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A bibliometric analysis of research papers published on photosynthesis: 1992-2009

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Abstract

We present here a bibliometric analysis of publications on photosynthesis research from 1992 to 2009 in the Science Citation Index Expanded (SCI-Expanded) Web of Science. This has allowed us to examine the growing trends and the key topics on this subject. We have assessed the document type, language of the publications, publication output, subject category, journal distribution, countries and territories of these publications, institutions involved, hot topics and highly cited papers. The top 30 countries/territories were ranked according to their total number of articles (TA), single country articles (SCA), internationally collaborative articles (ICA), first author articles (FAA) and corresponding author articles (CAA). Research directions on the subject of photosynthesis were also investigated and evaluated by statistically analyzing the distribution of author keywords in the database. Our analysis indicates that "water", "stress", "carbon dioxide", "nitrogen" and "climate change" are hot topics of research on photosynthesis during this period.

Additional key words: author keyword; research trend; scientometrics; science citation index expanded.

Introduction

Oxygenic photosynthesis is the process by which plants, algae and cyanobacteria use energy from sunlight to produce sugar and release oxygen (Blankenship 2002, Govindjee and Krogmann 2004), both of which are critical to supporting life systems on earth. Early photosynthesis-related research activities can be traced back to the 17th century when van Helmont examined the biomass accumulation of a willow tree in Belgium (Rabinowitch 1945, Clayton 1980, Hill 2011) and today is one of the most important research areas among many fields, such as plant science, environmental science, ecology and oceanography. For the history of various aspects of photosynthesis research, we refer the readers to Govindjee *et al*. (2005) who have included in their book "Discoveries in Photosynthesis" more than 100 perspectives by the discoverers (or their students).

Photosynthesis involves numerous biochemical and biophysical processes ranging from molecule to ecosystem scales. Many ground-breaking discoveries, such as light and dark reactions (Bassham *et al.* 1950, Calvin *et al.* 1950, Blankenship 2002), O_2 evolution (Hill 1937, 1939), energy and electron transport (Govindjee 2000, Govindjee and Krogmann 2004), chlorophyll fluorescence techniques (Schreiber *et al.* 1986, Strasser and Govindjee 1991, Papageorgiou and Govindjee 2004), carbon assimilation pathways (de Saussure 1804, Kortschak *et al.* 1965, Hatch and Slack 1966, Benson 2005, Bassham 2005) and photosynthetic modeling (Farquhar *et al.* 1980, von Caemmerer and Farquhar 1981, O'Leary 1981), have been achieved through the

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Abrreviations: CAA – corresponding author articles; FAA – first author articles; ICA – internationally collaborative articles; IICA – inter-institutionally collaborative articles; JCR – Journal Citation Reports; SCA – single country articles; SCI-Expanded – Science Citation Index Expanded; SIA – single institution articles; TA – the number of total articles; TC2009 – total citation of papers from their initial publication to the end of 2009.
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long history of photosynthesis studies. Meanwhile, a great number of publications have been published on photosynthesis and related fields. Until September 29, 2011, the Science Citation Index Expanded (SCI-Expanded) database alone has collected 95,198 papers on the photosynthesis published since 1899. In addition, hundreds of books have also been published on the topic in various languages.

With increasing concerns about global change, particularly climate change (Li *et al.* 2011), a growing number of studies have investigated photosynthesis in response to temperature change (*e.g.* Yamasaki *et al.* 2002, Ghannoum *et al.* 2010a,b), water- and drought stress (*e.g.* Huber *et al.* 1984, Flexas *et al.* 2009, Delaney *et al.* 2010), salt- and alkali stress (*e.g.* Chaves *et al.* 2009, Yang *et al.* 2009), nutrient levels (*e.g.* Platt *et al.* 1992, Ferrier-Pages *et al.* 2000), heavy metal stress (*e.g.* Awasthi and Das 2005), light intensity (*e.g.* Mohamed and Jansson 1989, Tjoelker *et al.* 1995) and CO_2 concentration (*e.g.* Harley *et al.* 1992, Reddy *et al.* 2010). This is because photosynthesis is a fundamental biochemical process which plays a critical role in carbon, water, and nutrient cycles in various ecosystems determining ecosystem carbon sequestration capacity and global biogeochemical cycles.

