J Data Sci. Info. Citation Studies. 2022; 1(1):22-34.
https://www.jcitation.org

Research Article

Scientometric Assessment and Mini Review of Graphitic Carbon Nitride ($g-C_3N_4$) for Photocatalytic CO_2 Reduction: An Evidence of Progress

Maxwell Selase Akple*, Charles Atombo, Gabriel Kwame Sipi Takyi, Arnold Dumenya

Department of Mechanical Engineering, Ho Technical University, Ho, GHANA.

ABSTRACT:
The scientific community globally have sought for alternative energy generation approaches and environmental remediation techniques to address the changes in consumption patterns of fossil fuel. Semiconductor photocatalysis has been reported as a potential technique to address the aforementioned challenge with graphitic carbon nitride ($g-C_3N_4$) identified as one of the novel nanomaterial exploration and applications in diverse fields. Many reviews have been reported on $g-C_3N_4$ focusing on photocatalysis principles, preparation techniques, photocatalytic enhancement strategies and various photocatalytic applications. However, in this study, a scientometric assessment was conducted to detail the research status on $g-C_3N_4$ semiconductor for photocatalytic reduction of CO_2 and visualization of the future research trends. The scientometric review covers 504 published articles retrieved from the SCOPUS database online spanning from 2010 to May 2021. The articles were analysed using the VOSviewer mapping tool software using 10 scientometric indices. The results show 461 authors globally contributed to the topic with 333 articles from China and progressive increase in published articles in diverse journals from 1 in 2010 to 88 in May 2021. Collaborations exist between authors and co-authors from various countries and institutions. The new trending areas for $g-C_3N_4$ photocatalysts include nanomedicine, biomedical systems, toxicological industries, food safety monitoring and mathematics.

Keywords: Scientometric analysis, $g-C_3N_4$, Semiconductor, CO_2 reduction, Photocatalysis.

Correspondence
Maxwell Selase Akple
Department of Mechanical Engineering, Ho Technical University, P.O. Box HP 217, Ho, GHANA.
Email id: makple@htu.edu.gh

Received: 25-04-2022
Revised: 14-05-2022
Accepted: 24-05-2022
DOI: 10.5530/jcitation.1.1.4

INTRODUCTION

The continuous development of human society has resulted in an increase in environmental waste generation and demand for energy globally. The current energy supply globally depends largely on fossil fuel sources such as coal, petroleum reserves and natural gases which have been depleted rapidly.[1-2] Furthermore, the consumption of energy from these fossil fuels also contributes to generation of harmful gases into the environment. Over three decades, the scientific community are engineering various materials to overcome the aforementioned challenge of environmental remediation and energy conversion as alternatives to fossil fuel.[3-4] Semiconductor photocatalysis has shown a potential promise as a green technology to generate solar fuels and for environmental remediation applications. Semiconductor photocatalysis has received great interdisciplinary attention for conversion of harmful CO_2 into valuable solar hydrocarbon fuels as well as approach for pollutants removal, water disinfection, and air purification. In addition, semiconductor photocatalysis has shown a great potential in splitting of water into oxygen (O_2) and hydrogen (H_2), where the hydrogen could be used as a source of energy.[2,5-7] To date, several high quality semiconductor photocatalysts have been developed and utilized under both ultraviolet (UV) and visible light.[1,8-11]

Among the several semiconductor photocatalysts fabricated is graphitic carbon nitride ($g-C_3N_4$) which is a metal free polymeric material. The research communities have conducted in-depth research into g-C_3N_4 because of its high physicochemical properties, easy facile preparation, moderate bandgap (≈2.7 eV), suitable electronic band structure, non-toxicity and earth abundant nature.[12-14] The pristine g-C_3N_4 photocatalyst is easily synthesized through thermal polycondensation of organic precursors such as thiourea, urea, melamine, cyanamide and dicyandiamide. However, the pristine g-C_3N_4 obtained from these synthesis process has limited photocatalytic performance from poor visible light harvesting ability, low surface area and rapid recombination of photogenerated charge carriers.[1,12-13] To overcome the aforementioned challenges, several modification techniques such as doping, heterostructuring, surface plasmon resonance effect, morphology tuning, metal deposition, semiconductor coupling etc. have been reported to enhance the photocatalytic performance of g-$C_3N_{4.}$[1,12,14-16] There is an increase interest in the study of g-C_3N_4 semiconductor photocatalysis recently with the past few years witnessing a surge in published literature reviews.[1,13,17-19] Most of the literature reviews regarding g-C_3N_4 photocatalysis focused on photocatalysis principles, physicochemical properties, preparation techniques, photocatalytic enhancement strategies and various photocatalytic applications.[1,17,20-27] However, to the best of our knowledge, detailed research status on g-C_3N_4 semiconductor photocatalysis and visualization of the future research trends have not been fully explored. Thus, in order to address this existing research gap, a scientometric analysis was conducted. A scientometric analysis involves quantitative study of science, communication in science and science policy.[28] It includes assessment and measurement of impact of published articles, authors, journals, institutions, scientific citations and visual mapping in the scientific area.[29] In this study, an attempt was made to conduct a scientometric review of published articles in the field of g-C_3N_4 photocatalysis and obtained a snapshot of trends in this field from 2010-2021. In addition, a mini review on the multifunctional applications of g-C_3N_4 as a photocatalyst was also conducted. The results from the study can provide researchers better understanding, development of current trends and hot topics in g-C_3N_4 photocatalysis.

METHODOLOGY

The study employed the bibliometric analysis on g-C_3N_4 and photocatalysis. Scientometric studies involved quantitative aspects of recorded information in a research field. The information for the study was obtained from SCOPUS database in CSV files format. The CSV files were exported into a VOSviewer software which is a mapping tool for Scientometric analysis. A Scientometric analysis is a measure of an evolution of a scientific domain, scholarly publications impact, authorship patterns and scientific knowledge production process. Thus, Scientometric analysis involved progress of research and researchers in a particular field of study and various relationships such as research institutes, universities, researchers, journal publishers and particulars of journals in a scientific domain.[30] In this study, ten (10) scientometric techniques were employed to carry out the analysis. They were analysis of documents, research by subject areas, publication trends, keywords, authors, countries and institutions, citations, co-citations and journals.

Data Collection

The data for the study was obtained from the online SCOPUS database. The SCOPUS database contained about 70 million items and regarded as one of the comprehensive and influential database for academic journal publications related to Elsevier publisher.[31] The search was conducted in May 2021 with the collection of documents spanning from 2010-2021. Keywords in publication titles, abstracts and keywords were searched in the Scopus database. Specifically, the query searched in Scopus was ((TITLE (“”carbon nitride” “OR ““g-C_3N_4”“OR ““graphitic carbon nitride ““OR ““photocatalysis””) AND PUBYEAR > 2009) AND (“”CO_2 reduction”” OR “” carbon dioxide reduction””))”. The search returned 504 documents which includes journal articles, reviews, chapter of books and book.

RESULTS AND DISCUSSION

Types of Documents and Numbers

In this analysis, the search conducted returned a total of 504 documents which was exported in a CSV excel statistic data format from Scopus database of Web of Science (WOS). Figure 1 shows the document types recorded with Articles being 390 (77.38%), Reviews were 106 (21.03%), Book Chapters were 7 (1.39%) and Book was 1 (0.20%). The publications were done in two (2) different languages with 99.6 % proportion in English (i.e. 502 documents) and 0.4% in Chinese (i.e. 2 documents). This implies that the almost all the publications relating to g-C_3N_4 for photocatalytic reduction of CO_2 into solar fuels are in English language.

Distribution According to Research Subject Areas

The numbers of subject areas of publication of g-C_3N_4 for photocatalytic reduction of CO_2 were also studied and analysed. Chemistry, Chemical Engineering and Material Science were the top three research subject areas for the field of g-C_3N_4 in photocatalysis (Figure 2). This is because g-C_3N_4 is a novel metal free semiconductor material which have gained enough research attention over the past two decades. The researches focused on application of the g-C_3N_4 materials in diverse fields such as environmental application, green energy system etc. Currently, the research direction of g-C_3N_4 is shifting to medicine and other multidisciplinary areas as depicted in Figure 2. According to Density Functional Theory (DFT)

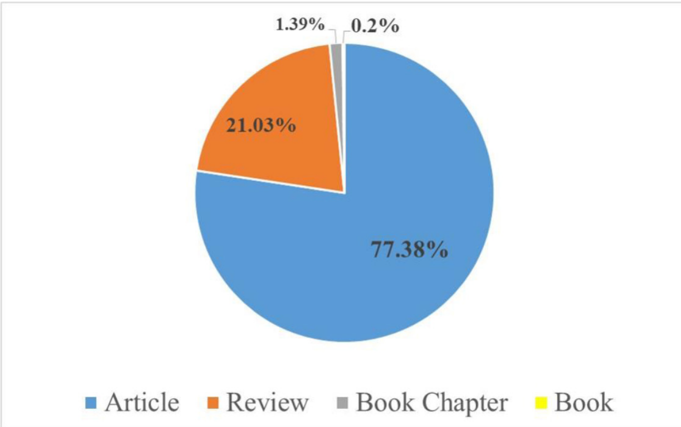

Figure 1: Distribution of proportions of document types in the field of g-C_3N_4 for CO_2 photocatalytic reduction.

