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Article

A General Overview of Scientific Production in China, Japan and Korea of the Water-Gas Shift (WGS) Process

Edoardo Magnone

High Efficiency and Clean Energy Research Division, Korea Institute of Energy Research (KIER), 152 Gajeong-ro, Yuseung-Gu, Daejeon 305-343, Korea; E-Mails: magnone@kier.re.kr; magnone.edoardo@gmail.com; Tel.: +82-42-860-3384; Fax: +82-42-860-3134

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Abstract: In today's economy, one of the most important national indicators of economic growth performance is the country's ability to produce new technology—and use it responsibly and efficiently—for environmental protection or energy conservation, production and consumption in agreement with international standards. The purpose of this study is to identify the Research and Development (R&D) capability in the area of environmentally friendly technologies in China, Japan and Korea over the last twenty years. As the field is very wide, Water-Gas Shift (WGS) reaction technologies were taken as a case study for the purpose of this article. During 1990–2011 a total of 788 papers in the field of WGS technologies were published by scientists in China, Japan and Korea. China was the top producing country with 394 papers (50%) followed by Japan with 250 papers (32%), and Korea with 144 papers (18%). The growth of the literature in the field was found to be exponential in nature for China. The R&D capabilities were found to correlate directly with the Gross Domestic Expenditures on R&D (GERD), Researchers in Full-time equivalents (FTE), and other economic parameters.

Keywords: rankings; scientometrics; economic comparison; China; Japan; Korea; water-gas shift reaction

1. Introduction

There is today a broad global consensus that—if certain demographic and economic trends persist—the 21st century will be dominated by Asian economies, similar to how the 20th century is often called the American Century, and the 19th century the British Century [1–3]. On the other hand, the production of scientific knowledge is recognized as the driver of productivity and economic growth [4–8]. Aghion and Howitt correctly recognized that "*growth results exclusively from technological progress, which in turn results from competition among research firms that generate innovations*" [9]. Arguably, national investments in Research and Development (R&D) for new technology are keys to economic growth because "*science and technology are the driving forces of our contemporary society*" [10].

The extent of Asia's impact on global research outputs has been widely documented [10–18]. The size and rapid growth of Asia's science and technology, together with its increasing R&D funds for hi-tech renewable and energy efficiency, represent a challenge to the new low-carbon development strategies. Moreover, the transition towards low-carbon energy is underway in China and Korea, although fossil fuels—coal, oil and natural gas—still play a leading role at a worldwide level. Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities and today China—and other Asian countries like Japan and Korea—can play a significant role in mitigating this greenhouse gas. The control of the CO_2 released to the atmosphere is a prior issue in most of the developed countries where it is well-known that the Water-Gas Shift (WGS) reaction is an important technological step for generating and purifying hydrogen (H_2), a necessary feedstock for many important new energy processes [19].

In this context, in the last few decades there has been a growing interest for the development of WGS reaction with regard to both fundamental and practical points of view in different fields of study. Broadly speaking, the WGS reaction is the chemical process in which carbon monoxide (CO) reacts with water (H_2O) to produce CO_2, H_2 and heat:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta H^0_{298} = -40.9 \text{ kJ/mol} \tag{1}$$

As the reaction is equimolar it does not depend on pressure and lower temperature can favor higher conversion but requires more catalyst. The usual reaction temperatures vary from 200 to 500 °C depending on the quality and operational temperature of the catalyst. In order to achieve high CO conversion, a two step catalytic process is regularly employed [20]. In fact, the reaction is normally carried out in two stages, one at high temperature and the other at relatively low temperature and the catalysts used are different in each case.

Many scientometric studies and research policy analyses have appeared in the scientific literature which focuses on the global trend for research productivity in the most varied of subjects [16,21–23], but currently there are no comparative studies analyzing the Asian literature in the selected field. This was one of the motivations for the present work. In particular, the aim of the present study was to quantitatively determine and compare the growth and development of Asia's literature on the WGS reaction in terms of the number of R&D papers for China, Japan and Korea. This study uses the WGS reaction as a case study of mitigation strategies of greenhouse gases and the number of R&D publication on the topic as a simple trick for representing the national productivity in environmental preservation activities. The authors collected scientometric data from Scopus database. The data so obtained was analyzed to study the R&D capabilities in the field of the WGS reaction in general and to see the change in the pattern of scholarly papers over time. Finally, this work examines the relationship between economic parameters and the number of papers in the field of energy technology.

2. Experimental Section

The assumption made for this comparative work is that the number of scholarly publications is directly proportional to the national scientific and economic efforts to support R&D in a new technological field like the WGS reaction.

An analysis of the R&D literature on WGS research fields—with particular emphasis on epistemology rather than chemical reaction—was performed on the basis of the keywords of the bibliographic database Scopus® (SciVerse Scopus, Elsevier B.V. http://www.scopus.com/home.url) [24]. The number of papers depends on the scientific databases used but the Scopus's database selected is sufficiently representative of the overall situation of the R&D progress of scientific knowledge [25,26]. Articles, reviews, conference papers, conference reviews, notes, letters, short surveys, errata, editorials, book, reports, and abstract report series in life (>4300 titles), health (>6800 titles), social sciences & humanities (>5300 titles), and physical (>7200 titles) fields were included in this analysis. Data collection was confined to the scholarly publications from 1990 to 2011 and involved the extraction of the number of papers with "*water-gas shift*" words in the Title, Abstract and list of Keyword fields and China, Japan and Korea in the Affiliation Country that were indexed in the Scopus® database [24] on January, 2012.

Applying the above selected strategies in Scopus® [24] the authors obtained 788 research papers submitted from China, Japan and Korea in the target-time window (1990–2011). Collectively, the result gives us a picture of the importance of WGS technology in Asian countries during the last two decades. The majority of economic data presented in this study are derived from the Organization for Economic Co-operation and Development (OECD).

To the author's knowledge no study has been published focusing on the correlations between the relative numbers of the R&D papers in the new technological field of WGS and GERD. Preliminary results of this work and some empirical notes are described in the next two sections of this study.

3. Results

3.1. Publication Source

During 1990–2011 a total of 788 papers were published on the WGS reaction field by researchers located in China, Japan and Korea countries. According to the Scopus database, there were 68 papers published in 2011 with the combination word "*water-gas shift*" in their Titles, Abstracts or list of Keywords. The average number of publications produced per year was 35.8 (1990–2011).

As introduced in the above section, a country's position in the international ranking can be estimated on the basis of some R&D output indicators, where the number of scientific publications is the most frequently used output indicator [16,22,23,27]. For the range of years between 1990 and 2011, 50% of papers were published by authors whose address was in China (394 papers), 32% were published by authors in Japan (250 papers), and 18% were published in Korea (144 papers).

