Scientometric Study of Superconductivity Research in South America from 1980 to 2019

J D González¹, J De La Hoz¹ and J R Beltrán¹
¹ Universidad del Magdalena, Santa Marta, Colombia
E-mail: jgonzaleza@unimagdalena.edu.co

Abstract. This paper presents the scientometric analysis of superconductivity research output in South America from 1980 to 2019 and compares it with Global output as reported in Web of Science. The study shows that superconductivity research in South America had a steep growth between 1980 and 2000, particularly an abrupt hike in 2005 that is noticeable followed by a more or less steady pattern thereafter up to 2019. South America superconductivity papers are analysed bibliometrically to indicate the authorship, collaboration pattern, to identify the major institutions and most relevant journals; apart from identifying the research field or application area of research in superconductivity.

1. Introduction

The history about superconductivity began when some scientists predicted a steady decrease in resistance with falling temperature until reaching a minimum value at 0 K and the current could flow with little or no resistance depending on purity. At that time, people had known that the resistance of metals decreased with falling temperature but people did not know what would happen at temperature approaching absolute zero (0 K). A lot of metals show zero electrical resistance to direct current (DC) when they are cooled below a characteristic critical temperature, \( T_c \). This phenomenon was discovered in 1911 at Leiden University when Dutch physicist Heike Kamerlingh Onnes observed the disappearance of the electrical resistance in mercury. Onnes was the first to liquefy helium by cooling it to 4.2 K in 1908 and study the electrical properties of metals at extremely low temperatures. Then, he studied mercury since very pure samples could be easily prepared by distillation. The resistance of the mercury sample suddenly disappeared at 4.2 K. Due to its extraordinary electrical properties, Onnes believed that mercury had passed into a new state. He called it superconductivity and the phase transition temperature is the \( T_c \). Other materials were found to exhibit superconductivity such as lead and tin. Due to his research, Onnes was awarded the Nobel Prize in Physics in 1913. All attempts to find at least to traces of resistance in bulk superconductor were no avail. On the basis of the sensitivity of modern equipment, we can argue that the resistivity of superconductors is zero, at least at level of \( 10^{-29} \) Ω.m. For comparison, we note that the resistivity of high-purity copper at 4.2 K is \( 10^{-12} \) Ω.

The first quantum (phenomenological) theory of superconductivity was the Ginzburg-Landau (G-L) theory postulated by Vitaly Lazarevich Ginzburg and Lev Landau, in 1950 [1]. The theory was later proven to be a very powerful theory for superconductivity. This quantum theory should be taken into account, firstly, that the superconducting state is more ordered than normal one...
and, secondly, that the transition from one state to another (without magnetic field) is a second order phase transition. This theory was initially given limited attention in the western literature because of its phenomenological foundation until: 1) in 1957 Abrikosov predicted the vortex states in type-II superconductors by solving the GL equations [2] and 2) in 1959 Gor’kov showed that the GL theory was, in fact, derivable as a rigorous limiting case of the microscopic theory [3], suitably reformulated in terms of Green functions to allow specially treating inhomogeneous regime. Nowadays, the GL theory is widely used for studying e.g. vortices in superconductors. Due to the pioneering contributions to the theory of superconductors and super fluids, Ginzburg and Abrikosov shared the Nobel Prize in Physics in 2003.

In 1957, the physical mechanism of superconductivity became clear only 46 years after the phenomenon had been discovered, when Bardeen, Cooper and Shrieffer published their theory (the BCS theory) [4]. The decisive step in understanding the microscopic mechanism of superconductivity is due to L. Cooper (1956). The fundamental element in this theory is the pairing of electrons close to the Fermi level into Cooper pairs through an attractive interaction mediated by phonons. For this contribution, the authors were awarded the Nobel Prize in Physics in 1972.

In 1987 Johannes Georg Bednorz and Karl Alexander Müller discovered the first high-$T_c$ superconductor, the layered copper oxide BaLaCuO with a $T_c$ of about 40 K [5] (the highest known critical temperature at the time for Nb$_3$Ge, 23K). They were awarded the Nobel Prize in Physics “for their important breakthrough in the discovery of superconductivity in ceramic materials”. Subsequently, shortly after it was found that replacing lanthanum with yttrium, i.e. making YBCO, raised the critical temperature to 92 K, which was important because of liquid nitrogen could then be used as a refrigerant. By 1993, cuprate with a $T_c$ of 133 K at atmospheric pressure was found (HgBa$_2$Ca$_2$Cu$_3$O$_8$) [6] and BSCCO with $T_c$ equal to 105 K [7]. After this discovery further efforts to find cuprates with higher $T_c$ failed until 2000, when a slight increase in the transition temperature was detected for fluorinated Ha-1223 samples ($T_c$ =138 K) [8], but until now, the higher values of $T_c$ are reached under high pressure such as Hg-1223 (at 164 K) [9] and HgBaCaCuO cuprates under 30 GPa pressure. High-$T_c$ superconductors are type-II superconductors. However, they can not be accounted for the conventional BCS theory. The mechanism that causes superconductivity in high-$T_c$ superconductors is one of the major unsolved problems of the theoretical condensed matter physics. In 1994, Sr$_2$RuO$_4$ was found to display superconductivity with $T_c$ ≈ 1 K. It has received considerable attentions because it is an unconventional $p$-wave spin-triplet superconductor, due to the superconductors until this time were spin-singlet paired including conventional or unconventional superconductors. The electronic structures of Sr$_2$RuO$_4$ are consistent with the quasi-two-dimensional Fermi liquid at low temperatures ($T < 40$K). The theoretical study of this material can be done by using the BCS theory and GL theory.