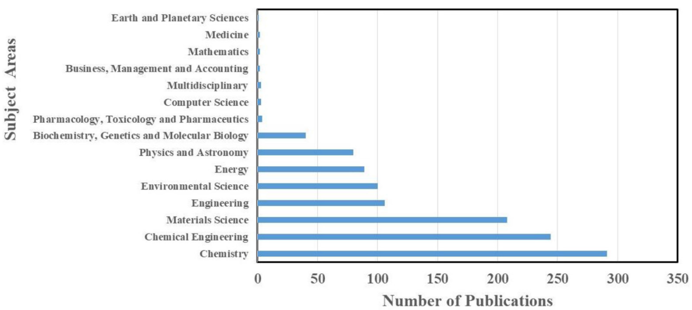

Figure 2: Distribution of publications based on subjects / disciplines.

studies, g-C_3N_4 has a chemotherapeutic potential as a drug carrier for carboplatin and cisplatin (anticancer drugs) in cancer treatment and thus applicable in medicine.[32-33]

Trend Analysis of Publications from 2010 – 2021

The global publication trend in the area of g-C_3N_4 for photocatalytic reduction of CO_2 from 2010-2021 is shown in Figure 3 It can be observed that published documents progressively increased over the years. From 2010 to 2017, the number of documents published was relatively small from 1 to 30 respectively. This could be attributed to the synthesis, characterizations and the application of g-C_3N_4 for photocatalytic CO_2 into solar fuels were still not clear which needed further probe. The number of documents published increased from 2018 (i.e. 68 documents) to 88 documents (i.e. May 2021) significantly due to further researches conducted in this field and the application process become very clear and understandable. The issue of climate change and energy shortage globally is attracting a lot of research. Currently, the development of visible light driven photocatalysts for converting CO_2 into a valuable solar fuels is a research hotspot of which g-C_3N_4 has more potential compared to other materials.[34-35] This also accounted for more published documents in this field recently.

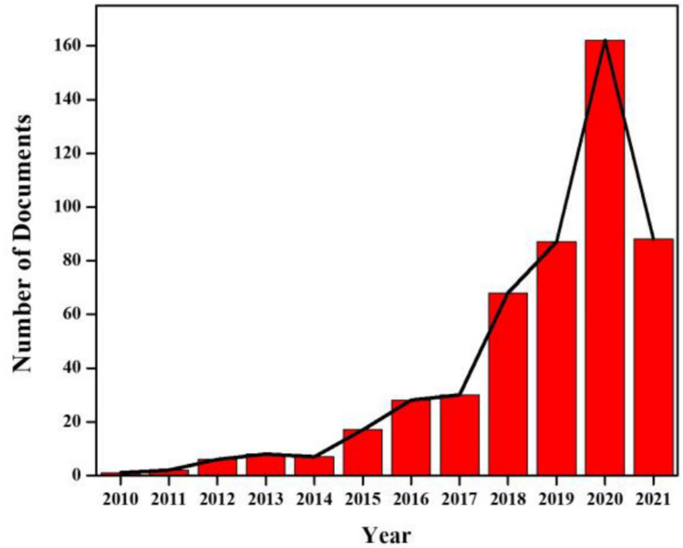

Figure 3: Publication of documents trend over the search period.

Keyword Co-occurrence Analysis and Clustering

Keywords are very important for published documents in a scientific domain for characterization in a specific field. It represents the main content of published articles and display the wide range of the research areas within the limit of any field.[30,36] In this study, clustering of keywords which is a process of placing analysed items with certain similarities into groups or sub categories was carried out. This implies that each cluster of keywords have items or data with similar characteristics but these characteristics differs among the clusters.[30] The cluster of keywords was also used to identify most suitable article or document among a prevailing list of publications in a scientific field and also shows relationship among each word. The Scopus database provides two types of keywords namely the" author keywords" (i.e. keywords that authors provided) and "index keywords" (keywords indexed by journals for article retrieval). Both keywords were employed in this study to ensure that all documents were retrieved.[29,30] The VOSviewer was used to construct and map the field of knowledge between photocatalysis and carbon nitride (g-C_3N_4) using keyword co-occurrence. The result of the scientometric analysis of published documents was shown in the visualization of keywords network of the VOSviewer. The VOSviewer output is a distance-based map where the distance represents the strength of the relation between the two knowledge domains. Generally, the larger or bigger the distance, the weaker the relationship between the two domains. Furthermore, item label size is directly proportional to the number of publications found for the keyword.[36]

The VOSviewer technique cluster the different knowledge domains using different colours as shown in Figure 4. In this study, the minimum number of occurrences was set to 2 and out of the 3583 keywords, 1085 met the threshold.

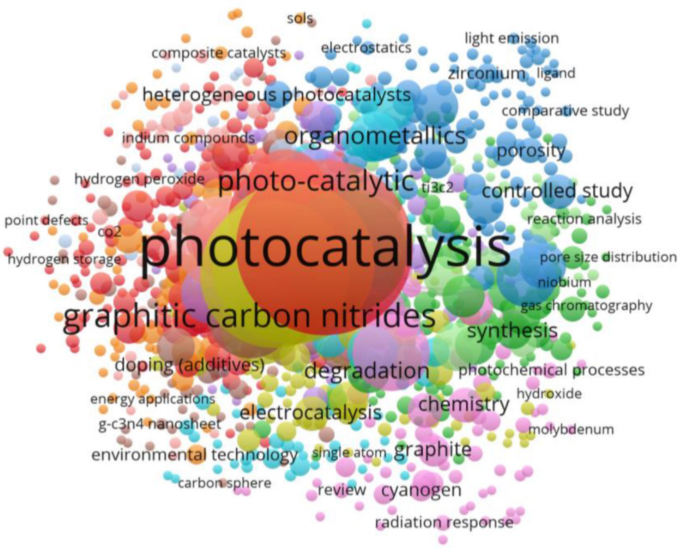

Figure 4: Visual keywords co-occurrence analysis.

To obtain optimal clusters, multiple experiments were used for the threshold selection. The network of co-occurring keywords produced 1000 nodes, 45367 links and 70623 total link strength with 12 clusters. Table 1 shows the first twenty (20) keywords occurrence from the various clusters, their links and total link strength. The top four keywords identified from the VOSviewer output were "Photocatalysis" (Frequency = 240), Carbon dioxide" (Frequency = 211), "carbon nitride" (Frequency =182) and "light" (Frequency = 134). The keywords belong to different clusters and were all subject terms in the field. The term "photocatalysis" is generic which is used to describe the process of utilization of light to stimulate a catalytic activity whiles the term "carbon nitride" represent a specific semiconductor material. Catalytic carbon dioxide conversion can be grouped into different classification namely electrocatalysis, photocatalysis, traditional thermal catalysis, plasma catalysis etc.[2] Therefore, these keywords evidenced that from 2010-2021, photocatalytic reduction of CO_2 into valuable solar fuels using g-C_3N_4 as a semiconductor has received a lot of attention. This is because it is among the important hottest research areas that has the potential of solving the current energy crisis and environmental problems facing the world. In addition, the g-C_3N_4 semiconductor material can easily be prepared, cheap, possess high chemical and physical stability among other characteristics[22,37] which has made it an ideal material worth researching.

For better clarification and understanding of the research hotspots, the keywords in the field of g-C_3N_4 were clustered into 12 by the VOSviewer software. Cluster 1 (made up of 128 items) focused on the general description and applications of photocatalysts such as artificial photosynthetic, doping, heterojunction, morphology, CO_2 reduction, environmental application, environmental pollution etc. Cluster 2 (126 items) generally represent terms which is used to described the chemical processes and mechanisms of CO_2 reduction such as absorption, adsorption, charge carrier recombination, chemical interaction, chemical structure, light etc. Cluster 3 (120 items) represent in-depth terms used to illustrate chemical and electronic structure or properties such as electron transport, excited state, light harvesting, light scattering, mesoporous etc. The frequency of the highest keywords in cluster 4 is associated with the atomic and electronic structure description. They involved keywords such as binding energy, atoms, DFT calculation, first principle calculation, photocurrent response etc. From Table 2, it can be seen that most of the keywords belongs to cluster 1 which described photocatalysis in general and very broad terms to accommodate other important sub areas.

