International research collaboration among the G-20 countries

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G-20 refers to an organization of 20 member countries/ units founded in 1999. Over the years, it has become an important political and economic platform to address various developmental concerns. The member countries collectively represent about 75% of global population, 85% of the global gross domestic product and 75% of the global trade. Given that the G-20 has 88.8% of the world's researchers and accounts for 93.2% of research spending and 90.6% of scientific publications at the global level, it would be interesting to analyse the international research collaboration patterns among the G-20 countries, including assessment of benefits and impact of such collaboration. The present study utilizes the publication data of these countries to estimate their collaborative research levels. A positive growth is observed in research collaboration along with a positive correlation with the national expenditure on R&D. Some countries (e.g. Saudi Arabia and South Africa) are found to have benefitted significantly from such collaborative research, as observed by a boost in productivity and citations. The results comprehensively account for international research collaboration among the G-20 countries.

Keywords: Citations, international research collaboration, member countries, publication data.

RESEARCH collaboration is defined as a group of researchers working together to achieve specific goals[1]. While collaboration in scientific research is not recent, it has become an integral part of the research ecosystem. Research collaboration involves cooperation at different levels – individuals, institutions and countries. Many national and international funding agencies have invested in policies fostering collaborative research after recognizing the benefits of international research collaborations[1–3]. Several factors, such as a desire to cultivate ideas and skills, share knowledge and resources, achieve high-quality outcomes, etc. have motivated international research collaboration. Many studies have found that international research collaboration has increased rapidly in the past 2–3 decades, transcending national and disciplinary boundaries[4–9]. The benefits of research collaboration in improving productivity and a strong correlation between collaboration, productivity and citations have been highlighted by several studies[4,10–13]. Some studies have also revealed that the greater the scientific wealth (publication and citation data), the greater the inequality of distribution[14].

The Group of Twenty (G-20) comprises 19 countries (Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Republic of Korea, Mexico, Russia, Saudi Arabia, South Africa, Türkiye, United Kingdom and United States of America) and the European Union. The G-20 is an intergovernmental organization established in 1999 to address several global economic crises (https://www.g20.org/). Together, the G20 countries account for almost two-thirds of the global population, 75% of global trade and 85% of the world's GDP[15]. The G20 is also known to have about 88.8% of the world's researchers, and it accounts for 93.2% of research spending and 90.6% of scientific publications[16]. Thus, the G-20 countries command a substantial share of global resources and have mandated to work on global priority areas such as green development, climate finance, inclusive growth, digital economy, public infrastructure, technology transformation and reforms for women empowerment in socio-economic progress. In this context, exploring the level of scientific research collaboration among G-20 countries would be equally interesting.

Previous studies on the research output and other relevant parameters of the G-20 countries are limited. A study examined the research output and preferences of 19 G-20 countries and found that the countries in the G-20 varied significantly not only in research output but also in research preferences[17]. The research output from the G-20 countries is also captured in the Annual G-20 Scorecard of Research Performance by the Institute of Scientific Information, published by Clarivate[18]. This yearly report presents country-wise metrics on publications, their impact in terms of citations, open-access status, publications per GERD and per researcher, etc. However, none of these studies focused on international research collaboration among the G-20 countries and the benefits of such collaboration for productivity and citation impact. The present study tries to bridge this gap by systematically analysing international research collaboration among the G-20 countries.

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The objectives of the study were to determine and characterize the international research collaboration patterns among the G-20 countries, particularly considering the benefits that such collaboration may have to boost productivity and citations. Research publication data for a period of 20 years (2001–20) were used for the analysis, as this is a suitable period for appropriately capturing the collaborative efforts of the G-20 countries. More precisely, this study attempts to answer the following research questions:

(1) What volume of research output has been produced by the G-20 countries during the last 20 years, and how does it relate to their GDP/GERD?
(2) Has research collaboration among the G-20 countries increased during the last 20 years, and how has the relative intensity of collaboration changed?
(3) How much boost in productivity and citations do the G-20 countries get from research collaborations within the group?

Related work

Many previous studies focused on determining and characterizing international collaboration patterns of individual countries with respect to benefits accrued owing to involvement in research collaboration, such as for Brazil[19,20], Mexico[21], Korea[22], Vietnam[23], UK[24] and Russia[25]. Several previous studies focused on international collaboration in different regions, such as Africa[26,27], Asia[28–30], Europe[31,32] and BRICS countries[33–36].