Superconductivity in magnesium diboride (MgB$_2$) was discovered as late as 2001 , with $T_c$ at 39 K, a record by far in ordinary metallic compounds and it is considered another important event in the history of superconductivity. The remarkable properties of MgB$_2$ open a new window in superconductivity for fundamental as well as applied research. The main disadvantage of early MgB$_2$ samples is their low critical magnetic field $H_{c2}$. But $H_{c2}$ can be increased up to more than 40T in bulk and up to near 60T in oriented thin films by Carbon doping. MgB$_2$ was found to be a two-band BCS superconductor with a much higher critical temperature and a significantly smaller isotope effect. The critical temperature of MgB$_2$ of 39 K enables the realization of electronic circuits based on this material which gives a significant advantage for this material as compared to the low-temperature superconductors. Compared to the High-$T_c$ superconductors, MgB$_2$ is simpler, cheaper, and more stable over time. This material is expected to be very promising for applications. In addition, in Tokyo Institute of Technology, Japan, was discovered a new superconductor based in iron (LaFeOP). However, the critical temperature was to stay at
4-6 K irrespective of hole/electron-doping. A large increase in the $T_c$ to 26K was then found in LaFe[O$_{1-x}$F$_x$]As, but under pressure this material can reach $T_c$ = 43K [10, 11, 12, 13, 14, 15, 16].

In the past century, most 2D superconductors were fabricated by deposition of metallic thin films, which led to strongly disordered, amorphous or granular samples. More recently, atomic layers grown by molecular beam epitaxy, interfacial superconductors, exfoliated atomic layers and electric double-layer transistors have been fabricated. These systems are highly crystalline, in marked contrast with older samples. The deposited films are of three kinds: InO$_x$, MoGe and Ta are sputtered thin films; Sn, Ga, Al, In, Pb and Bi are MBE-grown thin films; and YBa$_2$Cu$_3$O$_y$ (YBCO) was deposited by reactive evaporation. Bi$_2$2212, Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$; LAO, LaAlO$_3$; LCO, La$_2$CuO$_4$; LSCO, La$_{2-x}$Sr$_x$CuO$_4$; STO, SrTiO$_3$ [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28].

Until now no study has been undertaken to analyse the production of superconductivity publications and their characteristics, patterns and trends in the in South America over a reasonable duration. This study examines, for the first time, the growth, trends and patterns in the production of scientific publications in the natural sciences in South America over a long period of time (longer than any previous study). Visible trends in publications in superconductivity are visible in the literature by affiliation, country, per year by source, subject area, CiteScore publication, source documents by year, percentage review articles by year, source normalized impact per paper by year SNIP help and related area of application.

The main characteristic features of the publications, the relationship between the production of publications and the Institutes, Universities and centres where the superconductivity has been developed in collaboration. South America science was also influenced by external forces, such as the international scientific community specially from Europe, that affected its nature, growth and development, taking into account, that the majorities of the researchers in South America obtained their Ph. D. degrees in Europe.

The study should be viewed against the historical and political context of South America. Specifically, this analysis pertains to the period between 1980 and 2019, during which the scientific system in the most of the countries was influenced by different socio-economic and political factors.

2. Methods

Our analyses are based on publication and citation data extracted from the Science Citation Index component of the Scopus database, which is Widely used in bibliometric works. The database provides generous information for the study of publications in superconductivity. Scopus limitations aside due to it does not index all South American journals related to superconductivity, Scopus, relative to several other bibliographic databases, has the advantage of a wide coverage of recognized, widely read scientific journals and citation-based. Scopus contains high-quality published research output and citations, and is indexed on the basis of certain strict citation criteria, which assists in reliable analyses. Searches were carried out on the Scopus by using the following descriptors: TITLE-ABS-KEY ( "Superconductor" OR "Ginzburg-Landau" OR "London’s theory" OR "mesoscopic" OR "superconductivity" OR "low temperature superconductivity" OR "high temperature superconductivity" OR "Latin America" ) AND PUBYEAR from 1979 AND PUBYEAR until 2020. Topic search that retrieves occurrences of the search term in the title, abstract, author keyword or KeyWords Plus sections of an article.