Table 1: Summary of Top 20 Occurrence Keywords and Each Individual Node Strength.

Keyword	Cluster	Occurrences	Links	Total link strength
Photocatalysis	1	240	891	3849
Carbon dioxide	4	211	844	3661
Carbon nitride	4	182	792	3075
Light	2	134	732	2548
Photocatalytic activity	1	124	674	2138
CO_2 reduction	1	112	581	1742
Heterojunctions	10	87	532	1504
Graphitic carbon nitrides	8	74	481	1368
Nitrides	8	70	462	1288
Photocatalytic performance	1	70	505	1230
Graphitic carbon nitride	4	68	463	1063
Hydrogen production	4	66	470	1156
Light absorption	1	63	492	1176
Catalysis	9	62	520	1290
g-C_3N_4	2	55	373	790
Solar energy	7	55	448	1012
Photo-catalytic	5	49	388	761
Catalysts	7	46	418	790
Charge transfer	10	46	379	760
Catalyst activity	4	45	360	658

Co-occurrence Analysis (e.g., countries, institutions, and authors)

Author-Co-authors network

The contribution of authors in the field of photocatalysis and g-C_3N_4 was extracted from the VOSviewer software. This information would help identify and mapped out lead or highly productive researchers in the field as well as collaboration or cooperation between the researchers. A total of 461 authors were retrieved and the top 25 productive authors in the studied field during 2010-2021 was presented in Table 2. Zhang X

Table 2: The Top 20 Productive Authors during 2010-2021 in the Field of g-C_3N_4 and Photocatalysis for CO_2 Reduction.

Ratings	Authors	Article Frequency	Citations	Country
1	Zhang X.	27	1547	China
2	Zhang J.	25	603	China
3	Li Y.	24	1300	China
4	Li X.	24	786	China
5	Wang Y.	23	754	China
6	Li Z.	22	1543	China
7	Wang H.	22	557	China
8	Li H.	21	329	China
9	Wang X.	20	1308	China
10	Zhang Y.	18	932	China
11	Wang L.	16	1006	China
12	Wang C.	13	1890	China
13	Wang S.	12	819	China
14	Liu Y.	12	446	China
15	Zhang T.	11	1627	China
16	Xu H.	11	575	China
17	Wang Z.	11	265	China
18	Liu J.	11	251	China
19	Zhang H.	10	585	China
20	Zhao Y.	10	156	China

produced the largest number of articles (27). Zhang J, Li X and Li Y were rated as second, third and fourth productive authors with 25, 24 and 24 articles respectively within 2010-2021 period. Figure 5 shows the author and co-authorship network.

In this network, the nodes denote an author and the relationship of the collaboration between the author and co-authors of a publication are represented by the links. The size of the node represent the number of articles published whiles the thickness of the link represent the level of collaboration or cooperation between the authors.[29] In all, 461 nodes and 3356 links were generated with a total link strength of 4108.

Figure 5 depicts that there were a lot of collaborations between author and co-authors represented by both the closed-loop and small circuits. The researchers in the circuits show establishment of collaboration or cooperation such as circuit of Zhang X and Zhang J. Furthermore, the study also identified other numerous research communities where many authors had a collaborative working relationship with one or two highly productive author(s). Generally, this research field has several international collaboration or cooperation which would be beneficial to the scientific communities globally.

To determine the extent of many connections or links within the nodes (i.e. authors and co-authors), Betweenness Centrality (BC) analysis was conducted. The BC is defined as

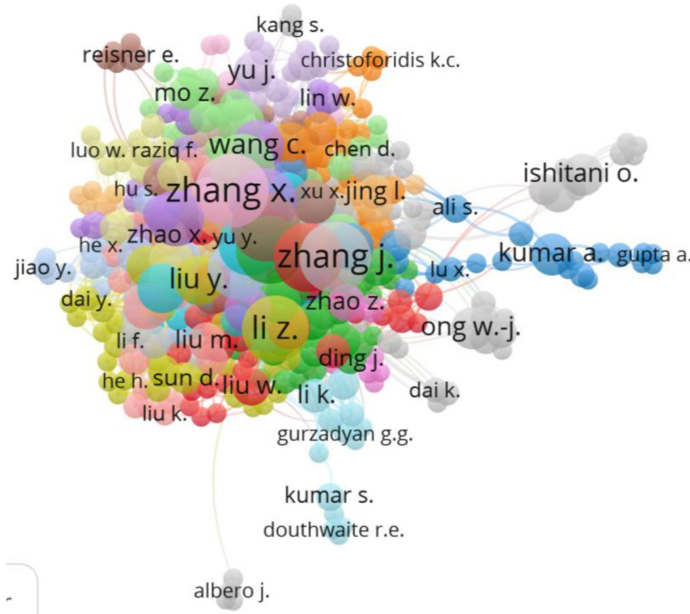

Figure 5: The author and co-authorship map generated from the VOSviewer.

the ratio of the shortest path between two nodes to the sum of all such shortest paths.[38-39] In other words, BC determines the centrality of nodes and nodes value lying in a range of 0 to 1. A node with BC one (1) means it has maximum intermediates (i.e. there is usually connection of two or more large groups of nodes with the node itself in-between) whiles BC of zero (0) implies that only one line connects two ending nodes.[30] In this study, Zhang J have the highest BC of 0.03, which is a quite low, an indication of a weak collaboration between researchers which may need further improvement.

Network of countries and institutions

To further explore the distribution of research publication outputs in field of g-C_3N_4 and photocatalysis for CO_2 reduction, a network map based on countries and institutions were generated. The VOSviewer produced 37 nodes, 118 links and a total link strength of 265. The size of the node represents the total number of published articles within the study period of 2010-2021. China (333 articles), United States (54), India (38) and Japan (30) were the top four main published article contributing countries on the field of g-C_3N_4 and photocatalysis (Table 3). The large number of published articles in these countries suggested that advance research has been conducted in the area of g-C_3N_4 and photocatalysis. In this search, China had the highest number of articles of 333 and could be attributed to the fact that almost all the Universities are having Material Science, Engineering and Processing Departments where published articles were produced. Furthermore, researchers from China have a wide range of international collaboration with other researchers as shown in the author and co-authorship map (Figure 6)

Table 3: Contribution of Published Articles from Different Countries on g-C_3N_4 and Photocatalysis for CO_2 Reduction.

Rank	Country	Articles	Citations
1	China	333	14467
2	United States	54	6260
3	India	38	1384
4	Japan	30	1866
5	Australia	27	4894
6	Unite Kingdom	26	1318
7	Germany	23	864
8	Singapore	22	1041
9	Malaysia	20	4227
10	Saudi Arabia	15	1366
11	South Korea	15	824
12	Hong Kong	13	1195
13	Canada	9	61
14	France	8	364
15	Taiwan	8	1213
16	Iran	6	585
17	Pakistan	6	261
18	Qatar	6	28
19	Spain	6	650
20	Vietnam	5	44

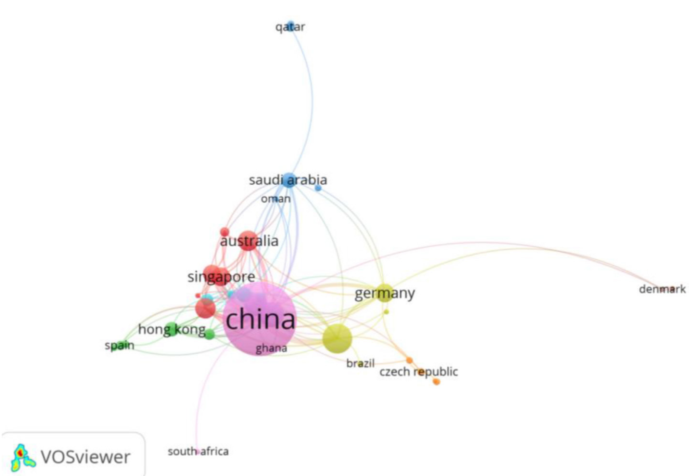

Figure 6: A visual map generated from the VOSviewer based on contribution of publications by countries.

which could be a contributing factor to the high number of published articles been churned out.

The BC for the top five countries were India (0.51), Australia (0.40), Japan (0.38), United States (0.30) and China (0.17). This also shows there is research activities connection and network between different countries globally. The contributions of organizations or institutions in the field of g-C_3N_4 and photocatalysis were also produced.