Figure 1a gives an illustration of the annual growth in the selected WGS field. It can be clearly visualized that the growth of the cumulative numbers of R&D literature was very slow during 1990–1996 and it peaked during the last decade, indicating that research on WGS received a major boost during the last period. The phenomenal increase in the number of research papers is, however, an indication of growing interest in the selected subject area. In particular, it can be noted that during 1999 the number of papers increased considerably in absolute terms in China. As displayed in Figure 1a even though there are fluctuations in number of papers every year, a significant mathematical correlation was found between the yearly cumulative numbers of R&D papers in the considered time range (1990–2011). The cumulative document result progression was represented by three exponential equations. Therefore, it can be concluded that the number of academic papers on the topic of WGS is still growing at a high rate in China and Korea but not in Japan. Moreover, based on the mathematical model, during 1990–2011, it can be predicted that the number of Korean R&D outputs on the topic of WGS will be equal to Japan's outputs in 2012–2013.

Figure 1. (**a**) Trend in R&D production (as number of research outputs or papers) by countries; (**b**) Proportion of national publication output produced between 1990 and 2011.

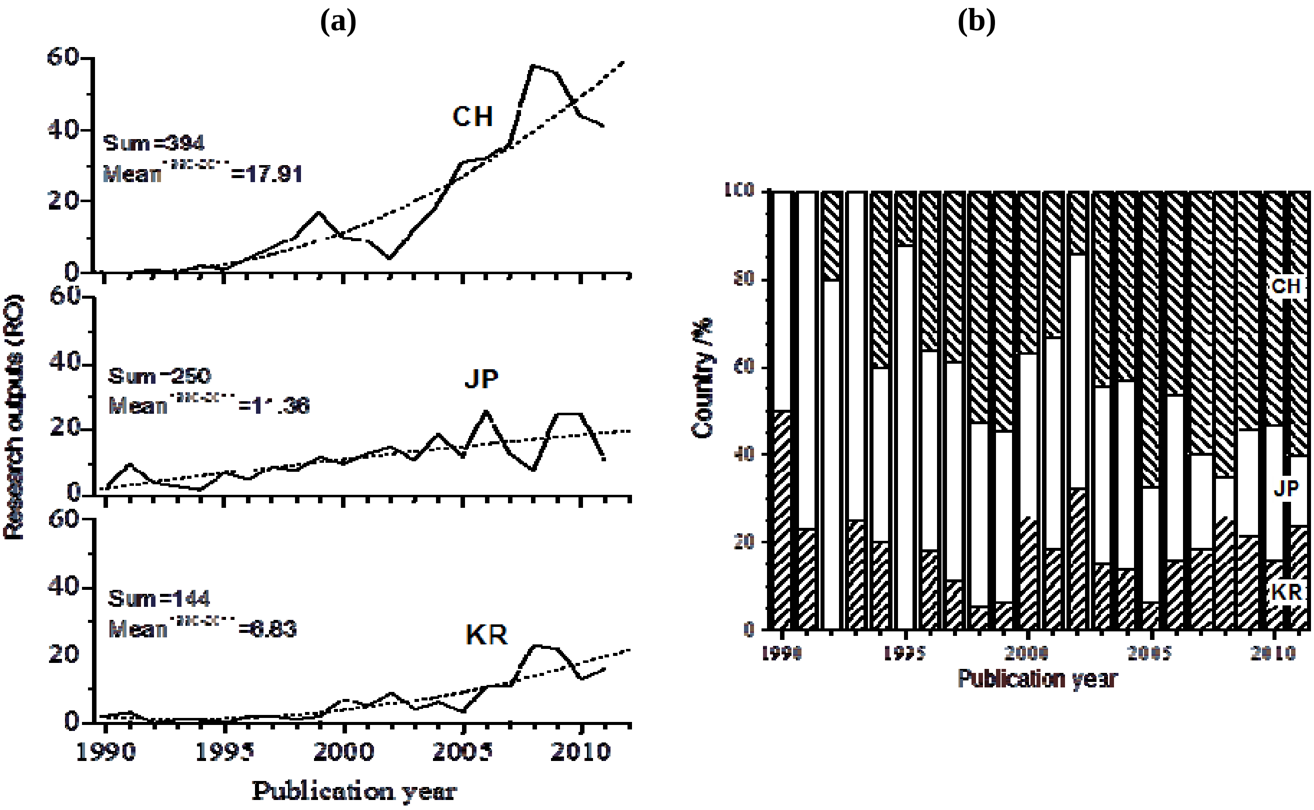
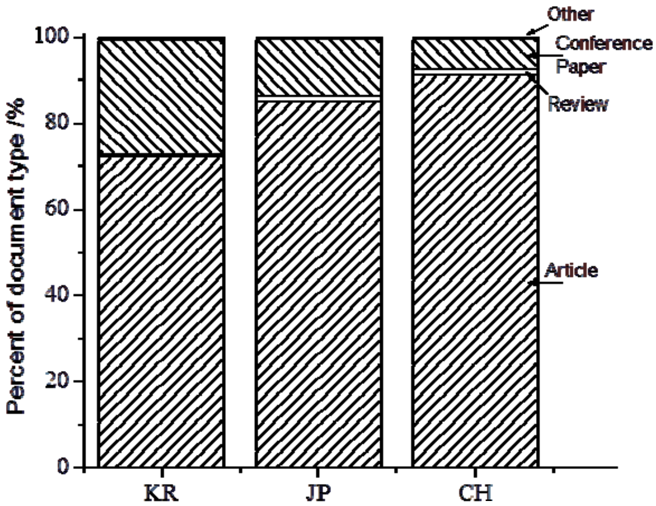


Figure 1b presents the values of research papers from 1990 to 2011 expressed as a percentage by countries. The percent of R&D outputs from China increased strongly for the entire period. Just a decade before the end of the last century the percentage of Chinese research papers published in the international journals was very low (about zero). It should also be noted that the research papers from Korea show statistically increasing trends. Moreover, it becomes clear that Japan's papers in the selected topic declined for the entire period. Japan's share of the output production in this field was more than 37% in 2000 and about 24% in 2009.

Figure 2 depicts the research papers (1990–2011) from selected countries by publication sources. Like any other discipline and subject of science, scholarly outputs account for the majority of papers with 674 records (83.58%) followed by conference papers and reviews with 4236 (11.90%) and

879 publications (2.47%), respectively. In particular, papers represent 91.1%, 85.1% and 72.2% of the national papers in China, Japan and Korea, respectively. Moreover, according to Figure 2, it can be observed that many Korean researchers prefer to publish their works in this field as conference papers (26.4% of national output), whereas Japan's was 13.2% and China's only 7.1% (1990–2011).

Figure 2. Proportions of publication sources produced in the field (1990–2011).