3. South America Research

The global output of superconductivity research indexed in Scopus database during the period of study is found to be significant number of papers. The analysis reveals that a meaningful of superconductivity research is concentrated in Brazil, Argentina and Colombia, but a growing
number of literature has been written in Venezuela, Chile, Peru, Uruguay and Ecuador (See Fig. 1).

Figure 1: (Color online) Country-wise and affiliation distribution of superconductivity research papers.

The publication productivity of top 3 countries actively involved in superconductivity research (based on author affiliation) is depicted in Fig. 1. Among the top 15 most productive institutes, ten are universities from Brazil, four are major universities in South America, whereas the two research institutes with more papers published are located in Argentina and Colombia contribution is related with the two major Universities in the Country. This shows that superconductivity researches are concentrated in major universities and research institutes, while no research is currently conducted in private companies. Fig. 2 shows the institutes in South America that promote the study of superconductivity by financing projects that also promote collaborative work between Universities of Argentina and Brazil, above all. This is evidenced in Fig. 2 where most of the institutes are located in these two countries, who have promoted the study of superconductivity to the other countries of the southern cone, through scholarships for masters and doctoral students. The results obtained using the Scopus database do not clearly reveal the relationship of these institutes with their counterparts in the United States of America, Asian countries and Europe, but we are sure that the projects financed in these America that promote the study of superconductivity by financing projects that also promote collaborative work between Universities of Argentina and Brazil, above all. This is evidenced in Fig. 2 where most of the institutes are located in these two countries, who have promoted the study of superconductivity to the other countries of the southern cone, through scholarships for masters and doctoral students. The results obtained using the Scopus database do not clearly reveal the relationship of these institutes with their counterparts in the United States of America, Asian countries and Europe, but we are sure that the projects financed in these
countries have definitely developed superconductivity in South America, by as a large number of researchers in the area have developed their doctoral studies in these countries, especially in the European Union. The original articles for the South America’s countries by subject areas is shown in Fig.2. The three most common areas are: Physics and Astronomy (35.8%), Materials Science (29.4%), Engineering (19.6%) and Energy (11.0%), these results show that the greatest contributions to knowledge in superconductivity are concentrated in physics and astronomy, revealing that theoretical developments are mainly those contributing to the generation of new knowledge. On the other hand, materials science makes a great contribution, taking into account that the majority of articles on this subject have an experimental component aimed at the application, especially through the study of high temperature ceramic materials which have a high application in the actuality. In the area of engineering, despite the fact that the percentage of polished articles is lower than the areas shown above, the use of the knowledge generated in them is applied in technologies that today are used by society. The case of AmpaCity project is a good example about the the implementation of superconductivity technology where a cable one kilometer long connects the city center with two substations through which the test route has already transmitted more than 200 million kilowatt-hours, protected from a short-circuit by superconducting fault current limiter installed in the system. We obtained academic article data from the superconductivity field. Yearly trends of publishing from 1980-2019 are shown in Fig. 3 (left), which sets a growing trend in particular years. Superconductivity is a large field that aggregates multiple types of technology and research. We can see the two maximum of publications from 2000 until 2005 and a larger amount of publications. We can observe that after these two great peaks we obtain an average trend of 25 papers per year in the journals with the highest impact in the area, as we can see in Fig. 3 (right) where we relate the analyzed journals. For this analysis, we use the journal evaluation metric that was launched in December 2016 by Elsevier, the CiteScore (CS). The CS of an academic journal is a measure reflecting the yearly average number of citations to recent articles published in that journal. The JCR impact factor and CiteScore are similar in their definition, nevertheless, CiteScore is based on the citations recorded in the Scopus database rather than in JCR, and those citations are collected for articles published in the preceding three years instead of two or five. The above can be seen reflected in the curves shown in Fig. 3 (right), because traditionally the Journal Physical review Letter (orange curve) has a high citation in the scientific community, followed as shown by New Journal of Physics (green curve), Superconducting Science and Technology (blue curve), IEEE Transactions on Applied Superconductivity (red curve) and Physica C: Superconductivity and
its Applications (purple curve), all of them are prestigious journals. It is important to highlight that these important journals have considered the publication of the results in the area of superconductivity produced in South America, which shows the level of research achieved by Universities and Institutes.