It is necessary to analyze the vast amount of publications on photosynthesis in order to (*1*) understand the dynamics of the topic, (*2*) identify key research areas in the field, and (*3*) provide guide lines to future studies on photosynthesis issues. The bibliometric method which takes advantages of the modern technologies in computer engineering, database management, and statistics is ideal for this purpose. Bibliometric analysis has been successfully applied to many fields, such as biology (*e.g.* Sainte-Marie 2010), solid waste research (*e.g.* Fu *et al.* 2010), atmospheric simulation (*e.g.* Li *et al.* 2009a), water research (*e.g.* Wang *et al.* 2010) and lung cancer (*e.g.* Ho *et al.* 2010).

The aim of this study is to systematically analyze all the peer-reviewed articles on photosynthesis published in the SCI-Expanded database from 1992 to 2009 to (*1*) characterize the spatial and temporal dynamics of these publications by language, country/territory, institution, journal and research field; (*2*) identify popular topics and the most-cited articles; and (*3*) recommend guide lines for future potential research directions on photosynthesis and related fields, especially under future global climate change and increasing environmental pressures.

Methodology

Documents used in this study are derived from the Thomson Reuters Web of Science database which is based on the online version of SCI-Expanded. According to the *Journal Citation Reports* (JCR), this database indexed 7,387 journals with citation references across 174 scientific disciplines in 2009. Documents published with the words "photosynth*", "photosystem" and "photorespira*" (but not including "photosynth" and "photosynthetica" as abbreviations in journal titles) in titles, abstracts, author keywords and keywords plus from 1992 to 2009 were downloaded from the database and analyzed with bibliometric techniques in the current study. Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified as being from the United Kingdom (UK). Articles from Hong Kong published after 1997 were not included in the China category, but as a separate territory for consistency. Collaboration type was categorized and determined by the addresses of the authors as: (*1*) single country articles (SCA) with address(es) from the same country, (*2*) internationally collaborative articles (ICA) with author addresses from more than one country or territory (Li *et al.* 2009a), (*3*) single institution articles (SIA) with address(es) from the same institution, and (*4*) inter-institutionally collaborative articles (IICA) with author addresses from more than one institution (Malarvizhi *et al.* 2010). The impact factor of a journal was determined for each document as reported in the JCR 2009.

Results and discussion

Document types and the language of publications: We identified 18 document types in a total of 64,993 publications during the 18-year study period. Journal articles (53,724) were the most frequently used document type accounting for 83% of the total publications. They were followed by proceeding papers (4,299; 6.6%), reviews (3,837; 5.9%), and meeting abstracts (1,833; 2.8%), with the remainder of less than 2% including notes (454), editorial material (392), letters (166), corrections (110), news items (60), additional corrections (37), biographical items (29), bibliographies (17), reprints (13), items about an individual (8), discussions (6), book reviews (4), software reviews (3) and database review (1). We focus on the journal articles in the current study because journal articles are not only the majority of the publications but include full descriptions of the research. Our further analysis was based on 53,724 journal articles which were published in 19 languages and 98% of the articles were published in English during the study period. The non-English articles were published in Russian (353), Chinese (203), Japanese (180), Portuguese (149), German (115), French (104), Spanish (72), Czech (32), Korean (14), Hungarian (12), Lithuanian (9), Rumanian (6), Croatian (3), Slovak (3), Polish (2), Turkish (2) and one each in Serbian and Italian, accounting for only 2% of the total journal articles.

Characteristics of publication output: The SCI-Expanded database does not include the "abstract" section of the articles published before 1991, but it includes article titles for a much longer period since 1900. It is noted that the database features all the four components, namely titles, abstracts, author keywords and keywords plus from 1991. Therefore, we conducted a long-term trend analysis from 1900 to 2009 by using article titles only. In total, we found 38,312 related documents published from 1900 to 2009 and 29,938 of which were articles, accounting for 78% of the overall documents. The annual publication of articles increased slightly before 1950, jumped nonlinearly from the 1950s to the 1980s and leveled off since the early 1990s (Fig. 1). The scarcity of articles published before 1950 might be attributed to the lack of understanding of photosynthetic mechanisms. A breakthrough in the field was marked by an article entitled "The path of carbon in photosynthesis. V. paper chromatography and radioautography of the products" (Benson *et al.* 1950) published in *Journal of the American Chemical Society*, with a total citation of 591 times from its initial publication to the end of 2009. In this article, the mechanism, known as the famous "Calvin-Benson Cycle" was proposed. The discovery of the Calvin-Benson cycle is a milestone in the history of photosynthetic research. Studies on photosynthesis have increased remarkably following this famous article, which is demonstrated by the rapid increase of the total number of articles published since the early 1950s.