3.2. Subject Categories

There has been a great diversity in the WGS subject areas during the last twenty years. The most common subject areas were Chemical Engineering, Chemistry, Energy, Materials Science, Engineering, Physics, and Environment Science. The total number of papers by major subject area in the last 20 years is given in Figure 3a. China is top for research papers in the fields of Chemical Engineering, Chemistry, Energy, Materials Science, Engineering, Physics and Environment Science. The total research output for China, Japan and Korea on WGS-related research from the top three subject categories (Chemical Engineering, Chemistry and Energy fields), amounted to about 80%. Furthermore, Japan ranks at the top of the charts in Materials Science with 39 papers. Figure 3b presents the percent of R&D outputs with their distribution by subjects (1990–2011).

From Figure 3b we can see that, in comparison with China, a distinct decrease of ranking appeared in energy-related research areas in Japan (24%) and Korea (15%). Another important point to mention is that Japan's research is closely linked to Material Science (39%). Over the last 20 years, engineering disciplines with Korean affiliations showed an increase in the number of published papers (23%). More specifically, the proportion of R&D outputs per subject area exhibited some variation during the time period covered (Figure 4); what is in fact remarkable is that Chemical Engineering and the relative Energy subject area in China increased exponentially with time as shown in Figure 4. The number of China's R&D capacities in these fields indicates the growing interest in Experimental Development (ED) [28] in the last twenty years. The two subject areas in Figure 4 are significant because of their implications for national economies and R&D strategies in the renewable energy field. In comparison to the other countries investigated, however, it should first be noted that Japan also began from a very low base line—for instance similar to Korea's outputs in the year 1995 as a reference point—but the decrease in Chemical Engineering from Japanese institutions was bigger than that for Korea.

Figure 3. (**a**) Subject category distribution of literature on WGS-related research; (**b**) Percentage proportion of subject category distribution in China, Japan and Korea.

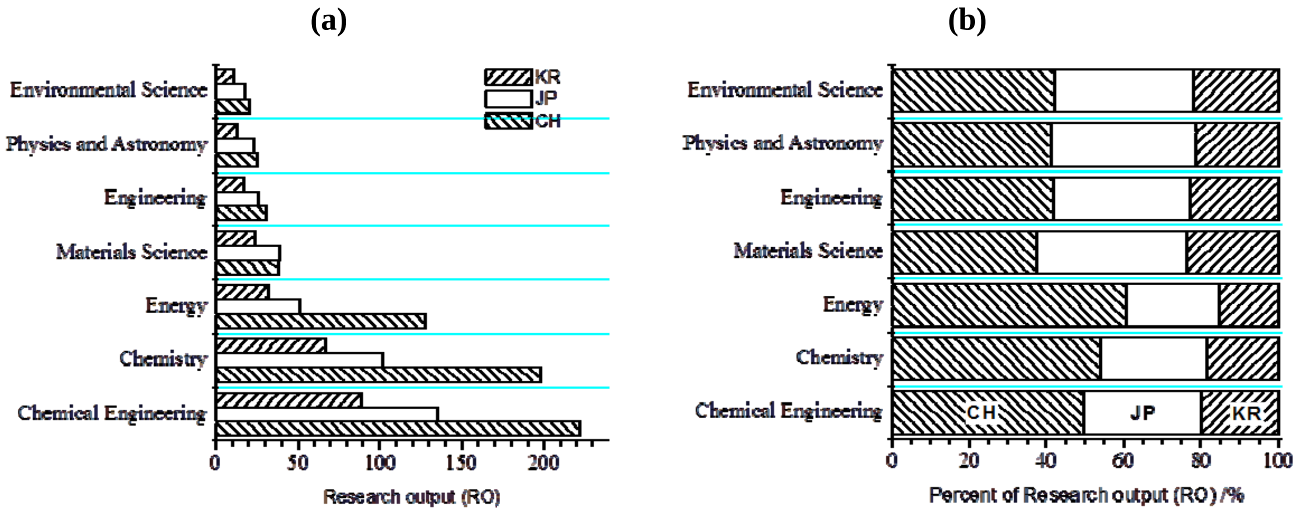
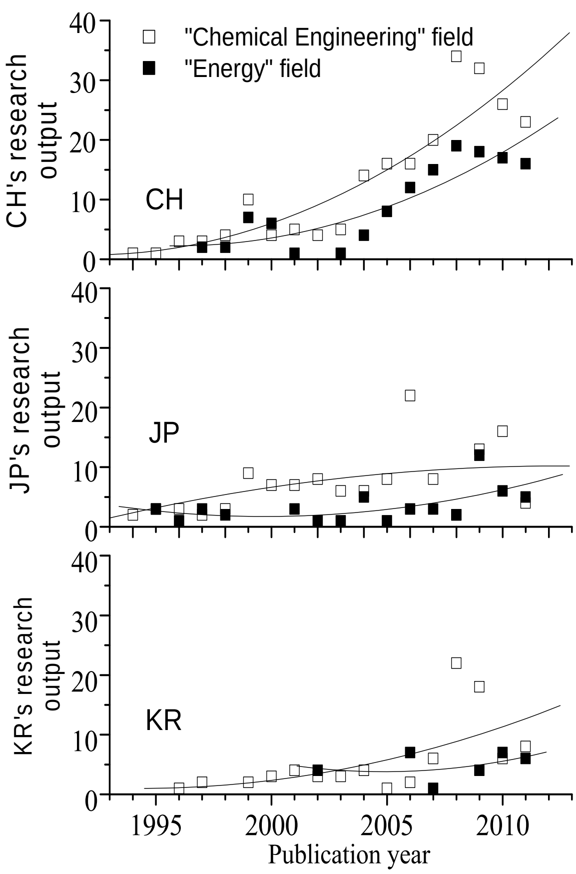


Figure 4. Growth in the number of papers for selected subjects (chemical engineering and energy-related research).



3.3. Journal Sources and Language-Wise Distribution of Paper

The total number of 788 scholarly outputs related to WGS research were scattered in 160 individual journals. The total number of paper on WGS-related research from the top 10 journals amounted to about 35% in the following order: *Applied Catalysis A: General* (48 papers), *International Journal of Hydrogen Energy* (37 papers), *Catalysis Letters* (26 papers), *Catalysis Today* (26 papers), *Journal of Catalysis* (24 papers), *Industrial and Engineering Chemistry Research* (23 papers), *Catalysis Communications* (21 papers), *Chinese Journal of Catalysis* (20 papers), *Journal of Power Sources* (19 papers), and *Journal of Natural Gas Chemistry* (18 papers).

The three journals with the highest impact factor were *Journal of Catalysis* (Impact Factor: 5.415), *Journal of Power Sources* (Impact Factor: 4.283) and *International Journal of Hydrogen Energy* (Impact Factor: 4.053). The distribution of papers (1990–2011) per geographical location in the top-fourteen journals is show in Figure 5. *Applied Catalysis A General* (Impact Factor: 3.383) ranked first with 29 papers from Japanese affiliations, *International Journal of Hydrogen Energy* (Impact Factor: 4.053) with 21 papers from China, and *Korean Journal of Chemical Engineering* (Impact Factor: 0.748) with 13 papers from a Korean institution.