A total of 97 different organizations or institutions were found. Among the top twenty (20) organizations or institutions, seventeen (17) were from China, two (2) from Japan and one (1) from Australia. The Chinese Academy of Sciences was rated as the first organization or institution contributing seven (7) articles, followed by Jiangsu University, (5) articles and Tianjin University (4) articles. This implies that Chinese organizations or institutions are leading in the research field of g-C_3N_4 and photocatalysis.

Authors and citation

Authors and citation relationship established the frequency of which published articles of author(s) are mentioned or cited in documents. It also shows the collaboration among the authors and the impact of cited articles in the field of study. The academic impact of an article is measured based on the number of citations the article received. In all, 472 authors were generated into sixteen (16) clusters with 11702 links and a total link strength of 17012. The top twenty (20) most cited author(s) are presented in Table 4 with Ong W. J. (Citation frequency = 2986) being the top-ranked highly cited author. Zhang T. (Citation frequency = 1351), Zhao Z. (Citation frequency = 1037) and Wang C. (Citation frequency = 1029) were ranked second, third and fourth respectively. The highly cited article was published in Chemical Reviews in the year 2016. This was a review article which have received many readings and hence citations from the scientific community. Other journals such as Chemical Society Reviews, Nanoscale and Journal of the American Chemical Society were the publishers of the second, third and fourth highly cited articles. The first four highly cited articles were published by Chinese researchers. This clearly shows that the highly cited author(s) published articles in diverse journals and in different years. This is an indication that research on g-C_3N_4 and photocatalysis is on a wide increase and receiving global attention.

Documents and co-citations of Journals

The sources of g-C_3N_4 and photocatalytic articles from 2010 to 2021 were retrieved from 142 journals with 734 links. Table 5 shows the 20 top-ranked journals and their citations. The top ranked journal "Applied Catalysis B: Environmental" published 36 documents that have received 2327 citations. The "Chemical Engineering Journal" have 19 documents and received 437 citations. The "Journal of Materials Chemistry A" (citations = 400) and "Applied Surface Science" (citations = 233) were ranked third and fourth with published documents of 16 and 15 respectively. This clearly shows that articles relating to g-C_3N_4 and photocatalysis published in these top four journals have received high attention from researchers in the field.

Table 4: The Top Twenty (20) Highly Cited Authors and Journals in the Field of g-C_3N_4 and Photocatalysis for CO_2 Reduction.

Rank	Author(s)	Title of article	Year	Name of Journal	Citation
1	Ong W. J.	Graphitic Carbon Nitride (g-C_3N_4)-Based Photocatalysts for Artificial Photosynthesis and Environmental Remediation: Are We a Step Closer to Achieving Sustainability?	2016a	Chemical reviews	2986
2	Zhang T.	Metal–organic frameworks for artificial photosynthesis and photocatalysis	2014a	Chemical Society Reviews	1351
3	Zhao Z.	Graphitic carbon nitride- based nanocomposites: A review.	2015	Nanoscale	1037
4	Wang C.	Doping metal–organic frameworks for water oxidation, carbon dioxide reduction, and organic photocatalysis	2011	Journal of the American Chemical Society	1029
5	Hou W.	A review of surface plasmon resonance-enhanced photocatalysis	2013	Advanced Functional Materials	926
6	Fu J.	g-C_3N_4-Based Heterostructured Photocatalysts	2018	Advanced Energy Materials	903
7	Zhang X.	Plasmonic photocatalysis	2013	Reports on Progress in Physics	820
8	Wang J. L.	Metal–organic frameworks for light harvesting and photocatalysis	2012	ACS Catalysis	566
9	Gao G.	Single atom (Pd/Pt) supported on graphitic carbon nitride as an efficient photocatalyst for visible-light reduction of carbon dioxide	2016	Journal of the American Chemical Society,	555
10	Mamba G.	Graphitic carbon nitride (g-C_3N_4) nanocomposites: a new and exciting generation of visible light driven photocatalysts for environmental pollution remediation	2016	Applied Catalysis B: Environmental	550
11	Dhakshinamoorthy A.	Catalysis and photocatalysis by metal organic frameworks	2018	Chemical Society Reviews	522
12	Fateeva A.	A water-stable porphyrin-based metal–organic framework active for visible-light photocatalysis	2012	Angewandte Chemie International Edition	475
13	Wang S.	Multifunctional metal–organic frameworks for photocatalysis	2015	small	366
14	Sun D.	Studies on Photocatalytic CO_2 Reduction over NH_2-Uio-66 (Zr) and Its Derivatives: Towards a Better Understanding of Photocatalysis on Metal–Organic Frameworks	2013	Chemistry–A European Journal	366
15	Zhou Y.	Monolayered Bi_2WO_6 nanosheets mimicking heterojunction interface with open surfaces for photocatalysis.	2015	Nature communications	362
16	Park H.	Photoinduced charge transfer processes in solar photocatalysis based on modified TiO_2.	2016	Energy and Environmental Science	360
17	Luo B.	Recent advances in 2D materials for photocatalysis.	2016	Nanoscale	357
18	Wen J.	Photocatalysis fundamentals and surface modification of TiO_2 nanomaterials	2015	Chinese Journal of Catalysis	347
19	Samadi M.	Recent progress on doped ZnO nanostructures for visible-light photocatalysis	2016	Thin Solid Films	314
20	Zheng J	Zn phthalocyanine/carbon nitride heterojunction for visible light photoelectrocatalytic conversion of CO_2 to methanol	2019	Journal of Catalysis	305

Multifunctional Applications of g-C_3N_4 Based Photocatalyst

Graphitic carbon nitride (g-C_3N_4) has emerged as a metal free semiconductor photocatalyst over the last three decades. It possesses exceptional properties which are favourable for multifunctional applications such as environmental remediation, renewable solar fuel generation, water splitting, optoelectronic uses among others.[19,25,40-41]

Environmental Degradation of Pollutants

Population growth and industrialization of economies has resulted in the emission of high toxic and hazardous substances into the environment. These issues have a potential of posing health risks to human health. Photocatalysis promised to be a green technology the scientific community has explored and considered to be a potential remedy to preserve the environment.[1] A lot of studies have been conducted extensively on g-C_3N_4 for environmental applications such as water purification, air purification, and hazardous

Table 5: Top Twenty (20) Productive Journals from 2010-2021in the field of g-C_3N_4 and Photocatalysis.

Rank	Journal Sources	Documents	Citations
1	Applied Catalysis B: Environmental	36	2327
2	Chemical Engineering Journal	19	437
3	Journal Of Materials Chemistry A	16	400
4	Applied Surface Science	15	233
5	Angewandte Chemie - International Edition	13	1384
6	Journal of The American Chemical Society	12	2131
7	Chemcatchem	11	203
8	Journal of Colloid and Interface Science	10	210
9	ACS Applied Materials and Interfaces	9	621
10	ACS Catalysis	8	1003
11	Catalysis Science and Technology	8	226
12	Chemical Communications	8	377
13	Solar RRL	8	46
14	Chemistry - A European Journal	7	695
15	Chemsuschem	7	107
16	International Journal of Hydrogen Energy	7	86
17	Journal Of Catalysis	7	315
18	RSC Advances	7	80
19	Small	7	592
20	Advanced Materials	6	579

waste treatment.[19,42-43] This is because the modified g-C_3N_4 photocatalysts possess high visible light harvesting ability, efficient charge separation and transportation abilities, and high capacity for adsorption of pollutants for enhanced photocatalytic environmental performance.[1,20]

The industrial wastes such as textiles dyes, effluents, etc. must be treated to meet the acceptable standard before being released into the environment. Thus, their released into the environment even in very low concentration without treatment possess health risk to both human and animals. But treatment of these industrial wastes as well as purification of surface and ground water for drinking either through a biological or chemical process is challenging and requires alternative approach (es). A lot of researches have shown that semiconductor photocatalysts is an excellent alternative method for treatment of low concentrated organic compound waste waters.[44-46]

The mechanism of photocatalytic environmental remediation involves important active species of photoexcited holes. These photoexcited holes are produced under light irradiation of the semiconductor photocatalyst in the valence band (*h+vb*) whiles the electrons are in the conduction band (e^-_{cb}) as shown in equation 1. The photoexcited holes are the most important oxidants reacting directly with the adsorbed organic pollutant molecules (equation 2) or water to generate hydroxyl radicals (·OH) which has a strong oxidation potential of 2.8 eV (NHE) (equation 3) which consequently oxidize the adsorbed organic pollutant molecules (equation 4). A reaction can also occur between the electrons and the organic pollutants to produced reduction products (equation 5). This mechanisms have been discussed extensively in literature[44-45,47-48] and a summary is shown below using g-C_3N_4 as an ideal photocatalyst. Furthermore, Table 6 shows the summary of some g-C_3N_4 based photocatalysts and their organic pollutant removal rates.

