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Bibliometric analysis of carbon dioxide reduction research trends during 1999–2009

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ABSTRACT

The objective of this study is to conduct a bibliometric analysis of the literature regarding CO_2 reduction trends published in the Science Citation Index-listed periodicals from 1999 to 2009. These documents were obtained by subscription from the Information Science Institute (ISI) Web of Science, Philadelphia, PA, USA. A total of 3,177 authors from 56 different countries wrote 855 articles published in 355 journals in 102 subject categories. Of these, the most titles were found in *Abstracts of Papers of the American Chemical Society* (3.9%). The most frequently cited paper was "Chemical CO_2 fixation: Cr(III) salen complexes as highly efficient catalysts for the coupling of CO_2 and epoxides", and the same paper contained the most often-used keyword.

1. Introduction

Greenhouse gases such as carbon dioxide (CO_2), chlorofluorocarbons (CFC_s), and methane (CH_4) are currently considered the primary causes of global warming. The amount of atmospheric CO_2 has historically been between 180 and 260 ppm. However, according to the French National Center for Scientific Research (CNRS) [1], the atmospheric concentration of this gas over the last 100 years has risen to between 260 and 380 ppm, mainly through the burning of fossil fuels associated with increased population and industrialization [2,3], such as in thermal power plants [4]. Over the past few decades, the atmospheric concentration of CO_2 has been increasing as a result of expanded human activity, which has accelerated the so-called "greenhouse effect" [5].

CO_2 can be photocatalytically reduced to produce methanol (CH_3OH), CH_4, and ethylene (C_2H_4) in a steady-state optical-fiber reactor under artificial light and/or real sunlight irradiation. A maximum methanol yield of 4.12 μmol g-cat^{-1} h^{-1} has been acquired when a 1.0 mass% Ag/TiO_2 photocatalyst was used under a light intensity of 10 W cm^{-2} [5]. Titanium oxide catalysts have been prepared and employed as photocatalysts for the reduction of CO_2 with H_2O to generate CH_4 and CH_3OH [6,7].

The process of CO_2 fixation in a microalgae cultivation system, commonly called a photobioreactor, is interesting because of the effects of cellular metabolism, irradiance distribution, and gas–liquid mass transfer. The green algae *Chlorella vulgaris* has been considered a suitable medium for the biological fixation of CO_2 because it has a relatively good photosynthetic capacity and a high rate of reproduction and is easy to apply in engineering systems [8,9]. For *Scenedesmus obliquus* and *Spirulina sp.* cultivated in a three-stage serial tubular photobioreactor, the maximum daily CO_2 biofixation was found to be as high as 53.29% for 6% (v/v) CO_2 to *Spirulina sp.*, with the corresponding value for *Scenedesmus obliquus* being 28.08% [10]. Similarly, a membrane-photobioreactor was designed using a hollow fiber membrane module integrated inside of it to remove CO_2 with *C. vulgaris* [11,12]. Still another method involved the use of chemical solvents in the same module [13]. By means of electromagnetic field effects on algae growth, CO_2 biofixation can therefore be improved [14]. This method can also fully exploit the further conversion of CO_2 into synthesized chemicals, such as hydrocarbons, carboxylic acid, and alcohols, by various chemical routes [15]. Furthermore, microelectronic processes for the cleaning and rinsing of circuit wafers have more recently been using CO_2-based solvents because CO_2 is nonflammable, virtually inert, and abundant [16]. Certain materials, such as cage-type zeolites [17], Pebax®/polyethylene glycol blend thin film composite membrane [18], and amine-enriched fly ash carbon sorbents [19] have also been found to capture and separate CO_2.

Furthermore, "green energy" wind power will replace conventional thermal power because of its ability to alleviate CO_2 emissions. In Europe, the total wind power generation currently available will help eliminate approximately 90 million tons of CO_2 emissions annually and produce 119 TWh of electricity per year [4].

The purpose of this study is to bibliometrically analyze literature published in Science Citation Index (SCI)-listed periodicals from 1999 to 2009. These documents were analyzed and evaluated

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according to publication distribution and were employed to determine the quantitative characteristics of CO_2 reduction research worldwide.

2. Methodology

The documents used in this study were taken from the database of the SCI obtained by subscription from the Information Science Institute (ISI) Web of Science, Philadelphia, PA, USA. Several terms were adopted as research keywords to facilitate investigation and reference, including "CO_2 fixation", "carbon dioxide fixation", "CO_2 reduction", "carbon dioxide reduction", and "carbon dioxide biofixation".