Figure 5. Number of R&D outputs from China, Japan and Korea institutions for selected journals between 1990 and 2011.

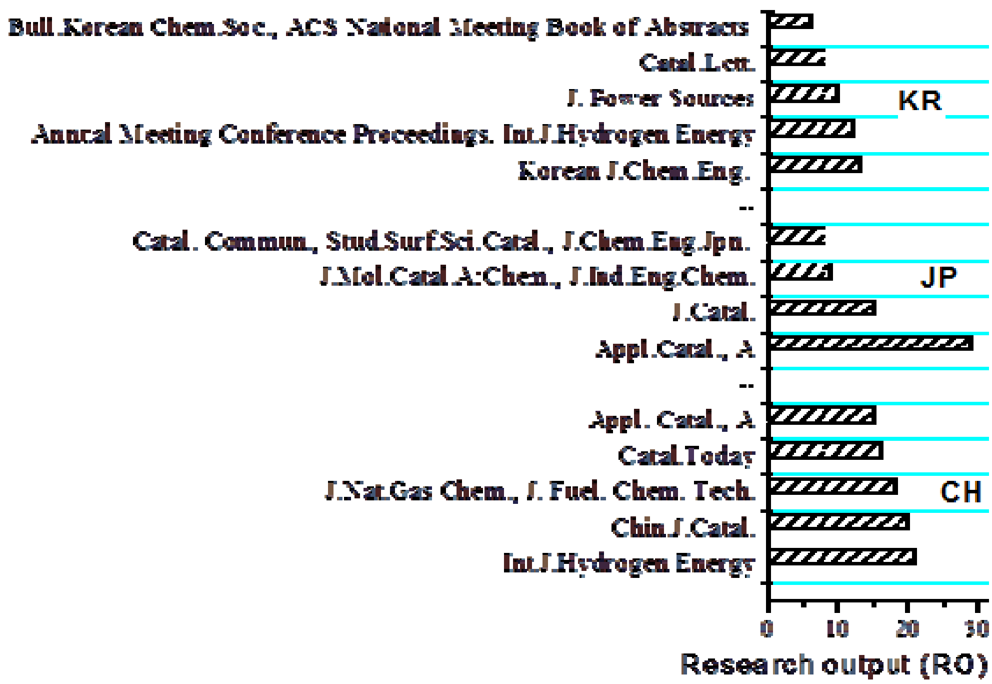
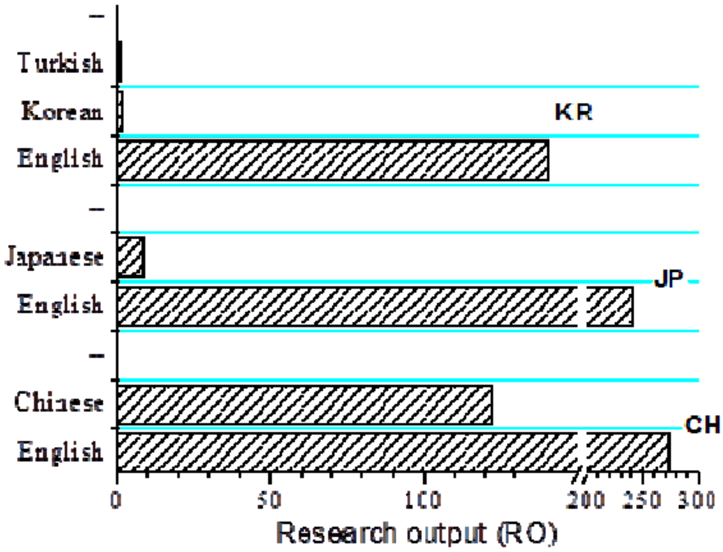


Figure 6 shows the language-wise distribution of papers in three selected countries during the entire studied period (1990–2011); 83.01% of papers were published in the English language, 15.46% in Chinese, 1.14% in Japanese, and 0.25% in the Korean language.

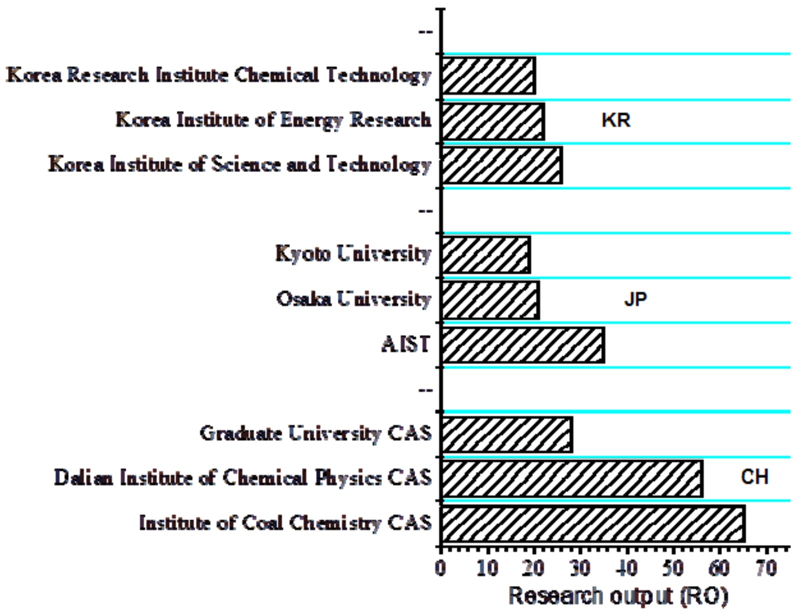
Figure 6. Increase in time of the world's papers written in English, Chinese and Russian languages.



3.4. Organization-Wise Distribution of Publications

This section reviews the cumulative number of papers by institutions in China, Japan, and Korea from early 1990 to the end of last year (2011). During the entire study period (Figure 7), the highest-productive countries in Asian institutions were the *Institute of Coal Chemistry* of the *Chinese Academy of Sciences* (China), which published 65 papers, *Dalian Institute of Chemical Physics* (China), which published 56 papers, *National Institute of Advanced Industrial Science and Technology* (Japan), which published 35 papers, and *Graduate University CAS* (China) which published 28 papers on WGS related research. Indeed, it is remarkable to note that among the top-five are universities from China (3), Japan (1) and Korea (1). In general, these results are acceptable and concur with the rest of the literature [16]. Representative studies on this topic include the work of Du and Teixeira [21].