g-C_3N_4 + *hv* (light irradiation) $\longrightarrow$ g-C_3N_4 ($h^+_{vb} + e^-_{cb}$) …….equ. 1

Adsorbed organic pollutant + h^+ $\longrightarrow$ degraded products……..equ. 2

$h^+ + H_2O \longrightarrow \cdot OH + H^+$ ………… equ. 3

Adsorbed organic pollutant + ·OH $\longrightarrow$ degraded products……equ. 4

Adsorbed organic pollutants + e^-_{cb} $\longrightarrow$ degraded products (reduction reaction)…equ. 5

Photocatalytic reduction of CO_2 into Renewable Solar Fuels

One of the important sources of green renewable energy is solar fuels which can be obtained from photocatalytic conversion of CO_2 and water. This process is mimicking of the natural photosynthetic steps involved in the conversion of solar energy into chemical energy.[13] The valuable hydrocarbon fuels that can be obtained from this process include methane (CH_4), methanol (CH_3OH), formaldehyde (HCHO), carbon monoxide (CO) among other hydrocarbon fuels as a sustainable energy source and production of chemicals. The mechanism involved in the CO_2 photocatalytic generation of solar fuels over a photocatalyst is a multi-electron transfer process which comprise generation of photoexcited electrons and holes. It is also involved the breaking of C–O bond and formation of C–H and O–H bonds.[56] The photocatalytic process begins generation of photoexcited holes and electrons in the valence and conduction bands respectively by light irradiation on the photocatalyst as shown in equation 1. The molecular CO_2 is adsorbed on the surface of photocatalyst and reacted with the photoexcited electrons. Based on the reaction kinetics and its thermodynamics, one CO_2 molecule would require 12, 10, 8, 6 and 4 photoelectrons for conversion to ethanol (C_2H_5OH), ethane (C_2H_4), methane (CH_4), methanol (CH_3OH) and formaldehyde (HCHO), respectively (equations 2-6).[44,56] Furthermore, the photoexcited holes will react with adsorbed water on the surface of the photocatalyst to produce oxygen (equation 7). The summary of the CO_2 photocatalytic conversion into renewable solar fuels and hydrocarbon chemicals is shown using g-C_3N_4 as an ideal photocatalyst.

Table 6: Summary of some g-C_3N_4 based photocatalysts and their pollutant removal rate.

Photocatalyst	Photocatalytic Experiment	Percentage Degradation or Removal	Ref.
Graphitic carbon nitride (g-C_3N_4) hollow sphere	Photocatalytic degradation of Rhodamine B (RhB) in an aqueous solution under visible light irradiation (λ=4420 nm).	About 100 % concentration of RhB was decomposed after 180 min illumination	49
Activated carbon (g-C_3N_4/AC)	Photocatalytic AO7 dye degradation in aqueous solution activated by PMS degrade AO7	96.4 % of AO7 was removed within 10 min	50
Silver-decorated ultrathin g-C_3N_4 nanosheets (Ag@U-g-C_3N_4-NS).	Photocatalytic degradation of MB and phenol under visible-light irradiation.	88.5 % of MB degraded in 40 min under visible-light irradiation 89 % of phenol degraded in 80 min	51
2D graphitic carbon nitride	A photocatalytic degradation of bisphenol A (BPA) was carried out.	99 % of bisphenol A removal was achieved by exfoliated graphitic carbon nitride after 90 min	52
Oxygen-doped (O-doped) graphitic carbon nitride (g-C_3N_4) nanosheets	A photodegradation of aqueous RhB solution under visible light (λ=400) nm irradiation was carried out.	99 % degradation of RhB was achieved after 3 min	53
Sulfur doped g-C_3N_4 microrods with silver chromate (g- C_3N_4/Ag_2CrO_4)	A photocatalytic degradation of Methyl orange (MO), organic dye, was carried out under visible light (λ=420 nm)	90.27 % degradation of MO was achieved with within 20 min	54
Pipe-like g-C_3N_4	Photocatalytic activity of was evaluated by the photodegradation of methylene blue (MB) under visible-light irradiation	96 % degradation of MB within 30 min	55

g-C_3N_4 + *hv* (light irradiation) $\longrightarrow$ g-C_3N_4 (h^+_{vb} + e^-_{cb}) …..equ 1

$$CO_2 + 12H^+ + 12e^- \longrightarrow C_2H_5OH + 4H_2O \text{…equ 2}$$

$$CO_2 + 10H^+ + 10e^- \longrightarrow C_2H_4 + {}_3H_2O \text{……. equ 3}$$

$$CO_2 + 8H^+ + 8e^- \longrightarrow CH_4 + {}_2H_2O \text{……...equ 4}$$

$$CO_2 + 6H^+ + 6e^- \longrightarrow CH_3OH + H_2O \text{…..equ 5}$$

$$CO_2 + 4H^+ + 4e^- \longrightarrow HCHO + H_2O \text{…...equ 6}$$

$$2H_2O + 4h^+ + 4e^- \longrightarrow O_2 + 4H^+ \text{…………equ 7}$$

In addition, a summary of some of the various g-C_3N_4 based photocatalysts and solar fuels generated is shown in Table 7.

Photocatalytic Hydrogen Generation

One of the green energies been explored by the scientific community as alternative source of energy to fossil fuels and addressing the global energy crisis is hydrogen. Hydrogen can be generated photocatalytically by splitting water over a semiconductor photocatalyst. But the challenge facing this process for practical application is the large energy barrier required.[42,44]

Generally, the photocatalytic hydrogen generation process is made up of three stages: (i) the first stage involved irradiation of the photocatalyst to generate electrons and holes (i.e. charge carriers) by the photons. (ii) in stage two, there is separation of the charge carriers and their migration to the surface of the photocatalyst. (iii) the stage three involves a reduction process of H^+ to H_2 by the electrons and oxidation of H_2O to O_2 by holes.[62]

For effective overall H_2 generation by water splitting, the photocatalyst should satisfy basic requirements such as the valence band potential must be more negative than H^+/H_2 and more positive than OH^-/O_2 potential. This standard is achieved by photocatalysts that have a minimum bandgap energy of 1.23 eV. However, practically water splitting process needed higher energy of 1.8 eV because of overpotential associated with the evolution reactions for hydrogen and oxygen. This makes the process very challenging under visible solar light for efficient water splitting with a single photocatalyst.[63–64] However, composite photocatalysts with and without co-catalysts and hole scavenger have high hydrogen generation capacity[44] Generally, the overall reaction is:

$$2H_2O_{(l)} \longrightarrow 2H_{2(g)} + O_{2(g)}); G = +474 \text{ kJ/mol}$$

The mechanistic stepwise reaction for the hydrogen generation process is summarize from equ. 1 to 4. The overall reaction redox potential at a pH = 7 is E_H = –1.23 eV (NHE).[44]

$$2H_2O \longrightarrow 2H_2 + O_2 \text{………………..equ. 1}$$

$$H_2O \longrightarrow H^+ + OH^- \text{……………..……equ. 2}$$

$$2H_2O + 2e^- \longrightarrow H_2 + 2OH^- \text{…..…………….equ. 3}$$

$$2H_2O \longrightarrow O_2 + 4H^+ + 4e^- \text{………….equ. 4}$$

Table 8 shows a summary of g-C_3N_4 based photocatalysts with enhanced hydrogen generation rate.