One study examining the research output and preferences of 19 G-20 countries found variations in both aspects among these countries. It associated significant affinity between (i) research performance, (ii) research preferences and (iii) collaboration of G-20 countries with their economic level and/or geographic location. Interestingly, developed countries conducted more research in biology and medical sciences whereas, developing countries emphasized more on physical sciences and computer science. The research collaboration between G-20 countries is also captured in the Annual G-20 Scorecard of Research Performance by the Institute of Scientific Information[18]. This yearly report presents country-wise metrics on publications, their impact in terms of citations, open-access status and publications per GERD and per researcher. These however do not investigate specific aspects such as inter-G-20 collaboration patterns, impact and potential benefits of such collaboration for involved countries.

Thus, there are only a few studies on the research output from G-20 countries, specifically those focusing on research collaboration and its impact. As stated earlier, each country in the G-20 has its importance in terms of GDP, global population, economy, skills and trade to contribute in terms of collaboration. Therefore, collaboration among the G-20 countries can play a crucial role in addressing global challenges, which are largely covered under the sustainable development goals. Thus, there is a need to determine and characterize the international research collaboration patterns of the G-20 countries and analyse the impact of such collaboration patterns on the research productivity and citations of the G-20 countries.

Data and method

Data description

This study is based on research publication data for the G-20 countries accessed from the dimensions database (https://www.dimensions.ai/) through subscription-based access. The period of data collection was 2001–20. The metadata fields accessed for analysis included the year of publication, DOI, author details, open access, citations, author(s), country affiliation, etc. Different search queries were formulated to fetch the results. For example, one such search query used is specified in Box 1 for reference.

In the search query mentioned here, the G-20 countries are listed in abbreviated form. Data from the European Union (EU) were not considered in this study, as the EU is an administrative conglomeration of selected countries and a superset of selected countries in the G-20 group. Further, the publications data do not indicate affiliation to the EU but are affiliated to individual countries.

From the downloaded publication records for the G-20 countries, different metrics were computed. First, the volume of research output during 2001–20 and the growth in research output of the G-20 countries during the same period were estimated. The growth in research output was measured by computing CAGR (compounded annual growth rate) as

$$\mathrm{CAGR} = \left(\left(\frac{V_{\mathrm{final}}}{V_{\mathrm{begin}}} \right)^{\frac{1}{t}} - 1 \right) * 100, \tag{1}$$

where V_{final} denotes the publication output of a G20 country in 2020, V_{begin} denotes the publication output of a G20 country in 2001 and t denotes the number of years, which is 20 in this case.

Next, the international research collaboration patterns for the G-20 countries were analysed. The collaboration between the countries was identified using the research_org_countries metadata in the publication records. Further,

Box 1. Search query.

Search publications where year in [2001:2020] and research_org_countries in ["AR", "AU", "BR", "CA", "CN", "FR", "DE", "IN", "ID", "IT", "JP", "MX", "KR", "RU", "SA", "ZA", "TR", "GB", "US"] and type in ["article", "proceeding"] return publications [id+doi+title+authors_count+times_cited+year+type+research_org_countries+open_acces+…]

the percentage of internationally collaborated papers was calculated with respect to the total number of papers published by a G-20 country during 2001–20. The percentage of collaboration of a G-20 country was computed with respect to the total number of internationally collaborated papers published by all G-20 countries. Thereafter, the growth in internationally collaborated papers of a G-20 country was measured by computing CAGR (eq. (1)). Here, total number of internationally collaborated papers of the country in 2020 and 2001 were used as V_{final} and V_{begin} respectively.

Finally, different collaboration indicators such as relative intensity of collaboration (RIC), boost in productivity and citations were calculated for the G-20 countries. The RIC index compares the collaboration share of one country with another country relative to the collaboration of the country with the rest of the world[37]. This index was estimated with respect to the G-20 countries for the period 2001–20. RIC was formulated as the ratio of the share of the collaborations of actors X and Y within all collaborations of X to the share of collaborations of Y within all collaborations of the system, excluding collaborations of X. It is expressed as

$$\text{RIC}\ (X, Y): \frac{C_{XY} * (T - C_X)}{C_X * (C_Y - C_{XY})}, \tag{2}$$

where C_{XY} denotes the number of collaborations between two countries X and Y, C_X the total number of collaborations of country X, C_Y the total number of collaborations of country Y and T represents the total number of pairwise collaborated publications of the countries under study. The rationale behind the RIC index is that it does not depend solely on C_{XY} rather, it depends on C_Y. In short, RIC (X, Y) is proportional to (C_{XY}/C_Y). In the present case, the system comprises the G-20 countries. The value of RIC is observed to increase over time when the collaboration of a country with a selected group (in this case, the G-20 countries) increases. The RIC computation helps in understanding the relative intensity of collaboration of the G-20 countries.