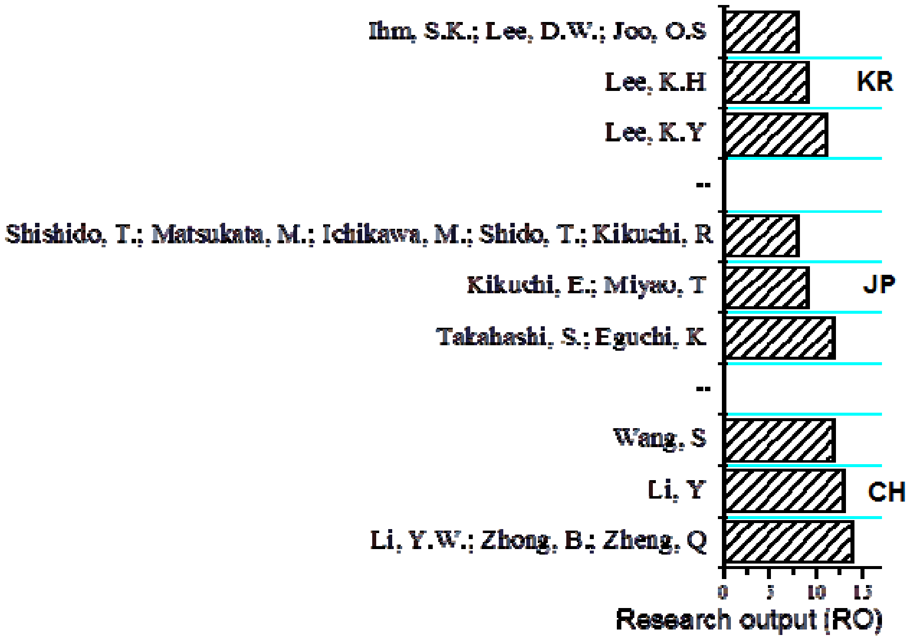
Figure 7. Distribution of R&D papers by top-nine institutions in China, Japan and Korea.



3.5. Authors

R&D productivity of eminent scientists and the impact of research are essential in participatory research processes [23], and the objective here is not to create a ranking of scholars in Asian countries. As Figure 8 shows, the most prolific authors were Y.W. Li (China, 14 outputs), B.Zhong (China, 14), Q.Zheng (China, 14) and Y.Li (China, 13) who topped the list followed by S.Wang (China, 12), S.Takahashi (Japan, 12) and K. Eguchi (Japan, 12). When interpreting these data, the reader should keep in mind that maybe many of those who have had their work published in the selected topic do not appear in the Scopus database [27,28] and that the ranking is based only on data available in January, 2012.

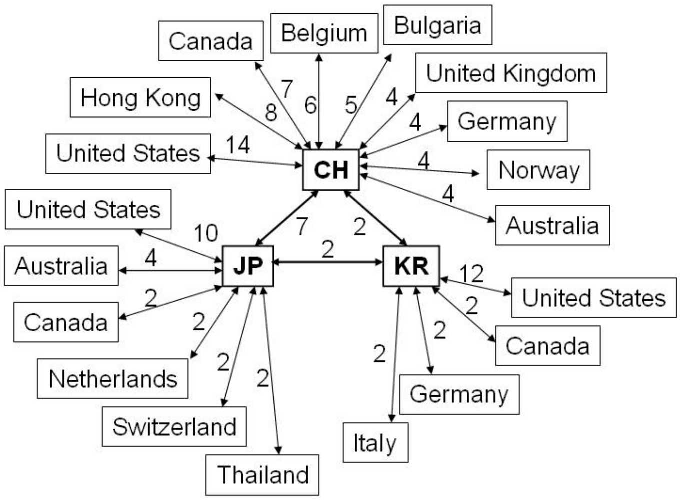
Figure 8. Ranking of the most productive Chinese, Japanese and Korean authors in the selected field.



3.6. Collaboration Patterns in China, Japan and Korea

Common sense seems to dictate that the most characteristic tendency of modern society is intensification of scientific collaboration [29]. In this connection, this section provides such an analysis of co-affiliation in the field of WGS related research between China, Japan and Korea and between these three countries and the rest of the world. A network mapping approach has been used to visualize China's most frequent international collaboration partners. The network structure in Figure 9 is obtained only from co-authorship ties inside the field of WGS in China, Japan and Korea. Collaborative relationships are mapped as bi-directional lines of equal thickness. The internal triangle represents the relative R&D volume of collaborations between the countries of China, Japan and Korea. Significantly, over the period 1990–2011, China's most frequent collaboration partners were also among the largest producers of R&D in the world: United States (14), Hong Kong (8), Canada (7), Belgium (6) and Bulgaria (5) comprise the top five.

Figure 9. International collaboration map for China, Japan and Korea in the period 2006–2010.



3.7. Citations Analysis

King correctly emphasizes that "*the number of citations per paper is a useful measure of the impact of a nation's output*" [16]. In this context, we selected the most cited articles in each year published since 1990 for examination. The top most-cited articles in WGS related research for the period 1990–2011 are tabulated in Table 1. Considering cited R&D papers published since 1990, we find that the number of citations increased from one in 1993 to 102 in 2002. All together, a total of 91 scholars authored the top 20 most cited articles (1990–2011) in the 17 journals. Research output shows an average of 4.55 authors per article in the last twenty-years. In particular, the *Journal of the American Chemical Society* was associated with the most authors per trial [30]; the *Combustion and Flame* [31] and the *Journal of Molecular Catalysis* with the fewest [32]. In the journal ranking list *Journal of the American Chemical Society* was placed 1st (number of citations = 32) with an impact factor of 9.023 [30].

Table 1. Most cited R&D papers in each year published since 1990.

Year	Authors	Title	*Journal*, volume and pages	Citation
1990	Chung, S.H., Williams, F.A.	Asymptotic structure and extinction of CO-H_2 diffusion flames with reduced kinetic mechanisms	*Combustion and Flame*, 82 (3–4), pp. 389–410.	11
1991	Kim, I.-W., Edgar, T.F., Bell, N.H.	Parameter estimation for a laboratory water-gas-shift reactor using a nonlinear error-in-variables method	*Computers and Chemical Engineering*, 15 (5), pp. 361–367.	6
1993	Chu, J.-W., Shim, I.-W.	The chemistry of ruthenium in cellulose acetate: Reactions with CO, H_2, O_2 and H_2O	*Journal of Molecular Catalysis*, 78 (2), pp. 189–199.	9
1994	Song, M.-S., Kim, S.-J., Shim, I.-W., Oh, S.-J., Yang, Y.-S., Suh, H.-K.	Chemistry of ruthenium in polysulfone: Reactions with various small gas molecules	*Reactive Polymers*, 22 (1), pp. 35–46.	1