Emerging Trends in g-C_3N_4 Photocatalysis

This scientometric evaluation indicated that they are new emerging areas where g-C_3N_4 based photocatalyst are being applied. In medicine, it is applied in drug delivery because it's

Table 7: Summary of some g-C_3N_4 based photocatalysts and solar fuel generation.

g-C_3N_4 based Photocatalyst	Photocatalytic Experiment	Enhancement factor over pure g-C_3N_4	Ref.
Noble-metal Pt nanoparticles and graphitic carbon nitride (Pt/CN)	Photocatalytic reduction of CO_2 using water as a sacrificial reagent under visible light irradiation	g-C_3N_4 (2Pt/CN) nanocomposites produced the highest CH_4 yield of 13.02 μmol g catalyst^{-1} after 10 h of light irradiation, which was a 5.1-fold enhancement in comparison with pure g-C_3N_4	57
Potassium Hydroxide (KOH) on g-C_3N_4.	CO_2 photocatalytic conversion in the presence of H_2O was conducted under visible light (λ> 420 nm).	3-fold enhancement in CO_2 photocatalytic reduction is achieved on KOH-decorated g-C_3N_4	58
Ultrathin Br-doped g-C_3N_4 nanosheet	Photocatalytic reduction of CO_2 under visible light (λ > 400 nm) irradiation for	CO_2 photocatalytic reduction of 0.4 μmolh^{-1}g^{-1} of CH_4 and 0.6 μmolh^{-1}g^{-1} of CH_3OH formation, which is 4.0 and 7.5 times higher than the pure g-C_3N_4 NS.	59
Hybride of cobalt phthalocyanine tetracarboxylic acid and g-C_3N_4 (g-C_3N_4/ CoPc-COOH)	Photocatalytic CO_2 reduction was performed in DMF/water/ triethylamine system saturated with CO_2 in the presence of visible light.	methanol yield using g-C_3N_4/CoPc-COOH) was found to be 646.5 μmol. g^{-1}cat g-C_3N_4 yielded 59.2 μmol (1184 μmol.g^{-1}cat) yield of methanol	60
Carbon nitride (g-C_3N_4) shell encapsulating Cu_2O nanowire arrays/Cu mesh (g-C_3N_4/Cu_2O NAs/CM)	Photocatalytic CO_2 reduction was carried out under visible-light	CH_3OH formation rate reached 22.6 ppm cm^{-2} h^{-1}	61
Honeycomb-like morphology (HC-C_3N_4)	Photocatalytic CO_2 reduction was carried out under visible-light using $Ni(OH)_2$ as c cocatalyst	A CO_2 photocatalytic reduction activity of 1.48 μmolh^{-1} g^{-1} of CH_4 and 0.73 μmolh^{-1} g^{-1} of CH_3OH generation which is 3.5 and 4.3 times more than pure g-C_3N_4	12

Table 8: Summary of some g-C_3N_4 based photocatalysts and hydrogen generation.

g-C_3N_4 based Photocatalyst	Photocatalytic Experiment	Amount of Hydrogen generated / Enhancement factor	Ref.
porous graphitic carbon nitrides (g-C_3N_4)	The photocatalytic H_2 evolution experiments were measured in a double-wall inner irradiation-using water and methanol as sacrificial agent	The photocatalytic hydrogen evolution under visible light is around five times higher if urea is used as the g-C_3N_4 precursor instead of thiourea or melamine	65
Two-dimensional (2D) black phosphorus (BP) quantum dots (BPQDs) onto graphitic carbon nitride (BPQDs/g-C_3N_4) hybrid	The photocatalytic hydrogen evolution was carried under visible light with Pt as a co-catalyst	5 wt% BPQDs/g-C_3N_4 with cyclability exhibits the greatest hydrogen evolution rate of 271 μmol h^{-1} g^{-1} that is 5.6 and 4.2 times greater than that of pristine g-C_3N_4 and BPQDs	66
g-C_3N_4 nanosheet	Photocatalytic water splitting reactions were carried out under visible light visible light (λ > 400 nm)	photocatalytic activity, which is 1.77 times than that of g-C_3N_4 obtained via 3 h thermal treatment under visible irradiation	67
Hybrid of g-C_3N_4/free-base meso-tetrakis (carboxyphenyl) porphyrins	The photocatalytic experiments for H_2 production were carried out at room temperature under visible light, (λ > 400 nm) using EDTA as sacrificial electron donor and Pt co-catalyst.	mTCPP-CN produced the highest amount of H_2 evolved, 48.4 μmol under 6 h	68
Zirconium dioxide and graphitic carbon nitride (ZrO_2/g-C_3N_4) composite	Photocatalytic hydrogen production was conducted under visible light using 500 W mercury lamp and methanol as sacrificial reagent with Pt as co-catalyst	The highest H_2 production rate obtained for ZrO_2/g-C_3N_4-5% is 603 μmol/h and it is 20 times higher than pure ZrO_2.	69
WS_2/graphitic carbon nitride (CN) 2D/2D nanosheet heterostructure decorated with CdS quantum dots (QDs) (CdS/WS_2/CN)	The photocatalytic hydrogen evolution rates were measured under visible-light irradiation (λ =420–780 nm) for 5 h without any cocatalyst using triethanolamine (TEOA) as a sacrificial agent.	The CdS/WS_2/CN Photocatalytically evolved H_2 1174.5 mmolh^{-1}g^{-1} under visible-light irradiation which is nearly 67 times higher than that of the pure CN nanosheets	70
Two-dimensional/one-dimensional molybdenum sulfide (MoS_2) nanoflake/graphitic carbon nitride (g-C_3N_4) hollow nanotube (MoS_2/g-C_3N_4 nanotube)	The photocatalytic test was carried out under visible light in aqueous solution (100 mL) containing 20% triethanolamine	MoS_2/g-C_3N_4 nanotube composite with 15 wt% MoS_2 shows the highest hydrogen (H_2) production rate (1124 mmolh^{-1} g^{-1}) much higher than bulk g-C_3N_4 (64 mmol h^{-1} g^{-1}) and g-C_3N_4 nanotubes (189 mmol h^{-1} g^{-1})	71

small size, covalent bonding which is non-interfering with the drug, low level of toxicity, and excellent optical property.[43] According to DFT evaluation carried out, g-C_3N_4 is an effective drug delivery material for cisplatin and carboplatin drugs for treatment of various cancers.[32-33] In practice, g-C_3N_4 quantum dots(g-CNQDs) was synthesized and incorporated into diamine-terminated oligomeric poly(ethylene glycol) (PEG) resulting in a high intensity blue-photoluminescent PEGylated g-CNQDs. The g-CNQDs–PEG was assessed to be a perfect drug delivery system for cancer (especially anti-cancer drug doxorubin).[72] Furthermore, a study on interaction of pyrazinamide and 5-fluorouracil anticancer drugs and bulk C_3N_4 with folic acid conjugation as shows a suitable combination for anticancer drug delivery.[73] Similarly, it has been shown that g-C_3N_4 can effectively mediate cancer therapy; both is *in vitro* and *in vivo* using Photodynamic therapy (PDT).[74]

In the mathematical science, g-C_3N_4 was used as an ideal material to compute topological index of the molecular structure. This has enhance the researcher's knowledge and understanding of the physical science and bioorganic attributes of the g-C_3N_4 for further application in graph theory.[75] Similar, the M-polynomial and NM-polynomial with graphical representations of g-C_3N_4 was computed as topological indices to be used in determination of pharmaceutical properties of drugs.[76]

Currently, other disciplines where in-depth researching is being carried out and utilizing g-C_3N_4 application included disease and toxin treatment, computer application systems, food safety monitoring, drug and biosensor detection.

Conclusion and Future Research Outlook

This study attempted to outline the progress and hotspots areas using a scientometric assessment in the field of photocatalysis and g-C_3N_4 for CO_2 photocatalytic reduction. A lot of articles and reviews have been reported on g-C_3N_4 showing its uniqueness and potential applications. However, this scientometric study explore the current trends and status revealing the emerging nature of g-C_3N_4 over relatively short period. In all, a total of 504 articles were collected from the Scopus database of Web of Science (WOS) spanning from 2010 to May, 2021. The scientometric techniques employed in the assessment are documents types and their numbers, research subject areas, trend analysis of publications, keyword co-occurrence analysis and clustering, co-occurrence analysis (i.e. for countries, institutions, and authors), authors and citations and documents and co-citations of journals. In this study, VOSviewer software was employed to map and visual the various scientometric techniques. Research articles (i.e. 390) dominated the documents recorded with Chemistry being the main area. There is a progressive increase in published documents over the years with the keyword "Photocatalysis" having the highest holding frequency of 240 suggesting it is a current hotspot area.

Regarding contributions in the field, Zhang X. from China is identified to be the lead productive researcher with 27 articles. There are some levels of international collaborations between the researchers and China emanating as the lead productive country in the field. Ong W. J. obtained the top researcher with the highest citation frequency of 2986 and Applied Catalysis B: Environmental journal ranked top for publishing in this area of study.

The g-C_3N_4 photocatalytic materials have been applied in a lot of areas including pollutant degradation, renewable solar fuels generation and water splitting into hydrogen and oxygen. This scientometric assessment is an evidence that there is a lot of scientific progress being made in the field of photocatalysis and g-C_3N_4 semiconductor material through the visualization of the trends and hotspots. In addition, the study provides important information for the scientific community, researchers, policy makers and practitioners in the photocatalysis field to develop more excellent materials from g-C_3N_4 for various fields of application.