The fast increase in the number of articles published in the 1980s can also be attributed to a couple of ground-breaking papers on photosynthesis modeling. In the early 1980s, Farquhar *et al.* (1980) and von Caemmerer and Farquhar (1981) published two highly important papers presenting a process-based biochemical model of photosynthetic CO_2 assimilation, with citations of 2,191 and 2,204 times, respectively, from the time of their initial publications to 2009. It is through this model that the complicated relationship between CO_2 assimilation and electron transport can be quantitatively and explicitly investigated. Furthermore, this model has provided a powerful tool in scaling up photosynthesis from single leaves to ecosystems and even global scales (Harley *et al.* 1986, Sellers *et al.* 1992, Rastetter 1996) and thus this model has been widely used in ecological, hydrological and bioclimate modeling. Only 116 articles were published on photosynthesis modeling in the SCI-Expanded database from 1900 to 1979, but the number of articles on the same topic jumped to 11,655 since the initial publication of Farquhar's model in 1980 to 2009. Until now, Farquhar's model is still the most commonly used photosynthesis model because of its enormous power in understanding and characterizing the complex processes of photosynthesis (von Caemmerer and Evans 2010).

Another milestone in photosynthesis research is represented by the paper of Genty *et al*. (1989) "The relationship between the quantum yield of photosynthetic electron-transport and quenching of chlorophyll fluorescence" (*see* Papageorgiou and Govindjee 2004). In the field of photosynthesis this is the paper which has been most frequently quoted; 2,892 times in the SCI-Expanded database by 2009. However, a breakthrough in the quenching analysis of chlorophyll fluorescence was published earlier by Schreiber *et al.* in 1986. These advances in chlorophyll fluorescence measurement have become some of the most extensively used techniques by plant physiologists and ecophysiologists (*see* Maxwell and Johnson 2000). Interestingly, the annual number of publications on photosynthesis since the early 1990s has not continued the fast growing trend in the 1980s following the publication of this important paper (Fig. 1).

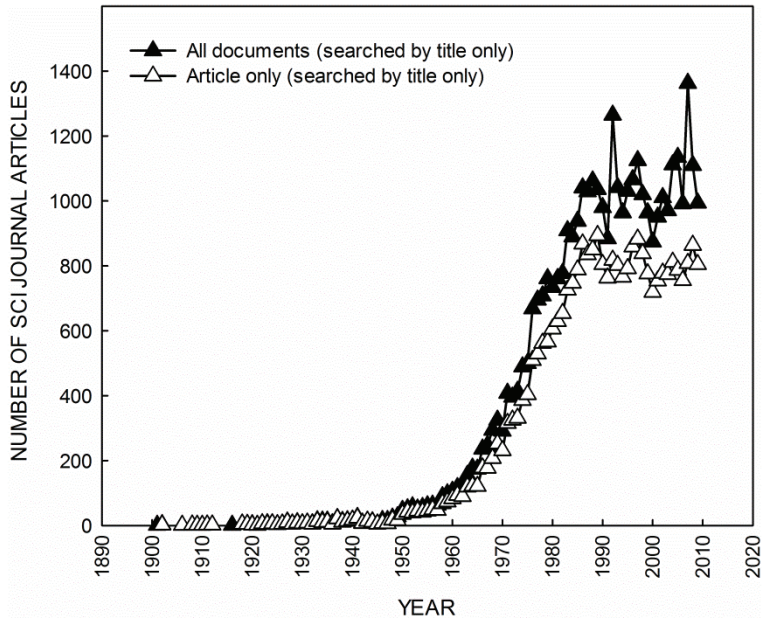

Fig. 1. World SCI-Expanded journal publications per year with "photosynth*", "photosystem", and "photorespira*" in titles during 1900-2009.