Table 1. *cont.*

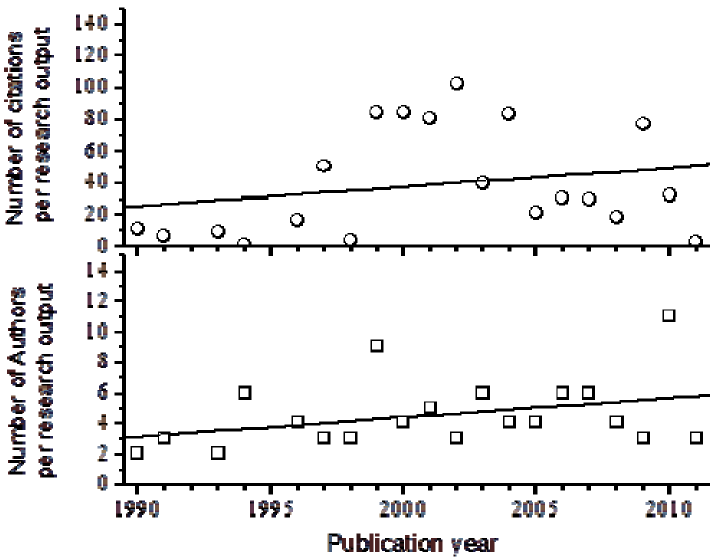
Year	Authors	Title	*Journal*, volume and pages	Citation
1996	Shim, I.-W., Oh, W.-S., Jeong, H.-C., Seok, W.-K.	Preparation of ruthenium-containing polycarbonate films and the chemistry of ruthenium in polycarbonate	*Macromolecules*, 29 (4), pp. 1099–1104.	16
1997	Fisher, I.A., Woo, H.C., Bell, A.T.	Effects of zirconia promotion on the activity of Cu/SiO_2 for methanol synthesis from CO/H_2 and CO_2/H_2	*Catalysis Letters*, 44 (1–2), pp. 11–17.	50
1998	Park, J.-N., Kim, J.-H., Lee, H.-I.	A study on the sulfur-resistant catalysts for water gas shift reaction I. TPR studies of $Mo/\gamma\text{-}Al_2O_3$ catalysts	*Bulletin of the Korean Chemical Society*, 19 (12), pp. 1363–1368..	3
1999	Riedel, T., Claeys, M., Schulz, H., Schaub, G., Nam, S.-S., Jun, K.-W., Choi, M.-J., Kishan, G., Lee, K.-W.	Comparative study of Fischer-Tropsch synthesis with H_2/CO and H_2/CO_2 syngas using Fe- and Co-based catalysts	*Applied Catalysis A: General*, 186 (1–2), pp. 201–213.	84
2000	Patt, J., Moon, D.J., Phillips, C., Thompson, L.	Molybdenum carbide catalysts for Water-Gas Shift	*Catalysis Letters*, 65 (4), pp. 193–195.	84
2001	Moon, D.J., Sreekumar, K., Lee, S.D., Lee, B.G., Kim, H.S.	Studies on gasoline fuel processor system for fuel-cell powered vehicles application	*Applied Catalysis A: General*, 215 (1–2), pp. 1–9.	80
2002	Lee, I.-G., Kim, M.-S., Ihm, S.-K.	Gasification of glucose in supercritical water	*Industrial and Engineering Chemistry Research*, 41 (5), pp. 1182–1188.	102
2003	Riedel, T., Schulz, H., Schaub, G., Jun, K.-W., Hwang, J.-S., Lee, K.-W.	Fischer-Tropsch on iron with H_2/CO and H_2/CO_2 as synthesis gases: The episodes of formation of the Fischer-Tropsch regime and construction of the catalyst	*Topics in Catalysis*, 26 (1–4), pp. 41–54.	39
2004	Oh, Y.-K., Seol, E.-H., Kim, M.-S., Park, S.	Photoproduction of hydrogen from acetate by a chemoheterotrophic bacterium Rhodopseudomonas palustris P4	*International Journal of Hydrogen Energy*, 29 (11), pp. 1115–1121.	83
2005	Ko, J.B., Bae, C.M., Jung, Y.S., Kim, D.H.	$Cu\text{-}ZrO_2$ catalysts for water-gas-shift reaction at low temperatures	*Catalysis Letters*, 105 (3–4), pp. 157–161.	21
2006	Youn, M.H., Seo, J.G., Kim, P., Kim, J.J., Lee, H.-I., Song, I.K.	Hydrogen production by auto-thermal reforming of ethanol over $Ni/\gamma\text{-}Al_2O_3$ catalysts: Effect of second metal addition	*Journal of Power Sources*, 162 (2 SPEC. ISS.), pp. 1270–1274.	30

Table 1. *cont.*

Year	Authors	Title	*Journal*, volume and pages	Citation
2007	Brunetti, A., Barbieri, G., Drioli, E., Lee, K.-H., Sea, B., Lee, D.-W.	WGS reaction in a membrane reactor using a porous stainless steel supported silica membrane	*Chemical Engineering and Processing: Process Intensification*, 46 (2), pp. 119–126.	29
2008	Kim, S.H., Nam, S.-W., Lim, T.-H., Lee, H.-I.	Effect of pretreatment on the activity of Ni catalyst for CO removal reaction by water-gas shift and methanation	*Applied Catalysis B: Environmental*, 81 (1–2), pp. 97–104.	18
2009	Park, E.D., Lee, D., Lee, H.C.	Recent progress in selective CO removal in a H2-rich stream	*Catalysis Today*, 139 (4), pp. 280–290.	76
2010	Park, J.B., Graciani, J., Evans, J., Stacchiola, D., Senanayake, S.D., Barrio, L., Liu, P., Sanz, J.Fdez., Hrbek, J., Rodriguez, J.A.	Gold, copper, and platinum nanoparticles dispersed on $CeO_x/TiO_2(110)$ surfaces: High water-gas shift activity and the nature of the mixed-metal oxide at the nanometer level	*Journal of the American Chemical Society*, 132 (1), pp. 356–363.	32
2011	Hwang, K.-R., Lee, C.-B., Park, J.-S.	Advanced nickel metal catalyst for water-gas shift reaction	*Journal of Power Sources*, 196 (3), pp. 1349–1352.	2

There was no marked association between the distribution of citations per article published in the selected R&D field and their journal's impact factors. Moreover, there was also no relation between the number of citations and the number of co-authors per R&D paper. In addition, there was a weak positive correlation of growth rates of the number of authors per paper since 1990 (Figure 10). Figure 10 also shows that the number of citations increased with increasing time. The average number of citations per paper was 38.8.

Figure 10. The number of co-authors and citations for research output of the most cited articles in each year published since 1990 (see Table 1).



4. Discussion

Although caution is necessary to draw conclusions from the information reported in the above section, it can be useful to show some interesting observations. The first one is that China had approximately double the number of the total publication of Japan and Korea in the considered time window (1990–2011) but the Korea trend line reported in Figure 1 was similar in shape to that observed in China, with Japan exhibiting a somewhat slower increase in growth. In particular, as summarized in Figure 1, the number of papers in China increases according to an exponential growth model. Japan appeared to exhibit higher numbers of papers, while China and Korea still exhibited rapid growth for the entire period. Based on these comparative trends, the prevision is that Korea will produce R&D results at the end of 2020 as today's China in terms of the number of papers in the field of WGS related research. Intuitively, it is quite possible that Japan is showing stagnation in number of R&D published papers because the number of researchers does not increase that much in comparison with the other two countries.