The documents were analyzed according to their type, language(s) of publication, types of documents, publication output, publication patterns, authorship, citation analysis of articles, impact factor (IF), country or countries of publication, keyword distribution, and cited reference analysis. Searching by document type revealed such items as articles, meeting abstracts, proceedings papers, reviews, letters, editorial materials, corrections, news items, and reprints. The impact factor of a given journal was determined for each document as reported in the 2010 Journal Citation Reports (JCR).

3. Results

3.1. Article characteristics

In total, we found six languages in which these documents were published; the dominant language of choice was English (817; 95.56%), followed distantly by Japanese (15; 1.75%), Chinese (10; 1.17%), German (10; 1.17%), Polish (2; 0.23%), and Russian (1; 0.12%). In types of document analysis, a total of 10 document types were found. Articles, comprising 78.48% (671) of the total, were the most frequent, followed distantly by proceedings papers (78; 9.12%), abstracts of meetings (53; 6.2%), reviews (16; 1.87%), editorial materials (11; 1.29%), news items (11; 1.29%), letters (9; 1.04%), corrections (4; 0.47%), book reviews (1; 0.12%), and reprints (1; 0.12%).

3.2. Publication output

As shown in Fig. 1, the number of CO_2 reduction articles was lowest in 1999, at six articles; this figure increased to 70 in the following year. The number of CO_2 reduction articles published has significantly increased since 2000, peaking at 102 articles in 2008. This number was lower, at 74 articles, in 2005, but 3 years later, in 2010, the number nearly reached 102 articles.

The distribution of citations per publication (CPP) from 1999 to 2007 is also shown in Fig. 1. The values of CPP for the period 2001–2007 oscillate: the average CPP was 10.1. The CPP was lowest in 1999, 2006, and 2007 at 4.0, 7.3, and 7.9, respectively. The CPP values were the highest in 2001, 2003, and 2005 at 13.7, 14.0, and 12.4, respectively. Using 2-year periods to minimize the year-to-year fluctuations, the average CPP values for 2000–2001, 2002–2003, 2004–2005, and 2006–2007 were 12.2, 11.95, 11.85, and 7.6, respectively. Alongside a slight decrease of CPP values in 2006–2007, the citation rates for the same period were also lower than other years, while the number of articles published after 2004 rose slightly compared with the number of articles published in the past.

From 1999 through 2009, the annual number of journal articles published and the number of pages devoted to CO_2 reduction research increased from six articles in 1999 to 88 articles in 2009, increasing approximately 15-fold over a 10-year period. A similar increase appears in number of total pages, authors, journals, and references cited. The average article length increased steadily, with a maximum of 8.3 pages in 1999 and a minimum of 6.2 pages in 2000, with an overall average length of 7.1 pages. The average number of authors per article also fluctuated slightly over the years, with a minimum of 3.2 authors per article in 1999 and a maximum of 4.1 authors in 2007, totaling an overall average of 3.7 authors per article. Approximately 48 related articles were published per journal in 2000 compared with 74 papers per journal in 2009, representing a roughly 1.5-fold increase. The number of references cited grew gradually, from 1,702 in 2000 to 2,604 in 2009, increasing more than 1.5-fold (Table 1).

We found 855 articles published in 101 subject categories. Of these categories, 24 (2.8%) categories contained only one article, and eight (0.94%) categories contained two articles. Table 2 presents the 10 subject categories with the most publications listed by the number of articles, percentage of total articles, and CPP. The total number of publications displayed was actually greater

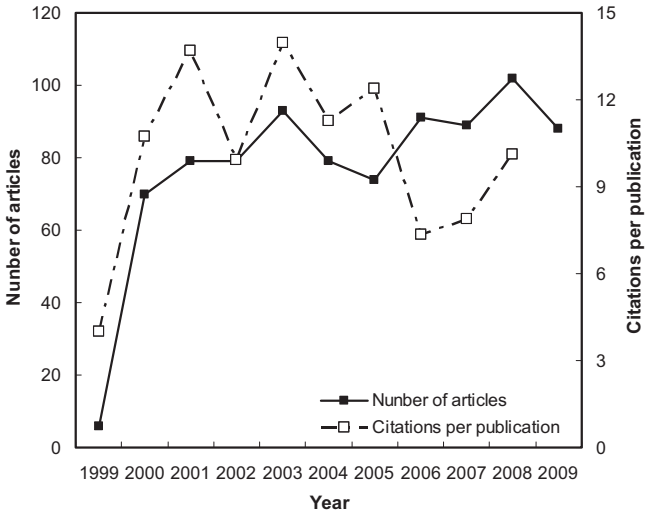

Fig. 1. Article output and CPP by year for CO_2 reduction research.