In order to understand the benefits of international research collaboration on productivity and the impact of research from the G-20 countries, the boost in productivity and citations was considered[38].

The boost in productivity, indicated by β_{p}, can be defined as

$$\beta_{\text{p}} = \left[\frac{\text{TP}}{\text{TIP}} - 1\right] \times 100\%, \tag{3}$$

where TP is the total publications of a country (comprising indigenous as well as internationally collaborated papers) and TIP is the total number of indigenous publications of a country.

The boost in citations, indicated by β_{c}, can be defined as

$$\beta_{\text{c}} = \left[\frac{\text{TC}}{\text{TIC}} - 1\right] \times 100\%, \tag{4}$$

where TC is the total citations accrued by a country (comprising citations for indigenous as well as internationally collaborated papers) and TIC is the total citations accrued on the indigenous publications of a country.

As underlined by Dua *et al.*[38], if the value of boost in productivity, $\beta_{\text{p}} > 50\%$, a country can depend more on foreign collaborations for productivity than the indigenous scholarly ecosystem. Similarly, in case of a boost in citation productivity, $\beta_{\text{c}} > 50\%$ of a country is more dependent on foreign collaborations for impact than the indigenous scholarly ecosystem.

Boost ratio of impact per unit boost in productivity denoted by γ_{c} is the net boost of impact per unit boost of productivity due to international collaborations, and is given by

$$\gamma_{\text{c}} = \frac{\beta_{\text{c}}}{\beta_{\text{p}}}. \tag{5}$$

If $\gamma_{\text{c}} < 1$, the collaborations are less rewarding and if $\gamma_{\text{c}} > 1$, they are rewarding. Greater the value of γ_{c}, more the benefit of collaboration.

Similarly, boost ratio of impact per unit boost in citedness, denoted by δ_{c} is the net boost of impact per unit boost of citedness due to international collaborations, and is given by

$$\delta_{\text{c}} = \frac{\beta_{\text{c}}}{\beta_{\text{rc}}}, \tag{6}$$

$$\beta_{\text{rc}} = \frac{r_{\text{T}}}{r_{\text{TI}}}, \tag{7}$$

$$r_{\text{T}} = \frac{\text{Total number of cited publications}}{\text{Total number of publications}} = \frac{\text{TP}_{\text{cited}}}{\text{TP}}, \tag{8}$$

$$r_{\text{TI}} = \frac{\text{Total number of cited indigenous publications}}{\text{Total number of indigenus publications}} = \frac{\text{TIP}_{\text{cited}}}{\text{TIP}}. \tag{9}$$

Thus, the greater the value of δ_{c}, the greater the effectiveness of the collaboration. If this ratio is very high, with not a reasonably high value of β_{rc} (i.e. $\beta_{\text{rc}} < 1\%$), it indicates that most collaborations are of good quality and rewarding. The high value of δ_{c} at the cost of reasonably high β_{rc} (i.e. $\beta_{\text{rc}} > 1\%$) indicates that some relatively less-rewarding collaborations exist. These can be reviewed, and decisions on whether to strengthen such collaborations or minimize focus on them can be taken.

Table 1. Publication output of the G-20 countries

Country	Abbreviation	TP (2001–20)	TP (2001)	TP (2020)	CAGR TP (%)	GERD* (billion US$, 2019)	R&D intensity of GDP* (2019)
Argentina	AR	208,788	5,103	19,689	6.98	2.6	0.49
Australia	AU	1,457,679	31,644	129,546	7.3	27.1	1.89
Brazil	BR	1,261,442	19,643	132,862	10.03	22.1	1.15
Canada	CA	1,809,339	43,560	140,218	6.02	27	1.57
China	CN	5,819,787	42,382	741,686	15.39	297.3	2.14
France	FR	2,059,414	58,643	138,568	4.39	61.1	2.19
Germany	DE	3,145,221	89,708	234,604	4.92	122.8	3.09
India	IN	1,778,346	19,457	220,463	12.9	17.6	0.65
Indonesia	ID	366,330	671	94,492	28.07	2.4	0.23
Italy	IT	1,757,107	43,742	153,749	6.49	29	1.38
Japan	JP	3,283,319	120,170	195,117	2.45	161.6	3.21
Mexico	MX	310,604	6,224	31,345	8.42	3.9	0.32
Russia	RU	1,126,678	30,584	143,602	8.04	16.3	0.98
Saudi Arabia	SA	219,433	1,683	37,905	16.85	6.8	0.83
South Africa	ZA	281,623	4,852	31,862	9.87	3.1	0.76
South Korea	KR	1,174,215	20,158	96,043	8.12	76.5	4.43
Türkiye	TR	558,435	8,216	53,454	9.82	7.5	0.96
United Kingdom	GB	3,511,921	106,639	263,844	4.63	48.8	1.68
United States of America	USA	12,270,163	383,956	862,510	4.13	581.6	2.83