To verify this assumption, R&D expenditure (as a percentage of GDP or GERD), number of researchers and other economic variables from the countries of China, Japan and Korea were collected from international sources as indicated in Table 2. It is interesting to observe that the total number of researchers in full-time equivalents (FTE) increased substantially from 810.5 to 1423.4 thousands (+75.6%), from 141.9 to 221.9 thousands (+56.3%), and from 646.5 to 710.0 thousands (+9.8%) in China, Korea and Japan, respectively, in a five-year period (2002–2007). For comparison the number of total researchers on a global scale grew from 5810.7 to 7209.7 thousands (+24%) from 2002 to 2007, respectively. This is one logical explanation of the important economic role that China plays in driving increases in R&D results (as number of publications) related to selected topics.

In addition, common observation tells us that this is not only because the percentage of world researchers in Japan have been significantly reduced but also because the GERD as percentage of the Japanese GDP has not increased with the same rapidity as China and Korea. In particular, Japan's expenditure on R&D increased only from 108.2 to 147.9 (37%), whereas Korea and China continually increased from 22.5 to 41.3 (83%) and from 39.3 to 102.4 (160%), respectively, during the same period of time.

The second general observation is that, as a useful simplification of Table 2, the GERD for China, Japan and Korea amounted to almost a quarter of that for all countries in the world; this means that these three countries have more than 30% of the world R&D in 2007. For instance, from Table 2 it is interesting to observe that the percentage of GDP on R&D expenditure has increased from 6.2% during 2002 to 8% during 2007 for the three selected countries. Generally speaking these economic data are in agreement with previous studies where China and Korea are often cited as rising powers in science [10,14,17,28].

The relative positions of China, USA, and South Korea have been studied extensively over the last few years (see for instance [33]) and numerous reviews have appeared on this subject [34]. In particular, the results reported in our study are consistent with the interpretation proposed by Zhou and Leydesdorff where the author correctly argues that in future "*our center of gravity of the world system of science may be changing accordingly*" [33]. Moreover, the recent report of The World Bank Group, "China 2030: Building a Modern, Harmonious, and Creative High-Income Society", shows how R&D policies and environmental regulation have contributed to green innovation in the field of green technologies in China [34].

To further validate the results obtained that GERD does play a role in the total number of researchers in full-time equivalents (FTE) and then in the number of R&D outputs of the Chinese, Japanese and Korean academic communities, we can reasonably compare both variables in the same plots. Figure 11 illustrates the weighting of the ratio between GERD and FTE in the world between 1997 and 2009. In 1997, the world ratio between GERD and FTE was found to be 3.37. During the period 1997 to 2009, it increased progressively to an average value of about 3.94.

Table 2. R&D Expenditure (GERD) and Researchers in China, Japan and Korea (2002 and 2007) [35].

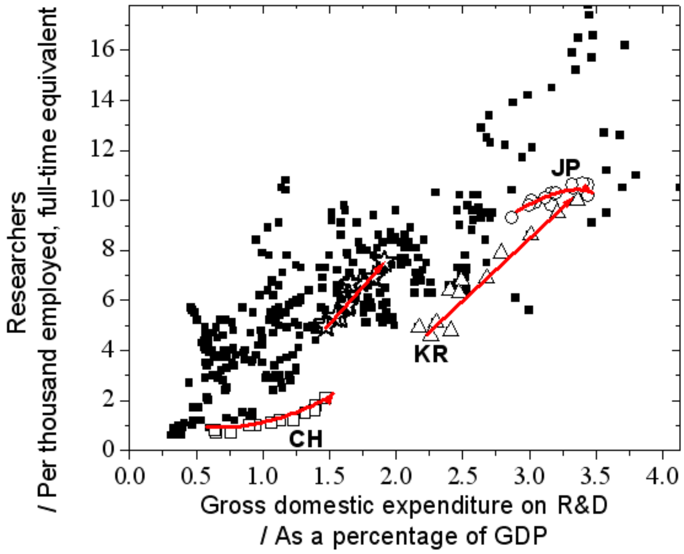
	Year	**China**	**Japan**	**Korea**	**Asia**	**World**
GERD (in billion PPP$) [1]	2002	39.2	108.2	22.5	213.9	790.3
	2007	102.4	147.9	41.3	369.3	1145.7
% world GERD	2002	5.0%	13.7%	2.8%	27.1%	100%
	2007	8.9%	12.9%	3.6%	32.2%	100%
GERD as % of GDP [2]	2002	1.1%	3.2%	2.4%	1.5%	1.7%
	2007	1.4%	3.4%	3.2%	1.6%	1.7%
Researchers (FTE) (thousands) [3]	2002	810.5	646.5	141.9	2064.6	5810.7
	2007	1423.4	710.0	221.9	2950.6	7209.7
% world Researchers	2002	13.9%	11.1%	2.4%	35.5%	100%
	2007	19.7%	9.8%	3.1%	40.9%	100%
Researchers per million in habitants [4]	2002	630.3	5087.0	3022.8	554.2	926.1
	2007	1070.9	5573.0	4627.2	745.9	1080.8
GERD per Researchers (thousand PPP$)	2002	48.4	167.3	158.6	103.6	136.0
	2007	72.0	208.4	186.3	125.2	158.9

Notes: [1] Gross Domestic Expenditure on R&D (GERD) and researchers data: UNESCO Institute for Statistics (UIS) estimations, June 2010; [2] Gross Domestic Product (GDP) and Purchasing Power Parity (PPP) conversion factor (local currency per international $): World Bank; World Development Indicators, as of May 2010 and UIS estimations; [3] Researchers are in Full-time equivalents (FTE); [4] Population: United Nations, Department of Economic and Social Affairs, Population Division, 2009; World Population Prospects: The 2008 Revision and UIS estimations.

First of all, this means that the official policy of all countries in the world is that the number of researchers must increase over time also in order to create R&D in environmental conservation fields. On the other hand, at national level, it is important to note here that whereas the ratio rate—as an expression of national effort in R&D sectors—decreased little between 1997 and 2009 in Japan (from 3.24 to 2.96), expenditure/researchers ratio in China and Korea increased from 1.09 to 1.57 and from 2.13 to 3.01, respectively, during this same time period. In order to make this change more comprehensive, we should note that the Japanese ratio of GERD to FTE increased marginally during the period up to 2006 reaching a high of 3.15, before declining modestly through to 2009 (3.03), whereas the China- and Korea-ratio represents exponential growth and a contribution with linear growth in time, respectively.

The results of the experimental section of the three selected countries show other points of interest. As previously stated, another significant discussion comes from a deep analysis of the proportion of types of publication produced in the WGR field between 1990 and 2011. In fact, according to Figure 2, the third important consideration is related to the different nature of the R&D activities between papers, reviews and conference papers.