4. Special case: Colombian Universities and Authors

The collaboration is an important component of research in the world which involves projects among universities that generate knowledge and highly specialized expertise to increase the number of publications of the research results in superconductivity. The Fig. 4 (up), It shows the large number of articles published by Colombian Universities, which are in constant cooperation that includes master’s and doctoral students in both theoretical and experimental superconductivity, development of new materials and technological applications that give rise to the great growth of published papers of research, which mostly have the cooperation of European Universities. Fig. 4 (down) presents the leading Colombian authors ranked according to the number of paper published that appears in the Scopus database.
5. Conclusions
The bibliometric study of superconductivity research identified the evolution of published papers during a period of 39 years (1980-2019). It is observed that Brazil is the predominant performer in the field by way of quantity and impact, followed by Argentina, Colombia and Venezuela. Colombia has also made a significant headway being the 3rd most active country, but not as striking as Brazil, there is a long way. Nevertheless, during the period under reference, Colombia published huge number papers in a broad range of high impact journals.

Acknowledgments
This work was financed by the University of Magdalena (Fonciencias).

6. References
[1] Ginzburg V and Landau L 1950 Zh. Eksp. Teor. Fiz. 20 1064.
[2] Abrikosov A A 1957 Sov. Phys. JETP 5 1174.
[3] Gorkov L P 1959 Sov. Phys. JETP 36 1364.
[4] Bardeen J, Cooper L N and Schrieffer J R 1957 Phys. Rev. 108 1175.
[5] Bednorz J G, Müller A K 1986 Zeitschrift fur Physik B Condensed Matter 64 189.
[6] Schilling A, Cantoni M and Guo J D and Ott H R 1993 Nature 363 56.
[7] Maeda H, Tanaka Y, Fukutomi M and Asano T 1988 Japanese Journal of Applied Physics 27 1988 27.
[8] Putilin S N, Antipov E V, Abakumov A M, Rozova M G, Lokshin K A, Pavlov D A, Balagurov A M, Sheptyakov D V and Marazio M 2000 Physica C 338 52.
[9] Gao L, Xue Y Y, Chen F, Xiong Q, Meng R L 1994 Phys. Rev. B 50 4260.
[10] Rice T M and Sigrist M 1995 Journal of Physics: Condensed Matter 7 643.
[11] Nagamatsu J, Nakagawa N, Muranaka T, Zenitani Y, and Akimitsu J. 2001. Nature (London) 410 63.
[12] Canfield P C and Crabtree G W 2003 Physics Today 56 34.
[13] Hosono H and Z A 2009 Journal of Physics 11 025003.
[14] Ishida K, Nakai Y, and Hosono H 2001 Journal of the Physical Society of Japan 78 06.
[15] Haviland D B, Liu Y and Goldman A M 1999 Phys Rev Lett 62 2180.
[16] Hebard A F and Paalanen M A 1990 Phys. Rev. Lett 5 927.
[17] Liu Y and Haviland D B Phys. Rev. B 47 5931.
[18] Qin Y, Vicente C L and J Yoon 2006 Phys. Rev. B textbf73 100505.
[19] Nishio T, Ono M, Eguchi T, Sakata H, and Hasegawa Y 2006 Appl. Phys. Lett 8813115.
[20] Eom D, Qin S, Chen M Y and Shih C K 2006 Phys. Rev. Lett 96 27005.
[21] Qin S, Kim J, Niu Q, and Shih C K 2009 Science 324 1314.
[22] Zhang T, Cheng P, Li W, Sun Y, Wang G, Zhu X, He K, Wang L, Ma X, Chen X, Wang Y, Liu Y, Lin H, Jia H and Xue Q 2010 Nat. Phys. 6104.
[23] Reymen N, Thiels S, Cavigilia A D, Fitting-Kourkoutis L, Bollinger A T, Giannuzzi L A, Muller D A, and Bozovic I 2008 Nature (London) 317 1196.
[24] Gao Z, Logvenov G, Fitting-Kourkoutis L, Bollinger A T, Giannuzzi L A, Muller D A, and Bozovic I 2008 Nature (London) 455782.
[25] Wang Q Y, Li W Z, Zhang H, Zhang Z C, Zhang J S, Li W, Ding H, Ou Y B, Deng P, Chang K, and Wen J 2012 Phys. Lett. 29 37402.
[26] Staley N E, Wu J, Eklund P, Liu Y, Li L, and Xu Z 2009 Phys. Rev. B 80 184505.
[27] Jiang D, Hu T, Lixing Y, Li Q, Li A, Wang H, Mu G, Chen Z, and Zhang H 2014 Nat. Commun 5 5708.
[28] Cao Y, Mishchenko A, Yu G L, Khestanova E, Rooney A P, Prestet E, Kretinin A V, Blake P, Shalom M B, and Woods C 2015. Nano Lett 15 4914.