Consequently, a lot of efforts have been directed to the fabrication of various g-C_3N_4 based photocatalysts and their applications in environmental remediation, energy generation, waste disinfection, water splitting among others. However, this scientometric assessment shows that there are other potential areas for application of g-C_3N_4 photocatalyst based materials including medicine, biomedical systems, pharmacy and toxicological industries. In addition, other multidisciplinary fields such as computer science, mathematics, earth science etc. could also derive benefits from the application of a g-C_3N_4 material. Thus, further research in these areas must be strengthened by the scientific community.

ACKNOWLEDGEMENT

The authors acknowledge contributions from members of the Mechanical Engineering Department of the Ho Technical University, Ghana, for their diverse inputs into the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Ong WJ, Tan LL, Ng YH, Yong ST, Chai SP. Graphitic carbon nitride (g-C_3N_4)-based photocatalysts for artificial photosynthesis and environmental remediation: Are we a step closer to achieving sustainability? Chem Rev. 2016;116(12):7159-329. doi: 10.1021/acs.chemrev.6b00075, PMID 27199146.
2. Li X, Wang L, Su W, Xing Y. A review of the research status of CO_2 photocatalytic conversion technology based on bibliometrics. New J Chem. 2020;45(5):2315-25. doi: 10.1039/D0NJ04597G.
3. Ismael M. A review on graphitic carbon nitride (g-C_3N_4) based nanocomposites: Synthesis, categories, and their application in photocatalysis. J Alloys Compd. 2020;846:156446. doi: 10.1016/j.jallcom.2020.156446.

4. Khan K, Tareen AK, Aslam M, Sagar RUR, Zhang B, Huang W, *et al*. Recent progress, challenges, and prospects in two-dimensional photo-catalyst materials and environmental remediation. Nanomicro Lett. 2020;12(1):167. doi: 10.1007/s40820-020-00504-3, PMID 34138161.
5. Hou W, Cronin SB. A review of surface plasmon resonance-enhanced photocatalysis. Adv Funct Mater. 2013;23(13):1612-9. doi: 10.1002/adfm.201202148.
6. Tahir MB, Asiri AM, Nawaz T. A perspective on the fabrication of heterogeneous photocatalysts for enhanced hydrogen production. Int J Hydr Energy. 2020;45(46):24544-57. doi: 10.1016/j.ijhydene.2020.06.301.
7. Rafique M, Mubashar R, Irshad M, Gillani SSA, Tahir MB, Khalid NR, *et al*. A comprehensive study on methods and materials for Photocatalytic water splitting and hydrogen production as a renewable energy resource. J Inorg Organomet Polym. 2020;30(10):3837-61. doi: 10.1007/s10904-020-01611-9.
8. González-Rodríguez J, Fernández L, Bava YB, Buceta D, Vázquez-Vázquez C, López-Quintela MA, *et al*. Enhanced photocatalytic activity of semiconductor nanocomposites doped with ag nanoclusters under UV and visible light. Catalysts. 2020;10(1):31. doi: 10.3390/catal10010031.
9. Han G, Sun Y. Visible-light-driven organic transformations on semiconductors. Mater Today Phys. 2021;16:100297. doi: 10.1016/j.mtphys.2020.100297.
10. Lee SY, Kang D, Jeong S, Do HT, Kim JH. Photocatalytic degradation of rhodamine b dye by TiO_2 and gold nanoparticles supported on a floating porous polydimethylsiloxane sponge under ultraviolet and visible light irradiation. ACS Omega. 2020;5(8):4233-41. doi: 10.1021/acsomega.9b04127, PMID 32149253.
11. Wang A, Wu S, Dong J, Wang R, Wang J, Zhang J, *et al*. Interfacial facet engineering on the Schottky barrier between plasmonic Au and TiO_2 in boosting the photocatalytic CO_2 reduction under ultraviolet and visible light irradiation. Chem Eng J. 2021;404:127145. doi: 10.1016/j.cej.2020.127145.
12. Akple MS, Ishigaki T, Madhusudan P. Bio-inspired honeycomb-like graphitic carbon nitride for enhanced visible light photocatalytic CO_2 reduction activity. Environ Sci Pollut Res Int. 2020;27(18):22604-18. doi: 10.1007/s11356-020-08804-2, PMID 32314294.
13. Fu J, Yu J, Jiang C, Cheng B. g-C_3N_4-Based heterostructured photocatalysts. Adv Energy Mater. 2018;8(3):1701503. doi: 10.1002/aenm.201701503.
14. Gao G, Jiao Y, Waclawik ER, Du A. Single atom (Pd/Pt) supported on graphitic carbon nitride as an efficient photocatalyst for visible-light reduction of carbon dioxide. J Am Chem Soc. 2016;138(19):6292-7. doi: 10.1021/jacs.6b02692, PMID 27116595.
15. Ong WJ. 2D/2D graphitic carbon nitride (g-C_3N_4) heterojunction nanocomposites for photocatalysis: Why does face-to-face interface matter? Front Mater. 2017;4:11. doi: 10.3389/fmats.2017.00011.
16. Bora T, Dutta J. Plasmonic Photocatalyst Design: Metal-Semiconductor Junction Affecting Photocatalytic Efficiency. J Nanosci Nanotechnol. 2019;19(1):383-8. doi: 10.1166/jnn.2019.15785, PMID 30327045.
17. Mamba G, Mishra AK. Graphitic carbon nitride (g-C_3N_4) nanocomposites: A new and exciting generation of visible light driven photocatalysts for environmental pollution remediation. Appl Cat B. 2016;198:347-77. doi: 10.1016/j.apcatb.2016.05.052.
18. Li Y, Zhou M, Cheng B, Shao Y. Recent advances in g-C_3N_4-based heterojunction photocatalysts. J Mater Sci Technol. 2020;56:1-17. doi: 10.1016/j.jmst.2020.04.028.
19. Hao Q, Jia G, Wei W, Vinu A, Wang Y, Arandiyan H, *et al*. Graphitic carbon nitride with different dimensionalities for energy and environmental applications. Nano Res. 2020;13(1):18-37. doi: 10.1007/s12274-019-2589-z.
20. Zhao Z, Sun Y, Dong F. Graphitic carbon nitride based nanocomposites: A review. Nanoscale. 2015;7(1):15-37. doi: 10.1039/C4NR03008G, PMID 25407808.
21. Hasija V, Raizada P, Sudhaik A, Sharma K, Kumar A, Singh P, *et al*. Recent advances in noble metal free doped graphitic carbon nitride based nanohybrids for photocatalysis of organic contaminants in water: A review. Appl Mater Today. 2019;15:494-524. doi: 10.1016/j.apmt.2019.04.003.
22. Reddy KR, Reddy CV, Nadagouda MN, Shetti NP, Jaesool S, Aminabhavi TM. Polymeric graphitic carbon nitride (g-C_3N_4)-based semiconducting nanostructured materials: Synthesis methods, properties and photocatalytic applications. J Environ Manage. 2019;238:25-40. doi: 10.1016/j.jenvman.2019.02.075, PMID 30844543.
23. Jiang L, Yuan X, Pan Y, Liang J, Zeng G, Wu Z, *et al*. Doping of graphitic carbon nitride for photocatalysis: A I. Appl Cat B. 2017;217:388-406. doi: 10.1016/j.apcatb.2017.06.003.
24. Nasir MS, Yang G, Ayub I, Wang S, Wang L, Wang X, *et al*. Recent development in graphitic carbon nitride based photocatalysis for hydrogen generation. Appl Cat B. 2019;257:117855. doi: 10.1016/j.apcatb.2019.117855.
25. Akhundi A, Badiei A, Ziarani GM, Habibi-Yangjeh A, Muñoz-Batista MJ, Luque R. Graphitic carbon nitride-based photocatalysts: Toward efficient organic transformation for value-added chemicals production. Mol Cat. 2020;488:110902. doi: 10.1016/j.mcat.2020.110902.
26. Akhundi A, Habibi-Yangjeh A, Abitorabi M, Rahim Pouran S. Review on photocatalytic conversion of carbon dioxide to value-added compounds and renewable fuels by graphitic carbon nitride-based photocatalysts. Cat Rev. 2019;61(4):595-628. doi: 10.1080/01614940.2019.1654224.
27. Zhang M, Yang Y, An X, Hou LA. A critical review of g-C_3N_4-based photocatalytic membrane for water purification. Chem Eng J. 2021;412:128663. doi: 10.1016/j.cej.2021.128663.
28. Lin H, Zhu Y, Ahmad N, Han Q. A scientometric analysis and visualization of global research on brownfields. Environ Sci Pollut Res Int. 2019;26(17):17666-84. doi: 10.1007/s11356-019-05149-3, PMID 31028623.
29. Zhao X. A scientometric review of global BIM research: Analysis and visualization. Autom Constr. 2017;80:37-47. doi: 10.1016/j.autcon.2017.04.002.
30. Khalaj M, Kamali M, Costa MEV, Capela I. Green synthesis of nanomaterials – A scientometric assessment. J Cleaner Prod. 2020;267:122036. doi: 10.1016/j.jclepro.2020.122036.
31. Sabour MR, Jafari MA, Hosseini Gohar SMH. Si-based solar cells' conversion efficiency related publications bibliometric review during 2000-2017. Silicon. 2020;12(11):2705-20. doi: 10.1007/s12633-019-00366-4.
32. Perveen M, Nazir S, Arshad AW, Khan MI, Shamim M, Ayub K, *et al*. Therapeutic potential of graphitic carbon nitride as a drug delivery system for cisplatin (anticancer drug): A DFT approach. Biophys Chem. 2020;267:106461. doi: 10.1016/j.bpc.2020.106461, PMID 32919257.
33. Shamim M, Perveen M, Nazir S, Hussnain M, Mehmood R, Khan MI, *et al*. DFT study of therapeutic potential of graphitic carbon nitride (g-C3N4) as a new drug delivery system for carboplatin to treat cancer. J Mol Liq. 2021;331:115607. doi: 10.1016/j.molliq.2021.115607.
34. Madhusudan P, Shi R, Xiang S, Jin M, Chandrashekar BN, Wang J, *et al*. Construction of highly efficient Z-scheme ZnxCd1-xS/Au@g-C3N4 ternary heterojunction composite for visible-light-driven photocatalytic reduction of CO_2 to solar fuel. Appl Cat B. 2021;282:119600. doi: 10.1016/j.apcatb.2020.119600.
35. Truc NT, Pham TD, Nguyen MV, Van Thuan D, Thao P, Trang HT, Tran DT, Minh DN, Hanh NT, Ngoc HM. Advanced $NiMoO_4$/g-C_3N_4 Z-scheme heterojunction photocatalyst for efficient conversion of CO_2 to valuable products. Journal of Alloys and Compounds. 2020;842:155860. doi: 10.1016/j.jallcom.2020.155860.
36. Martinez P, Al-Hussein M, Ahmad R. A scientometric analysis and critical review of computer vision applications for construction. Autom Constr. 2019;107:102947. doi: 10.1016/j.autcon.2019.102947.
37. Liao G, Gong Y, Zhang L, Gao H, Yang GJ, Fang B. Semiconductor polymeric graphitic carbon nitride photocatalysts: The 'Holy Grail' for the photocatalytic hydrogen evolution reaction under visible light. Energy Environ Sci. 2019;12(7):2080-147. doi: 10.1039/C9EE00717B.
38. Freeman LC. A set of measures of centrality based on betweenness. Sociometry. 1977;40(1):35-41. doi: 10.2307/3033543.
39. Fan C, Zeng L, Ding Y, Chen M, Sun Y, Liu Z. Learning to identify high betweenness centrality nodes from scratch: A novel graph neural network approach Paper Presented at the proceedings of the 28th ACM International Conference on Information and Knowledge Management; 2019. doi: 10.1145/3357384.3357979.
40. Tian N, Huang H, Du X, Dong F, Zhang Y. Rational nanostructure design of graphitic carbon nitride for photocatalytic applications. J Mater Chem A. 2019;7(19):11584-612. doi: 10.1039/C9TA01819K.
41. Qi K, Liu SY, Zada A. Graphitic carbon nitride, a polymer photocatalyst. J Taiwan Inst Chem Eng. 2020;109:111-23. doi: 10.1016/j.jtice.2020.02.012.
42. Darkwah WK, Oswald KA. Photocatalytic applications of heterostructure graphitic carbon nitride: pollutant degradation, hydrogen gas production (water splitting), and CO_2 reduction. Nanoscale Res Lett. 2019;14(1):234. doi: 10.1186/s11671-019-3070-3, PMID 31300944.
43. Ajiboye TO, Kuvarega AT, Onwudiwe DC. Graphitic carbon nitride-based catalysts and their applications: A review. Nano Struct Nano Objects. 2020;24:100577. doi: 10.1016/j.nanoso.2020.100577.
44. Kumar S, Karthikeyan S, Lee AF. g-C_3N_4-based nanomaterials for visible light-driven photocatalysis. Catalysts. 2018;8(2):74. doi: 10.3390/catal8020074.
45. Chen D, Cheng Y, Zhou N, Chen P, Wang Y, Li K, *et al*. Photocatalytic degradation of organic pollutants using TiO2-based photocatalysts: A review. J Cleaner Prod. 2020;268:121725. doi: 10.1016/j.jclepro.2020.121725.
46. Koe WS, Lee JW, Chong WC, Pang YL, Sim LC. An overview of photocatalytic degradation: Photocatalysts, mechanisms, and development of photocatalytic membrane. Environ Sci Pollut Res Int. 2020;27(3):2522-65. doi: 10.1007/s11356-019-07193-5, PMID 31865580.
47. Huang X, Zhu N, Mao F, Ding Y, Zhang S, Li F, *et al*. Novel Au@C modified g-C_3N_4 (Au@C/g-C_3N_4) as efficient visible-light photocatalyst for toxic organic pollutant degradation: Synthesis, performance and mechanism insight. Sep Purif Technol. 2020;252:117485. doi: 10.1016/j.seppur.2020.117485.
48. Zhu D, Zhou Q. Zhou Q. Action and mechanism of semiconductor photocatalysis on degradation of organic pollutants in water treatment: A review. Environ Nanotechnol Monit Manag. 2019;12:100255. doi: 10.1016/j.enmm.2019.100255.
49. Cui Y, Tang Y, Wang X. Template-free synthesis of graphitic carbon nitride hollow spheres for photocatalytic degradation of organic pollutants. Mater Lett. 2015;161:197-200. doi: 10.1016/j.matlet.2015.08.106.
50. Wei M, Gao L, Li J, Fang J, Cai W, Li X, *et al*. Activation of peroxymonosulfate by graphitic carbon nitride loaded on activated carbon for organic pollutants degradation. J Hazard Mater. 2016;316:60-8. doi: 10.1016/j.jhazmat.2016.05.031,