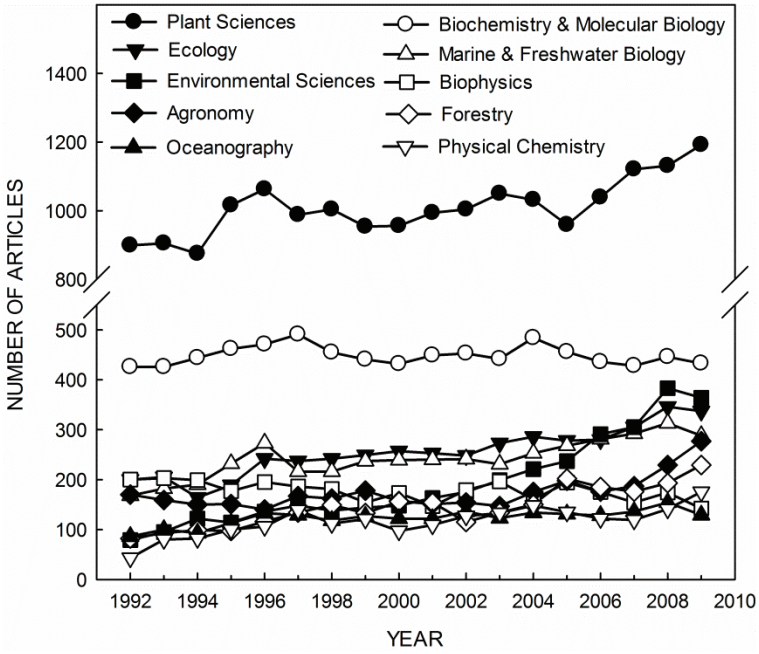

Fig. 2. Comparison of total articles among top ten subject categories.

The reason for this trend change is unclear, but this may shed some light on the limitations of chasing new techniques, which many young researchers are targeting, rather than asking pertinent scientific questions.

Output in subject categories and journals: Based on the classification of subject categories of the JCR in 2009, the output data of articles in photosynthesis research were distributed between 148 SCI subject categories. Plant sciences (18,182; 34% of all articles) was the most common category included in 174 journals; followed by the categories of biochemistry and molecular biology (8,075; 15%), ecology (4,591; 8.5%), marine and freshwater biology (4,360; 8.1%), environmental sciences (3,462; 6.4%), biophysics (3,189; 5.9%), agronomy (3,128; 5.8%), forestry (2,597; 4.8%), oceanography (2,214; 4.1%), and physical chemistry (2,089; 3.9%) (Fig. 2). Articles published in categories of agronomy and forestry have increased in recent years indicating that food security and forest carbon sequestration may continue to be the growing fields in the future study of photosynthesis. This is because photosynthesis is the central process for biomass accumulation in forests and grain production for crops.

There were 53,724 articles published in 2,150 different SCI-Expanded journals. *Plant Physiology*, listed in the category of plant sciences with an impact factor of 6.235, was ranked first with 1,347 (2.5%) articles on photosynthesis published in the journal. *Photosynthetica* (IF = 1.072) which is also listed in the category of plant sciences was ranked second with 1,246 (2.3%) articles published on the subject, followed by *Biochemistry* (IF = 3.226) in the category of biochemistry and molecular biology with 1,220 articles and *Photosynthesis Research* (IF = 2.303) with 1,138 articles. Moreover, *Acta Crystallographica Section A* with one published article had the highest impact factor (49.926). Other journals with a high impact factor, such as *Nature* (IF = 34.48), *Reviews of Modern Physics* (IF = 33.145), *Cell* (IF = 31.152) and *Science* (IF = 29.747) published 216, 1, 9, and 134 articles, respectively. We hope these statistical results will help researchers select journals when publishing their articles on photosynthesis-related research.

Publication performance of countries/territories and institutions: The contribution provided by different countries/territories was estimated by focusing on the location of the affiliation of at least one author of the published papers. Not all of the articles were included in this analysis as 67 (0.12%) articles were without author address information in the SCI-Expanded database. There were 53,657 articles with author address information, published from 1992 to 2009 from 156 countries. Of all the articles, 40,091 (75%), from 114 countries had authors of the same country (*i.e.* were SCA) and 13,566 (25%) involved international collaboration with 153 other countries. Forty-two countries had no SCA, while three countries had no ICA. Twenty-three countries contributed only one or two SCA and 30 countries contributed only one or two ICA. The top 20 countries/territories were ranked according to their number of total articles (TA). This included five indicators: TA, SCA, ICA, first author articles (FAA) and corresponding author articles (CAA) (Malarvizhi *et al.* 2010). The rank and percentage of internationally collaborative articles among the total articles for each country was also considered (Table 1). All the top five countries with the most publications on photosynthesis were G7 (the seven major industrial

Table 1. Top 20 most productive countries based on the total number of articles published. TA – the number of total articles; TAR – the rank of total articles and percentage; SCAR – the rank of single country articles and percentage; ICAR – the rank of internationally collaborative articles and percentage; FAAR – the rank of first author articles and percentage; CAAR – the rank of corresponding author articles and percentage; CR – the percentage of internationally collaborative articles in its total articles for each country and rank.