Table 1
Characteristics of journal articles on CO_2 reduction research.

PY[a]	A[b]	PG[c]	PG/A[d]	AU[e]	AU/A[f]	J[g]	A/J[h]	NR[i]	NR/A[j]
1999	6	50	8.3	19	3.2	5	1.2	97	16.2
2000	70	434	6.2	232	3.3	48	1.5	1,702	24.3
2001	79	523	6.6	293	3.7	58	1.4	1,875	23.7
2002	79	534	6.8	272	3.4	61	1.3	2,025	25.6
2003	93	639	6.9	325	3.5	71	1.3	2,586	27.8
2004	79	570	7.2	277	3.5	55	1.4	2,210	28.0
2005	74	526	7.1	295	4.0	48	1.5	2,074	28.0
2006	91	622	6.8	313	3.4	63	1.4	2,419	26.6
2007	89	680	7.6	365	4.1	71	1.3	2,548	28.6
2008	102	821	8.0	412	4.0	76	1.3	3,528	34.6
2009	88	581	6.6	354	4.0	74	1.2	2,604	29.6
Total	850	5,980		3,157				23,668	
Average			7.1		3.7	57.3	1.3		26.6

[a] Publication year.
[b] Number of articles.
[c] Total page count.
[d] Page count per article.
[e] Number of authors.
[f] Number of authors per articles.
[g] Number of journals.
[h] Articles per journal.
[i] Number of references cited.
[j] Number of references cited per article.

than 855, but this was because some publications appeared under more than one subject category. We found that CO_2 reduction research items were most often published in the engineering, chemistry, and environmental fields. It would seem that because CO_2 exists in the environment, engineering or chemistry would be the fields typically applied to solve the related problems, and indeed, most articles were published under those categories. Our laboratory has also used engineering methods (e.g., photoreactors) to reduce CO_2 with an electromagnetic field. With *Spirulina platensis* cultured at a 300 G electromagnetic field for 5 days, the CO_2 biofixation resulted in a 132% increase compared to when no electromagnetic field was applied.

3.3. Publication patterns

In total, 855 papers were published in 355 journals: 203 (57.2%) journals contained only one related article, 66 (18.6%) journals published two related articles, and 31 (8.7%) journals included three related articles. The remaining 427 articles were published in 86 other journals. Table 3 lists the titles of the 20 journals with the highest publication numbers, including the IF, the subject category of the journal, the position of the journal in its category, the number of papers, and the CPP. The journal *Abstracts of Papers of the American Chemical Society* published the most papers (33; 3.9%), followed by *Journal of the American Chemical Society* (19; 2.22%); CPP (37.13) was first in CO_2 reduction research. The journal with the highest IF (11.83) was *Angewandte Chemie-International Edition*, with 0.82% of all articles. The categories of these 20 journals conformed (90%) with the 10 subject categories given in Table 2.

Table 2
Number of articles and CPP by subject category.

Rank	Subject category	A[a]	CPP[b]
1	Chemistry, multidisciplinary	132	10.7
2	Chemistry, physical	114	12.3
3	Engineering, chemical	101	7.5
4	Environmental sciences	76	7.0
5	Energy and fuels	74	6.7
6	Electrochemistry	71	7.9
7	Chemistry, inorganic, and nuclear	64	9.4
8	Plant sciences	42	9.8
9	Chemistry, organic	40	20.4
10	Engineering, environmental	34	4.6

[a] Number of publications.
[b] Citations per publication.

3.4. Authorship

For the 855 articles published, there were 3,177 authors. The average number of authors per article from 1999 to 2009 was 3.7. Among the 855 articles with author information, 1,980 authors (62.3%) were credited in one article, followed distantly by 256 (8.06%) in two articles, 86 (2.7%) in three articles, 35 (1.1%) in four articles, and 37 (1.16%) in five articles.

3.5. Citation analysis of articles

There were 7,721 citations in the total 855 articles for an average of 9.03 citations per article over a period of 11 years. Among the CO_2 reduction research papers, "Chemical CO_2 fixation: Cr(III) salen complexes as highly efficient catalysts for the coupling of CO_2 and epoxides" was the most frequently cited, having been cited 209 times since it was first published in 2009. This paper was published in the *Journal of the American Chemical Society* (with an IF of 8.58), which is among the 20 journals publishing CO_2 reduction research, as given in Table 3.