TP, Total publications; CAGR, Compounded annual growth rate, R&D intensity, Percentage of GDP on R&D activities.
*Source: UNESCO Science Report, 2021.

Results

The results of analysis on international research collaboration among the G-20 countries are presented below.

Research output volume, internationally collaborated papers and growth rate

Table 1 shows the research output of the G-20 countries for the period 2001–20, along with CAGR. The G-20 countries are listed in the order in which they appear in the group. It can be seen from the table that the highest number of publications is recorded by the USA (12,270,163), followed by China (5,819,787), the United Kingdom (3,511,921) and Japan (3,283,319). India ranks eighth among the G-20 countries in terms of publications, with a TP of 1,778,346. Argentina stands last in total publication count among the G-20 countries, with a TP of 208,788. With regard to the growth of publications among the G-20 countries during 2001–20, a steady growth rate is observed among them. The highest CAGR is observed in the case of Indonesia (28.9%), where TP increased from 617 in the year 2001 to 94,492 in 2020. This is followed by Saudi Arabia (16.85%), China (15.39%) and India (12.9%). While the USA and UK have substantially high TP among the G20 countries, they report low CAGR values of 4.13% and 4.63% respectively. In terms of GERD (recorded for the year 2019), USA invests the highest amount in research and development activities (GERD = 581.6 billion US$), followed by China (297.3 billion US$), Japan (161.6 billion US$) and Germany (122.8 billion US$). However, in terms of R&D intensity for the year 2019 (expressed as % of GDP) South Korea (4.43) stands at the top, closely followed by Japan (3.21) and Germany (3.09). India stood 12th in GERD (17.6 billion US$) among the G-20 countries and recorded a considerably low percentage of R&D intensity in 2019 (0.65). The highest amount of GERD spent by the USA correlates well with its high productivity and R&D intensity of 2.83%. Such a correlation between productivity and GERD can be observed in other countries as well.

The number of internationally collaborated papers (ICP) was computed for each of the G-20 countries during 2001–20. In Table 2, the overall ICP percentage of the G-20 countries during 2001–20 and the growth in ICP of these countries from 2001 to 2020 are indicated. Additionally, the inter-collaboration trend of the G-20 countries, i.e. collaboration of a G-20 country with another, is also recorded. It can be seen that Saudi Arabia accounts for the highest percentage of ICP (66.7), followed by South Africa (47.11), France (46.27) and Australia (44.67). The USA, having the highest number of publication records among the G-20 countries, stands sixth in terms of ICP at 26.27%, while India records the third lowest value (17.65%). Thus, Indonesia, followed by Japan and India, have the highest percentage of indigenous publications (87.18, 82.62 and 82.35 respectively) and the lowest in internationally collaborated publications (12.82, 17.38 and 17.65 respectively). In terms of the growth of internationally collaborated publications from 2001 to 2020 for the G-20 countries, Saudi Arabia again accounts for the highest CAGR value of 23.7%, followed by Indonesia (16.77%), China (16.61%) and India (13.95%). The lowest growth in internationally collaborated papers from 2001 to 2020 is recorded by Russia (5.97%).