Country/territory	TA	TAR [%]	SCAR [%]	ICAR [%]	FAAR [%]	CAAR [%]	CR [%]
USA	16,026	1 (30)	1 (27)	1 (37)	1 (25)	1 (24)	13 (31)
Germany	6,341	2 (12)	3 (7.8)	2 (24)	2 (8.6)	3 (8.2)	48 (51)
Japan	5,163	3 (9.6)	2 (9.5)	5 (10)	3 (8.4)	2 (8.5)	8 (26)
UK	4,099	4 (7.6)	5 (4.9)	3 (16)	4 (5.3)	5 (4.9)	51 (52)
France	3,589	5 (6.7)	6 (4.0)	4 (14)	6 (4.6)	6 (4.5)	55 (55)
China	3,024	6 (5.6)	4 (5.4)	12 (6.4)	5 (5.0)	4 (5.5)	10 (29)
Canada	2,855	7 (5.3)	7 (3.9)	7 (9.4)	7 (4.1)	7 (3.9)	28 (45)
Australia	2,600	8 (4.8)	10 (3.2)	6 (9.7)	9 (3.5)	9 (3.6)	44 (51)
Spain	2,444	9 (4.6)	9 (3.4)	9 (8.0)	8 (3.5)	8 (3.7)	27 (44)
Italy	1,946	10 (3.6)	12 (2.6)	10 (6.8)	11 (2.7)	12 (2.8)	33 (47)
Russia	1,936	11 (3.6)	11 (3.0)	13 (5.3)	12 (2.7)	10 (2.9)	17 (37)
Netherlands	1,857	12 (3.5)	13 (1.8)	8 (8.5)	13 (2.4)	13 (2.3)	59 (62)
India	1,734	13 (3.2)	8 (3.5)	19 (2.5)	10 (2.9)	11 (2.9)	1 (19)
Sweden	1,562	14 (2.9)	14 (1.7)	11 (6.6)	14 (2.0)	14 (2.0)	49 (57)
Israel	901	15 (1.7)	17 (1.1)	15 (3.5)	15 (1.2)	17 (1.1)	43 (52)
Switzerland	870	16 (1.6)	21 (0.84)	14 (3.9)	18 (1.0)	21 (1.0)	53 (61)
Brazil	799	17 (1.5)	15 (1.2)	20 (2.2)	16 (1.1)	15 (1.2)	16 (38)
Denmark	756	18 (1.4)	20 (0.85)	16 (3.1)	20 (0.89)	19 (1.0)	45 (55)
Finland	748	19 (1.4)	18 (0.94)	18 (2.7)	19 (1.0)	18 (1.1)	34 (49)
Poland	744	20 (1.4)	16 (1.2)	23 (2.1)	17 (1.1)	16 (1.2)	16 (38)

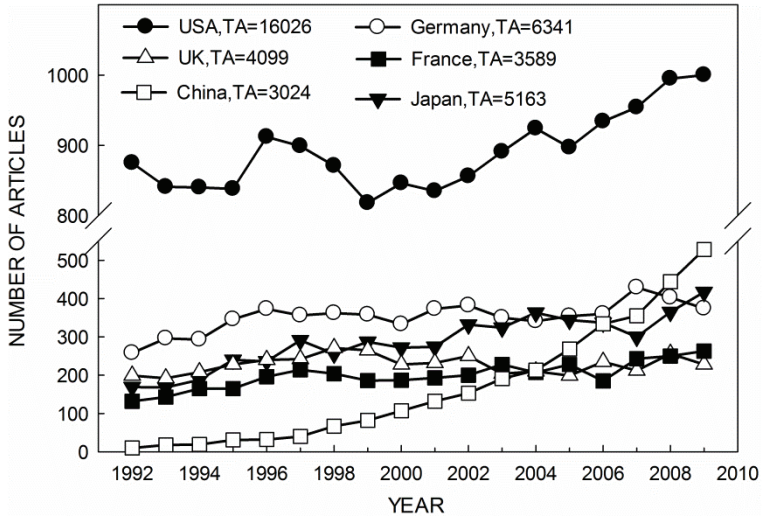

Fig. 3.Comparison of total articles (TA) of the top six most productive countries in the world.

countries in the world) countries: the USA, Germany, Japan, the UK, and France. Canada and Italy were ranked as the seventh and tenth on the list, respectively. China, Australia, and Spain were also ranked in the top ten. Moreover, the G7 had high productivity in SCA (60%), first author articles (FAR) (59%), and corresponding author articles (CAR) (57%). The USA published the most articles (30%), followed by Germany (12%) and Japan (9.6%). The USA also published most of the ICA (37%).

