area had been focused in scientific and technological innovation fields such as biomedicine, information technology, high-end equipment manufacturing, new materials, etc. It follows that the Implementation Opinions proposed to tackle core technology problems in key areas, such as next-generation information technology, high-end equipment manufacturing, green and
low-carbon innovation, biomedicine, digital economy, new materials, etc., as the solutions to such problems can be built on the existing scientific research integration advantages of the three regions in the Greater Bay Area.

Based on the above analysis of the evolution and quality distribution features of the article co-authorship networks in the three regions of the Greater Bay Area, the researchers put forward the following suggestions for research collaboration between universities in the Greater Bay Area. Firstly, efforts should be made to improve the density and quality of research collaboration in the universities in the three regions. The key lies in the circulation of talents and the rational allocation and complementary sharing of research resources, which requires the construction of a higher education innovation ecosystem [55] in the Greater Bay Area. Secondly, high-quality research collaborations among the universities in the three regions should closely comply with the governmental development strategy of the Greater Bay Area, build on the existing scientific research integration advantages, master core technologies, and occupy a new high point in international science and technology. Thirdly, according to the analysis of the structural holes, a high structural hole ranking indicates that node’s ability to act as the medium for a non-repetitive relationship within the network: research collaborations between other institutions need to be formed through that university. In that case, the higher education institutions that are ranked highly in terms of structural holes, such as Sun Yat-Sen University and the South China University of Technology, should be stimulated to take the leading role in facilitating multilateral research collaboration in the Greater Bay Area. This is beneficial for higher education regionalization in the Area. Finally, research collaboration in the field of the humanities and social sciences need to be strengthened, as the study indicates that the degree of centrality of higher education institutions specializing in humanities and social sciences and that of normal universities decreased, and the quality of co-authored articles in the fields of humanities and social sciences is relatively low. Chapter eight of the development plan for the Guangdong-Hong Kong-Macao Greater Bay Area proposes jointly building a humanistic Greater Bay Area. Research collaborations in the field of the humanities and social sciences would be conducive to achieving this goal by enhancing cultural identity among the three regions.

In closing, this study demonstrates the patterns of university research collaboration networks in the Greater Bay Area. The detailed casual analysis is insufficient, requiring further investigation. Moreover, future research is needed to answer the following questions: what is the evolvement mechanism of the research collaborations in the Greater Bay Area? What pull and push factors affect the research collaborations between universities in the Area? What can be done to facilitate research collaborations in humanities and social sciences in the Area?

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