Table 2. Collaborated publications among the G-20 countries during 2001–20

Country	TP	ICP (%)[#]	ICP (2001)	ICP (2020)	CAGR ICP (%)	Proportion of ICP with G-20 countries* (%)
Argentina	208,788	41.96	1,790	9,034	8.43	75.6
Australia	1,457,679	44.67	8,976	76,052	11.28	80.42
Brazil	1,261,442	24.03	4,493	36,726	11.08	76.19
Canada	1,809,339	42.84	13,363	76,906	9.14	85.12
China	5,819,787	21.5	8,351	180,549	16.61	84
France	2,059,414	46.27	21,251	80,584	6.89	69.99
Germany	3,145,221	40.75	28,757	113,551	7.11	70.81
India	1,778,346	17.65	3,318	45,171	13.95	79.82
Indonesia	366,330	12.82	401	8,909	16.77	69.12
Italy	1,757,107	40.58	13,348	74,103	8.95	75.31
Japan	3,283,319	17.38	14,948	48,369	6.05	81.5
Mexico	310,604	40.07	2,500	13,400	8.76	75.25
Russia	1,126,678	25.29	9,263	29,547	5.97	73.16
Saudi Arabia	219,433	66.7	394	27,715	23.7	62.63
South Africa	281,623	47.11	1,467	17,616	13.23	75.02
South Korea	1,174,215	25.25	4,058	30,500	10.61	88.59
Türkiye	558,435	21.21	1,374	15,489	12.88	75.48
United Kingdom	3,511,921	42.14	28,445	152,077	8.74	74.74
United States of America	12,270,163	26.27	65,457	302,560	7.96	76.49

[#]Computed with respect to total papers (TP) of a country. *Computed with respect to total ICP of a country.

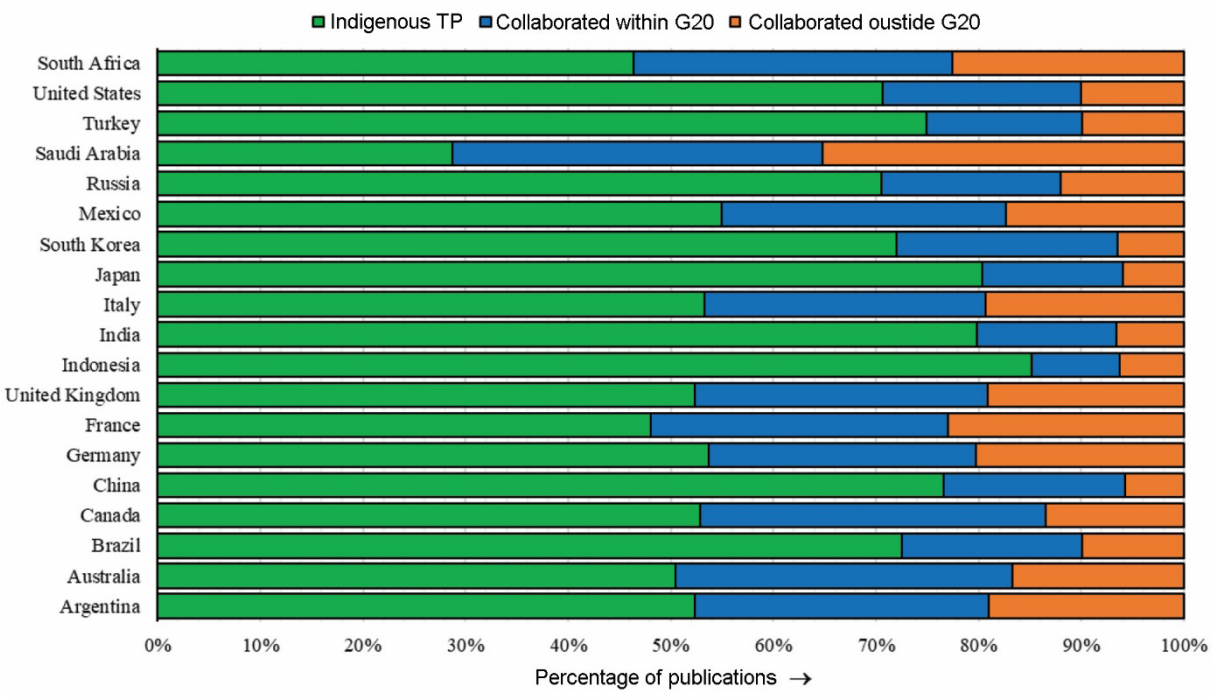

Figure 1. Proportion of publications among G-20 countries that are indigenous, collaborated within the G-20 and outside the group.