Fig. 3 shows the top six countries which have published more than 3,000 articles on photosynthesis. China, the 6th on the list ranked by TA, has published 3,024 (5.6%) articles with the fastest growing trend. Only 10 articles from China were published in 1992 but the number increased sharply to 528 by 2009. This rapid increase might be attributed to the large-scale initiatives on basic research in China, such as the "211 Project", "973 Plan" and "985 Project" initiated in 1995, 1997 and 1998 respectively (Chen 2006, Meng 2010). We note that "photosynthetic mechanisms" were highlighted in the "973 plan" (www.973.gov.cn). Fig. 4 shows research trends in the four largest high-growth emerging economies, Brazil, Russia, India and China (known as the

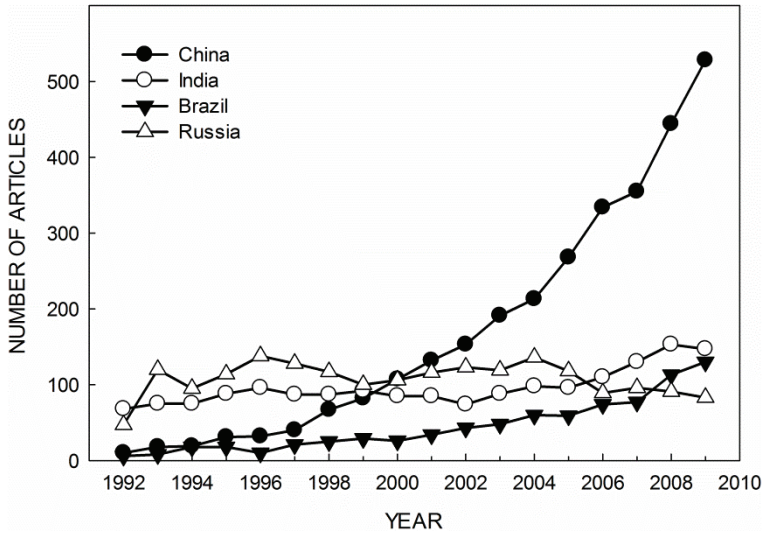

Fig. 4. Comparison of the growth trends of the "BRIC" countries.

Table 2. Top 20 most productive institutions based on the total number of articles. TA – the number of total articles; TAR – the rank of total articles and percentage; SIAR – the rank of single institution articles and percentage; IICAR – the rank of inter-institutionally collaborative articles and percentage; FAAR – the rank of first author articles and percentage; CAAR – the rank of corresponding author articles and percentage.

Institution	TA	TAR [%]	SIAR [%]	IICAR [%]	FAAR [%]	CAAR [%]
Chinese Academy of Sciences, China	1,435	1 (2.7)	1 (2.1)	1 (3.2)	1 (2.0)	1 (2.2)
Russian Academy of Sciences, Russia	1,112	2 (2.1)	2 (2.1)	2 (2.1)	2 (1.3)	2 (1.5)
Consejo Superior de Investigaciones Científias (CSIC), Spain	686	3 (1.3)	8 (0.65)	3 (1.8)	5 (0.70)	5 (0.70)
United States Department of Agriculture, Agricultural Research Service (USDA ARS), USA	665	4 (1.2)	5 (0.77)	5 (1.7)	4 (0.72)	4 (0.75)
Australian National University, Australia	606	5 (1.1)	7 (0.67)	6 (1.5)	6 (0.66)	6 (0.65)
Moscow MV Lomonosov State University, Russia	562	6 (1.0)	3 (1.1)	15 (1.0)	3 (0.75)	3 (0.80)
Centre National de la Recherché Scientifique (CNRS), France	560	7 (1.0)	67 (0.26)	4 (1.7)	20 (0.39)	18 (0.39)
INRA, France	558	8 (1.0)	6 (0.71)	8 (1.3)	9 (0.59)	7 (0.58)
University Tokyo, Japan	532	9 (1.0)	14 (0.57)	7 (1.4)	13 (0.55)	10 (0.52)
University of California Berkeley, USA	526	10 (1.0)	10 (0.62)	9 (1.3)	10 (0.57)	13 (0.50)
University of Illinois, USA	497	11 (0.93)	10 (0.62)	12 (1.2)	7 (0.62)	11 (0.52)
University of Sheffield, UK	488	12 (0.91)	13 (0.58)	13 (1.2)	11 (0.57)	14 (0.46)
Arizona State University, USA	480	13 (0.89)	4 (0.81)	18 (1.0)	8 (0.60)	11 (0.52)
Kyoto University, Japan	477	14 (0.89)	18 (0.47)	11 (1.3)	14 (0.53)	9 (0.53)
University of Florida, USA	450	15 (0.84)	15 (0.56)	14 (1.1)	12 (0.56)	8 (0.56)
National Research Council (CNR), Italy	447	16 (0.83)	41 (0.33)	10 (1.3)	19 (0.40)	15 (0.44)
University of California Davis, USA	420	17 (0.78)	12 (0.59)	20 (1.0)	15 (0.48)	19 (0.38)
University of Wisconsin, USA	412	18 (0.77)	9 (0.62)	21 (0.90)	16 (0.47)	17 (0.40)
Oregon State University, USA	357	19 (0.67)	63 (0.28)	15 (1.0)	37 (0.33)	30 (0.34)
Michigan State University, USA	351	20 (0.65)	16 (0.54)	41 (0.75)	17 (0.43)	19 (0.38)