Table 3
Twenty journals publishing CO_2 reduction research articles.

Journal	A (%)[a]	IF (rank)[b]	CPP (rank)[c]	Subject category	Rank
Abstracts of Papers of the American Chemical Society	33 (3.9)	–	–	–	–
Journal of the American Chemical Society	19 (2.22)	8.58 (2)	37.16 (1)	Chemistry, multidisciplinary	7/138
Journal of Electroanalytical Chemistry	18 (2.1)	2.34 (13)	10.39 (11)	Chemistry, analytical	25/70
				Electrochemistry	9/24
Energy Policy	16 (1.87)	2.44 (12)	5.19 (17)	Energy, and fuels	18/70
				Environmental sciences	47/180
Inorganic Chemistry	12 (1.4)	4.66 (6)	12.92 (8)	Chemistry, inorganic, and nuclear	3/44
Catalysis Today	11 (1.28)	3.53 (8)	14.64 (6)	Chemistry, Applied Chemistry,	2/64
				Physical, Engineering, Chemical	31/121
					4/126
Electrochemical Acta	11 (1.28)	3.33 (9)	13.55 (7)	Electrochemistry	4/24
Industrial & Engineering Chemistry Research	11 (1.28)	1.76 (15)	6.45 (14)	Engineering, chemical	35/126
Tetrahedron Letters	11 (1.28)	2.66 (11)	24.36 (2)	Chemistry, organic	21/57
Carbon Dioxide Utilization for Global Sustainability	10 (1.17)	–	0.90 (18)	–	–
Chemical Communications	10 (1.17)	5.50 (4)	21.2 (3)	Chemistry, multidisciplinary	15/138
European Journal of Inorganic Chemistry	10 (1.17)	2.94 (10)	11.8 (9)	Chemistry, inorganic, and nuclear	11/44
Journal of the Electrochemical Society	10 (1.17)	2.24 (14)	8.00 (12)	Electrochemistry	10/24
				Materials science, coatings, and films	1/16
Studies in Surface Science and Catalysis	10 (1.17)	–	–	–	–
Green Chemistry	9 (1.05)	5.84 (3)	7.00 (13)	Chemistry, multidisciplinary	14/138
Applied Catalysis B-Environmental	8 (0.94)	5.25 (5)	11.63 (10)	Chemistry, physical	15/121
				Engineering, environmental	3/126
				Engineering, chemical	1/42
Chemistry Letters	8 (0.94)	1.46 (17)	5.63 (16)	Chemistry, multidisciplinary	58/138
Journal of Applied Electrochemistry	8 (0.94)	1.70 (16)	6.00 (15)	Electrochemistry	16/24
Angewandte Chemie-International Edition	7 (0.82)	11.83 (1)	17.43 (5)	Chemistry, multidisciplinary	5/138
Applied Catalysis A-General	7 (0.82)	3.56 (7)	20.14 (4)	Chemistry, physical	30/121
				Environmental science	17/180

[a] Number of articles (percentage of all articles published in the field).
[b] Impact factor.
[c] Citations per publication.

3.6. Impact factor

Fig. 2 depicts the distribution of all publications by their IFs from 1999 to 2009. Over 11 years, the rate of publications with an IF smaller than three was approximately 55.4%, and their publication rates were 17.87%, 15.03%, and 22.49%, respectively. There are three articles with IFs greater than 10, which were published in two journals, *Nature* and *Science*, at IF 34.48 and 29.75, respectively. There are 85 papers (9.94%) for which no IF information was available. The mean IF for all papers in journals was 2.98.

3.7. International collaboration

In total, 855 articles were included in this analysis, and there were 72 articles without author address information on the ISI Web of Science. Fig. 3 shows the top 20 according to most publications by country from 1999 to 2009. Of these, 667 were single country publications (SP), of which 190 articles were international country publications (IP). Table 4 shows that Germany had the highest CPP of total articles (CPP_T) (13.6), while Germany and England had the highest CPP of independent articles (CPP_S) (13.3) and international articles (CPP_I) (18.0), respectively. The mean value of CPP_I (10.0) was higher than CPP_S (7.69), which indicates that international publications had higher citation rates in the fields of CO_2 reduction research.