Figure 11. GERD *versus* total number of researchers in full-time equivalents (FTE) for China (CH = □) Korea (KR = Δ) and Japan (JP = O) between 1997 and 2009. The star indicates the overall mean of the data set in the world between 1997 and 2009.



China's R&D effort in WGS related research is strongly centered on peer-revised papers in a ratio of 12.8 papers to each conference article. The average percentages of Papers published in international journals and conference papers with a Chinese affiliation (1990–2000) are about 91.1% and 7.1%, respectively, whereas in contrast conference papers are more than 26.4% of overall Korean R&D, over the same period of time. In other words, Korean researchers prefer to publish their research results in domestic/national journals and proceedings, while Chinese researchers prefer to publish their research results in international "high-impact" journals. Here we can also note that the review system at conferences is quite different to the extended, revised journal-paper version and conferences usually have a higher standard of novelty. So, the possible explanation for the findings in Figure 2 is that the national distribution of research outputs is correlated with the distribution of R&D expenditure between Basic Research (BR), Applied Research (AR) and Experimental Development (ED) across the countries considered. In this respect, according to the Frascati Manual, R&D is defined as the sum of three mutual activities described as follows: "*Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view. Applied research is also original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective. Experimental development is systematic work, drawing on existing knowledge gained from research and/or practical experience that is directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed*" [26].

R&D expenditure type, subdivided into its four different components (basic research, applied research, experimental development, and unknown) for each country is reported in Table 3.

Table 3. R&D expenditure type and its four components: Basic research (BR), Applied research (AR), Experimental development (ED) and Unknown (UK) in China, Japan and Korea (2008).

	GERD (in billion PPP$)	**GERD (in billion PPP$) by type of R&D activity**				**GERD (in percent) by type of R&D activity**			
		BR	**AR**	**ED**	**UK**	**BR (%)**	**AR (%)**	**ED (%)**	**UK (%)**
CH	121.4	5.9	15.1	100.4	–	4.8	12.5	82.8	–
JP	148.7	16.9	32.2	93.1	6.4	11.4	21.7	62.6	4.3
RK	43.9	7.0	8.6	28.2	–	16.1	19.6	64.3	–

From this point of view, Table 3 indicates that R&D expenditure in China was mostly concentrated in Experimental Development with 82% of all expenditure. In 2008, Applied Research in Japan accounted for 21.7% percent of the national R&D. Moreover, the Korean government investment in Basic Research was about 16.1%. Noteworthy is that, the data in Table 3 show that China's investment in Basic Research is especially low and quite insignificant compared to the other two countries. More specifically, these results suggest that there is concordance between single government investments in R&D and the number of peer-revised papers in international journals. These results also suggest that there is also an inverse relation between R&D investments in Basic Research and Conference Papers. On the one hand, the country's changes in government investments between basic research, applied research and experimental development can also be correlated with the subject category distribution between China, Japan and Korea (see Figures 3 and 4) in the Chemical Engineering, Chemistry and Energy fields. On the other hand, according to the results reported in Section 3.3 the journal distribution analysis also largely confirms previous findings related to R&D investments and interests in the international journals dedicated to catalysis, chemical engineering and energy-related research (see Figure 5).

There is also a possible explanation for the findings on the distribution of papers written in the English, Chinese, Japanese or Korean languages (see Figure 6). From a language perspective, about eight-tenths of the output on WGS related research from the selected countries is written in the English language (see Figure 6), which indicates that English—"*the lingua franca of research*" [33]—is consolidated as the main language of scientific communication in Asia. As a first approximation, we can consider that the distribution of the language of R&D outputs is tied to the geographical affiliations of researchers. For example, China has increased its publications also in the Chinese language to the extent that it is now the highest producer of R&D outputs in this language between the three considered countries in a ratio of 0.82 Chinese papers to each English paper from Korea.

It can be observed that the paper productivity in applied research in this field of the first two Chinese institutes is about four times higher than The National Institute of Advanced Industrial Science and Technology (AIST) in Japan, and five times higher than The Korea Institute of Science and Technology (KIST) in Korea. In particular, an interpretation based on the fact that the top-two universities (see Figure 7) and most productive authors (see Figure 8) in WGS topics are university institutions and authors from China, is consistent with the above economic considerations. Moreover, these results are in agreement with the results of Du and Teixeira [21], and the efficiency of the Chinese higher education system [36].

Finally, the last observation is that in Figure 10 there is somewhat of a local incentive in the selected countries to increase international collaboration with European researchers and an even stronger incentive for China-located researchers to collaborate multilaterally with USA-based authors. In fact, Figure 10 suggests that R&D policy actors in China pay more attention to the creation of new international mechanisms to encourage wider collaborations among scientists with other countries (*i.e.*, United States). Globally speaking, this is one logical explanation for the important role that international collaboration plays in R&D for a new technological field such as WGS-related research [20]. Moreover, this possible explanation is consistent with the earlier observations made on the number of authors per R&D efforts over the last year (Figure 10). In fact, one possible explanation for the trend towards increasing authorship includes the development of novel R&D strategies in the subject of greenhouse gases mitigation by multidisciplinary teams, with subsequent proliferation of multi-authors per R&D outputs. For instance, from Figures 9 and 10 it is clear that international and national collaborations are extensive and of great importance for the selected field of studies—as a case study of the strategies of greenhouse gases mitigation—and in particular for our future energy supply.

5. Conclusions

An interesting finding revealed by the present analysis is that Chinese researchers play a critical role in WGS-related research in Asian countries. In addition to discovering trends in WGS research in China, the study examined the R&D productivity of Korea and Japan by ranking these countries according to scientometric and econometric criteria.

It seems quite clear that—taking into account information from the Scopus database—the notable findings in the study include the fast growing increase in the number of R&D results on the subject. Developing countries—particularly the emerging China and Korea—are responsible for a large proportion of the increase in R&D publications in the field of emerging technologies for reducing greenhouse gas emissions. This is the context for the observations in this paper.

A brief analysis for the countries of China, Japan and Korea of the number of researchers in Full-time equivalents (FTE), Gross Domestic Expenditure on R&D (GERD) and the number of scholarly productions published in the field of WGS reactions suggests that the number of R&D publications in the three selected countries is directly proportional to the financial support for R&D and the number of researchers involved. Moreover, the R&D resource allocation between basic research, applied research and experimental development plays a strong role in the editorial type of scientific publications observed. In conclusion, this paper shows that China has been the major producer of R&D results (as number of publications) in the field of WGS over the last twenty years. Thus, it can be concluded that R&D in this field is closely tied to economic growth and the number of researchers devoted to R&D activities in both bilateral national and international collaborative efforts.

The relationship between R&D outlays and the number of scholarly outputs in the context of China, Japan and Korea collected in this study will be useful for future interdisciplinary research.

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