"BRIC" countries). Again, the fast economic growth in these countries has brought tremendous investment in basic research (Li *et al.* 2009a). Publications of both China and Brazil increased dramatically but the slower growth of Russia and India might be due to the different rate and pattern of technological advances (Tanaka and Ho 2011).

The contribution of different institutions was estimated by the affiliation of at least one author of the published article per institution. Of the 53,657 articles with author addresses, 25,357 (47%) were SIA and 28,300 (53%) were IICA. Table 2 shows the top 20 institutions which are ranked by TA. In the top 20 institutions, nine are in the USA, whereas Russia, France and Japan each have two and the UK, Australia, Italy, China and Spain each have one. Government institutions, such as the Chinese Academy of Sciences, Russian Academy of Sciences, Consejo Superior de Investigaciones Científias (CSIC) in Spain and United States Department of Agriculture, Agricultural Research Service

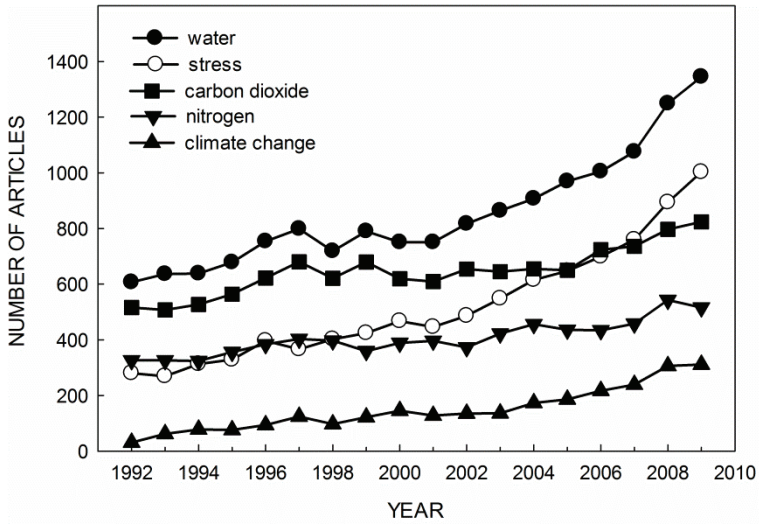

Fig. 5. Trends of hot topics of photosynthesis.

(USDA ARS) in the USA were ranked as the top 4 institutions by TA. Similarly, Centre National de la Recherché Scientifique (CNRS) in France, INRA in France and National Research Council (CNR) in Italy were also ranked in the top 20.

The future trend of hot topics: Author keywords supply the main information in articles and thus research trends can be obtained by analyzing the author keywords (Zhang *et al.* 2010). However, bibliometric methods using author keyword analysis were not possible until recent years (Chiu *et al.* 2007, Mao *et al.* 2010) and few studies have used the information for trend analysis (Xie *et al.* 2008, Li *et al.* 2009b). There were 35,397 articles with author keywords accounting for 66% of all the articles. All the author keywords of the 35,397 articles were ranked according to their frequency. "Water", "stress", "carbon dioxide", "nitrogen" and "climate change" were the most popular keywords among all the 58,675 author keywords examined (Fig. 5). Then, we found that 46,287 articles included at least one of the above five keywords, accounting for 86% of the total articles during the period. Articles referring to water, such as water cycle and water use, are the most popular ones with 15,356 counts (29%) and a continuously rising trend is expected in the coming years. "Carbon dioxide" is the second most popular keyword which appeared in 11,629 (22%) articles. The rise in the study of stress mechanisms in the field of photosynthesis started later than those of carbon dioxide and nitrogen (mainly nitrogen cycle and nitrogen use) and is primarily distributed between "drought and water stress", "temperature stress" and "salt stress". TA on stress has grown remarkably and it has exceeded TA on both "nitrogen" and "carbon dioxide". This suggests that study of the response to stress on the mechanisms of photosynthesis will be expected to be one of the hottest trends in the future.