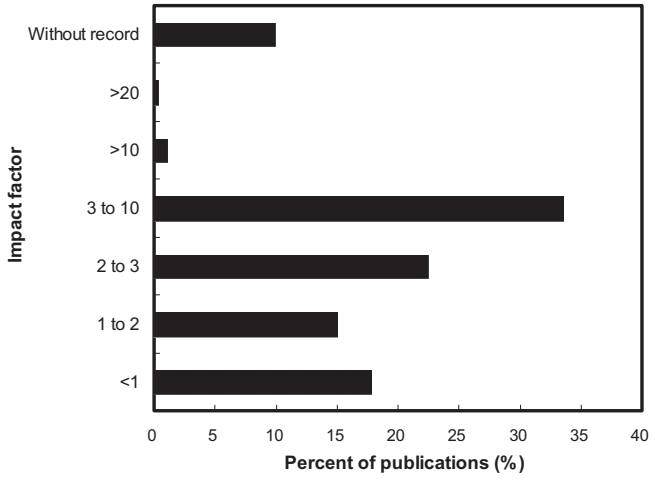

Fig. 2. Distribution of all publications by IF from 1999 to 2009.

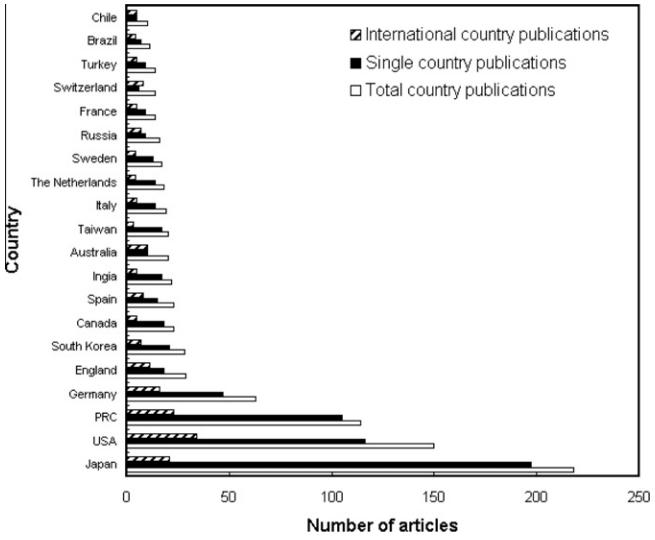

Fig. 3. Twenty countries with the highest number of publications from 1999 to 2009.

3.8. Keyword, cited reference analysis

Of the 855 articles included in the keyword distribution analysis, 365 were without keyword information on the ISI Web of Science. There were 1,520 words listed, 1,242 (81.7%) of which were used only once, and 147 (9.67%) of which were used twice. Fig. 4 lists the 20 most often used keywords from 1999 to 2009. "Carbon dioxide" was used 131 times, followed by "Carbon dioxide fixation" (20 times), "Photocatalysis" (26 times) and "Carbon dioxide reduction" (24 times). The most frequently cited paper was "Chemical CO_2 fixation: Cr(III) salen complexes as highly efficient catalysts for the coupling of CO_2 and epoxides". In that paper, the

Table 4
The 20 most-cited publications by country from 1999 to 2009.

Country	TP[a]	CPP_T (Rank)[b]	CPP_S (Rank)[c]	CPP_I (Rank)[d]
Japan	218	6.20 (17)	5.87 (15)	9.29 (11)
USA	150	12.21 (2)	12.90 (2)	9.85 (9)
China	114	10.70 (5)	9.91 (6)	14.30 (6)
Germany	63	13.60 (1)	13.30 (1)	14.38 (5)
England	29	10.86 (4)	6.50 (11)	18.00 (1)
South Korea	28	4.42 (19)	4.80 (17)	3.29 (20)
Canada	23	7.78 (11)	6.39 (13)	12.80 (8)
Spain	23	9.48 (7)	10.40 (4)	7.75 (14)
India	22	7.59 (12)	5.76 (16)	13.80 (7)
Australia	20	8.20 (10)	10.10 (5)	6.30 (15)
Taiwan	20	10.50 (6)	11.59 (3)	4.30 (18)
Italy	19	9.32 (8)	9.64 (7)	8.40 (12)
The Netherlands	18	9.27 (9)	6.57 (10)	14.75 (4)
Sweden	17	7.29 (14)	4.77 (18)	15.50 (2)
Russia	16	2.88 (20)	2.44 (20)	3.43 (19)
France	14	7.57 (13)	6.44 (12)	9.60 (10)
Switzerland	14	12.14 (3)	8.50 (8)	14.88 (3)
Turkey	14	4.86 (18)	4.44 (19)	5.60 (17)
Brazil	11	6.73 (16)	7.29 (9)	5.75 (16)
Chile	10	7.20 (15)	6.20 (14)	8.20 (13)

[a] Total country publications.
[b] Citations per publication of total country publications.
[c] Citations per publication of single country publications.
[d] Citations per publication of international collaboration publications.