The collaboration percentage of a G-20 country with the other G-20 countries during 2001–20 was calculated with respect to the total number of internationally collaborated papers of that G-20 country during 2001–20. This value indicates the percentage of collaboration of a country with the G-20 countries out of its total ICP. In terms of collaboration between the G-20 countries, South Korea has the highest proportion of research publications in collaboration with the other G-20 countries (88.6%), closely followed by Canada (85.12%), China (84%), Japan (81.5%) and Australia (80.42%). Most countries have a high percentage of ICP (>75) involving collaboration with the G-20 group, such as India, the USA, Brazil, Argentina, etc. For countries like Saudi Arabia, Indonesia, France, Germany and Russia, it is between 60% and 70% of their total ICP. Figure 1 shows what proportion of papers from a country are

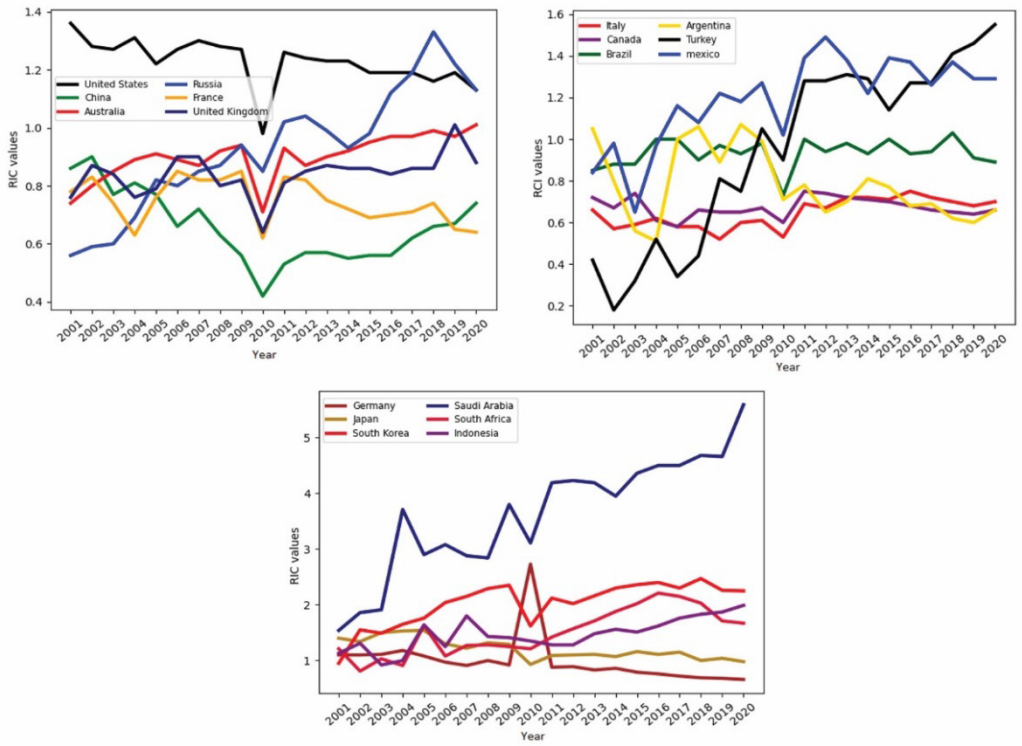

Figure 2. Relative intensity of collaboration of India with respect to the G-20 countries.

Table 3. Cited percentage and citations per paper of indigenous and collaborated papers from G-20 countries

	Cited percentage		Citations per paper (CPP)	
Country	Indigenous	Collaborated within G-20	Indigenous	Collaborated within G-20
Argentina	75.12	89.43	9.54	25.26
Australia	79.96	90.52	16.75	29.67
Brazil	71.01	88.92	7.25	21.31
Canada	78.06	88.75	17.70	31.27
China	78.21	91.49	9.98	21.53
France	70.88	88.40	14.75	31.22
Germany	69.17	88.51	14.40	32.00
India	77.08	87.85	8.47	19.00
Indonesia	47.82	85.98	0.77	14.19
Italy	79.76	88.84	14.67	30.16
Japan	55.49	86.64	9.39	27.88
Mexico	73.78	88.34	7.73	22.94
Russia	61.54	86.73	3.23	20.82
Saudi Arabia	80.64	91.85	8.60	20.73
South Africa	77.23	90.98	8.88	25.45
South Korea	80.55	90.30	11.71	25.03
Turkiye	82.94	89.39	10.14	21.63
United Kingdom	72.59	88.62	17.70	32.16
United States of America	75.15	88.80	22.01	31.03

indigenous, collaborated within the G-20 or outside the group.