The most frequently cited articles: Although a great many articles have been published, a relatively small number of individuals account for a large proportion of the citations within the period studied here, 1992-2009. Five most frequently cited articles have been cited more than 1,000 times since their initial publication to the end of 2009 (TC2009) (Fig. 6). Four of them were published in *Nature*. Two of the most frequently cited articles originated in Japan and Germany and one each in the UK, Austria and Netherlands. Among all the articles in the SCI-Expanded database from 1992 to 2009, the most frequently cited article was "Plastic solar cells", which was published in the *Advanced Functional Materials* (IF = 6.99) by Brabec *et al.* in 2001 with 1,572 times of TC2009. However, this article does not actually concentrate on "photosynthesis" but simply mentions the subject in its abstract. This was a great source of bias in our work but could not be avoided. Although we have successfully eliminated several flaws produced by Keywords Plus by separating words related to photosynthesis in article title, abstract, author keywords and Keywords Plus, limitations are still inevitable due to some inherent problems of citation analysis (Stern and Arndt 1999, Tsai *et al.* 2006). Thus, the other 4 articles that were the most frequently cited in the field of photosynthesis, showed a trend to decrease during their citation history (Fig. 6). This is probably due to the 5 to 15 years lifetime of the average cited paper, depending upon the field (Garfield 2000). The year of 2000 was a watershed for these articles cited more than 1000 times. For these 4 top cited articles, three reported crystal structures of light-harvesting complexes (Kuhlbrandt *et al.* 1994, Mcdermott *et al.* 1995) and photosystem II (Zouni *et al.* 2001) and one reported the discovery of the single molecule rotary motor of F1-ATPase (Noji *et al.* 1997). The annual citations of the four articles had declined by the late 2000s indicating the "cooling" trends

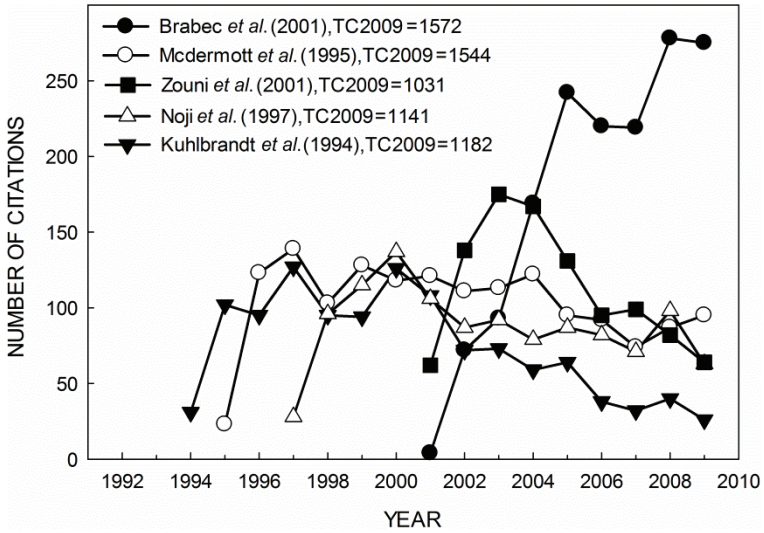

Fig. 6. Comparison of the citation lifetime of the top five articles from their initial publications to the end of 2009 (TC2009).

on these hot topics. It is noted that some highly cited articles published before 1992 are not included in the current analysis because our analyses of "the most frequently cited articles" is only based on articles published between 1992 and 2009.

Conclusion: Eighteen document types relating to photosynthesis were found in a total of 64,993 publications based on the SCI-Expanded database during the period from 1992 to 2009. Articles were published in 2,150 journals in 149 subject categories from 156 countries/territories. Seventy-five percent of the articles were SCA and 25% were ICA. The USA, Germany, Japan, the UK, and France were ranked as the top five countries by TA on photosynthesis. Keyword analysis successfully offered interesting insights into the dynamics of this field. This study shows that photosynthesis research mainly focuses on factors such as water, stress, carbon dioxide, nitrogen, and climate change which have been the hottest topics from 1992 to 2009 and will continue to be the key issues in photosynthetic research in the near future.

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