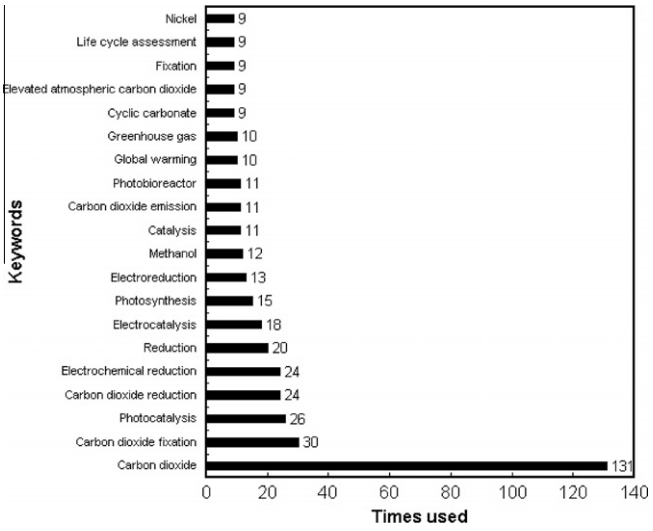

Fig. 4. The top 20 most frequently used keywords.

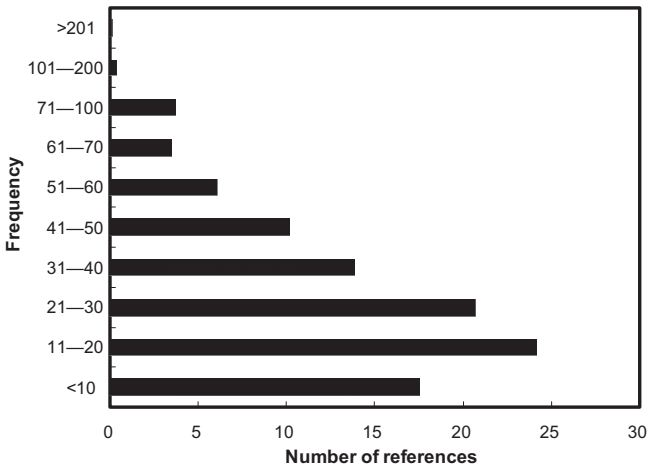

Fig. 5. Distribution of reference numbers.

most often used keyword, "Carbon dioxide", coincided with the most cited publication. These results show that keyword analysis can be applied to reveal research trends.

In total, of the 855 articles that were included in cited reference analysis, 70 were unreferenced on the ISI Web of Science. Of these 70, six documents types were found: Meeting Abstracts ($A = 49$), followed by News Items ($A = 10$), Editorial Materials ($A = 4$), Articles ($A = 3$), Proceedings Papers ($A = 2$) and Letters ($A = 2$). There were 23,991 references listed, and the number of cited references was seen to rise slightly over the years, as listed in Table 1.

Fig. 5 reveals that the majority of articles, 204 (24.14%), had 11–20 references, 175 articles (20.71%) had 21–30 references, and 17.51% had 10 references or fewer for every article. However, one article published in *Biochimica et Biophysica ACTA-proteins and Proteomics*, Vol. 1784, No. 12, in 2008 had 324 references listed.

4. Conclusions

Our bibliometric analysis indicates that the output of CO_2 reduction research articles has significantly increased since 2000. Articles published under the category "*Chemistry*, *Organic*" have generally higher CPP values than other categories. The journal that published the greatest number of articles was *Abstracts of Papers of the American Chemical Society*. The most published country was Japan, but international collaboration publications were less common from there than from the USA. The most frequently cited article was "Chemical CO_2 fixation: Cr(III) salen complexes as highly efficient catalysts for the coupling of CO_2 and epoxides", which was published by Paddock and Nguyen (2001) [20]. Of the research examined, the most frequently used keyword phrase (carbon dioxide) conformed to the most cited paper. These results indicate and reinforce that keyword analysis can be applied to reveal research trends globally.

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