Relative intensity of collaboration

RIC is a recent measure for estimating the trend in collaboration among countries[37]. It is calculated with respect to a specific country whose collaboration activity is to be studied. Figure 2 shows the RIC curves for India. It can be observed that the RIC values for India are high in collaboration with Saudi Arabia, Japan, Germany, Indonesia, South Africa, South Korea and the USA (between 1 and 2), thus indicating a higher affinity for collaboration in research. In the period of analysis, it can be seen that RIC between India and

Saudi Arabia increased at least four-fold. The RIC values increased for Russia (0.6 to 1.2), South Korea (1.0 to 2.0), Türkiye (0.4 to 1.5), and Mexico (0.8 to 1.2), indicating that collaborative research between India and these countries has increased. The RIC values have remained unchanged for Brazil, Italy, Canada and the United Kingdom. However, India's RIC has decreased with the USA (1.4 to 1.2), France (0.8 to 0.6), China (0.85 to 0.75), Argentina (1.0 to 0.6), Indonesia (1.0 to 0.5), and Japan (1.5 to 1.0) over time. This indicates that India has found newer collaborating partners in this period while maintaining the collaboration links with existing partners. The RIC for the rest of the G-20 countries can be computed and analysed in a similar fashion.

Impact of collaboration on productivity and citations

In order to understand the impact of collaboration, first, the cited percentage and citations per paper for indigenous and collaborated papers (collaborated with the G-20 countries) for the G-20 countries were estimated (Table 3). For all the countries, the cited percentage of papers collaborating with the other G-20 countries was higher than the indigenous papers. A similar difference was observed in the case of citations per paper for the G-20 countries.

The boost in productivity and citations from collaborations among the G-20 countries (2001–20) was determined (Table 4). Table 4 shows that the boost in productivity of countries like Brazil, China, Germany, Indonesia, India, Japan, South Korea, Russia, Türkiye, and the USA within the G-20 group is less than 50%. This indicates that these countries are not dependent on the G-20 collaboration and have a substantially stable domestic research ecosystem in terms of publication output. Australia, Canada, France and South Africa benefit significantly in productivity from collaborations. Saudi Arabia is seen to have a productivity boost of 125.47% due to collaborations and may be considered to depend highly on such collaborations for productivity.

Table 4. Boost in productivity and impact for G-20 countries on collaborating within the group

	Collaboration within the G-20 group				
Country*	β_p (%)	β_c (%)	γ_c	β_{rc} (%)	δ_c
AR	54.65	144.69	2.65	6.73	21.49
AU	64.94	115.01	1.77	5.20	22.14
BR	24.09	70.80	2.94	4.90	14.45
CA	63.81	112.73	1.77	5.34	21.12
CN	23.01	49.61	2.16	3.18	15.61
DE	48.70	108.23	2.22	9.16	11.82
FR	60.29	127.62	2.12	9.30	13.73
GB	54.43	98.89	1.82	7.78	12.71
ID	10.16	186.70	18.38	7.36	25.36
IN	17.11	38.37	2.24	2.04	18.80
IT	51.43	105.71	2.06	3.87	27.32
JP	17.14	50.90	2.97	8.21	6.20
KR	29.93	63.97	2.14	2.79	22.94
MX	50.30	149.22	2.97	6.60	22.60
RU	24.76	159.56	6.44	8.12	19.64
SA	125.47	302.40	2.41	7.74	39.09
TR	20.32	43.32	2.13	1.31	32.96
US	27.25	38.42	1.41	3.89	9.88
ZA	66.81	191.38	2.86	7.13	26.83

*Country codes are given as per the ISO 3166-1 catalogue.

In terms of boost in citations, collaboration with the G-20 countries proved to be rewarding for all of them, though the value varied for different countries. Argentina, Australia, Canada, Germany, France, Indonesia, Italy, the United Kingdom, Mexico, Russia, Saudi Arabia and South Africa boosted citations by more than 100%. Though Germany, Indonesia, and Russia are self-reliant, their indigenous scholarly ecosystems do not attract citations similar to those of their collaborated papers. The countries that are more rewarded from collaborations within and outside the G-20 are Indonesia and Russia; as for these countries, for each 1% boost in productivity achieved through the G-20 collaboration, there is an 18% and 6% boost in citations respectively. Countries like South Africa and Türkiye have high values of δ_c (39.06 and 32.96 respectively), which indicates that the collaboration is effective, but at a reasonably high-cost β_{rc} (i.e. $\beta_{rc} > 1\%$). Thus, there are some relatively less-rewarding ties in the G-20 collaboration. Hence, it can be observed that not only developing countries, but developed countries also depend on and benefit from such collaborations.

Figure 3 shows the boost in productivity and citations of the G-20 countries collaborating within the group. It can be observed that Saudi Arabia is highly dependent on collaborations for both productivity and citation. Brazil, Germany, China, Indonesia, India, Japan, South Korea, Russia, Türkiye and the USA show a boost in productivity of less than 50%, indicating these countries have strong indigenous research ecosystems. However, Brazil, Germany, Indonesia, Japan, South Korea, and Russia are dependent on collaborations to accrue citations. This indicates that these countries, despite having strong indigenous ecosystems, fail to attract sufficient citations. On the other hand, countries like Argentina, Australia, Canada, the United Kingdom, Italy, Mexico, and South Africa depend on collaborations for both productivity and citations.

Conclusion

This study has analysed the international research collaboration among the G-20 countries by computing the indicators of rate of growth, proportionate share, RIC and boost in productivity and citations due to such collaborations. It has been observed that the USA leads the group overall in terms of research productivity and collaboration. It also has the highest spending in terms of absolute value of GDP on R&D activities. In most cases, a direct correlation is observed between publication and national GERD. The RIC calculations for India show that it has developed

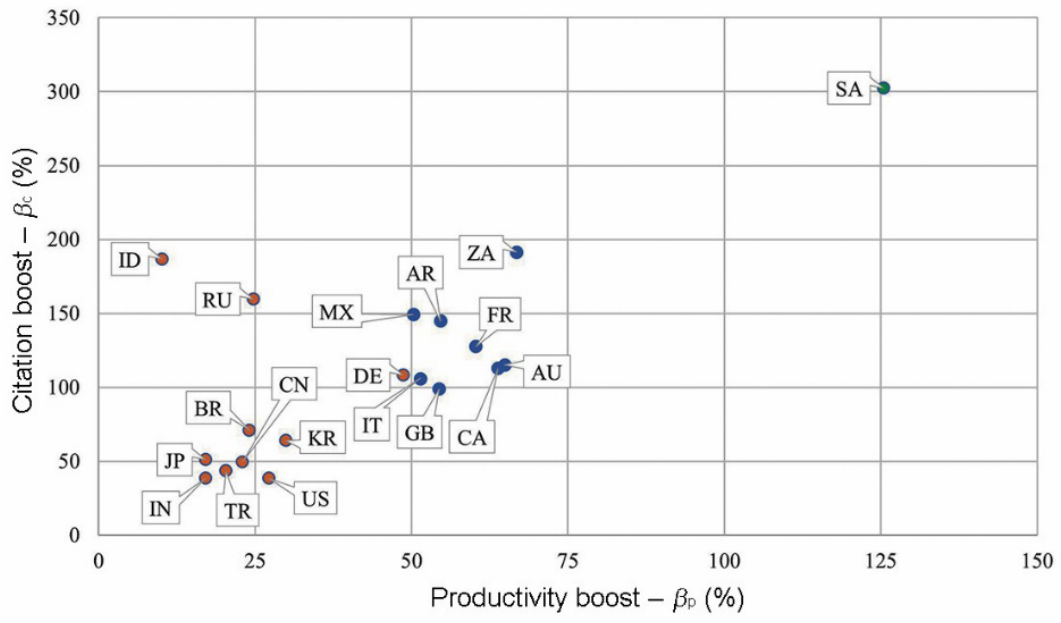

Figure 3. Citation boost versus productivity boost of countries when collaborating within the G-20.

research collaboration with new partners (like Saudi Arabia, Russia, South Africa and South Korea) while more or less maintaining collaboration ties with existing partners (such as Brazil, Canada and the United Kingdom). In general, the collaboration proved rewarding for most of the G-20 countries. The application of concept of boost in productivity and citation measures on collaborations within the G-20 showed that some countries are highly dependent on such collaborations in terms of productivity and citations with the other G-20 countries. Thus, the study presents an informative and useful account of research collaboration among the G-20 countries and its impact on productivity and citations. It can be useful for policymakers, Governments and researchers in various ways.

This study has certain limitations. It only relies on data from published research papers to determine and characterize research collaborations. However, such collaborations may involve several other factors like the development of technologies, filing of patents, etc. which are not easily reflected in bibliometric indicators. Future studies may explore these technology-related aspects of collaboration. It would be beneficial to analyse the collaborative practices across various disciplines and pinpoint the institutions, governmental bodies, or private enterprises spearheading the global collaborative efforts within the G-20 nations. Such research would enhance policymaking by offering comprehensive insights into the active fields and key players within the G-20 research milieu.

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