PMID 27214000.
51. Cai J, Huang J, Wang S, Iocozzia J, Sun Z, Sun J, *et al.* Crafting mussel-inspired metal nanoparticle-decorated ultrathin graphitic carbon nitride for the degradation of chemical pollutants and production of chemical resources. Adv Mater. 2019;31(15):e1806314. doi: 10.1002/adma.201806314, PMID 30697837.
52. Sahu RS, Shih YH, Chen WL. New insights of metal free 2D graphitic carbon nitride for photocatalytic degradation of bisphenol A. J Hazard Mater. 2021;402:123509. doi: 10.1016/j.jhazmat.2020.123509, PMID 32717544.
53. Huang Y, Ning L, Feng Z, Ma G, Yang S, Su Y, *et al.* Graphitic carbon nitride nanosheets with low O N1-doping content as efficient photocatalysts for organic pollutant degradation. Environ Sci.: Nano. 2021;8(2):460-9. doi: 10.1039/D0EN01198C.
54. Liu Z, Jiang Y, Liu X, Zeng G, Shao B, Liu Y, *et al.* Silver chromate modified sulfur doped graphitic carbon nitride microrod composites with enhanced visible-light photoactivity towards organic pollutants degradation. Composites Part B: Engineering. 2019;173:106918. doi: 10.1016/j.compositesb.2019.106918.
55. Akple MS. A unique pipe-like g-C_3N_4 with enhanced photocatalytic degradation of organic pollutant. Indian J Eng Mater Sci (IJEMS). 2020;27(2):431-7.
56. Yu J, Wang K, Xiao W, Cheng B. Photocatalytic reduction of CO_2 into hydrocarbon solar fuels over g-C3N4–Pt nanocomposite photocatalysts. Phys Chem Chem Phys. 2014;16(23):11492-501. doi: 10.1039/C4CP00133H, PMID 24801641.
57. Ong WJ, Tan LL, Chai SP, Yong ST. Heterojunction engineering of graphitic carbon nitride (g-C_3N_4) via Pt loading with improved daylight-induced photocatalytic reduction of carbon dioxide to methane. Dalton Trans. 2015;44(3):1249-57. doi: 10.1039/C4DT02940B, PMID 25415620.
58. Sun Z, Fischer JMTA, Li Q, Hu J, Tang Q, Wang H, *et al.* Enhanced CO_2 photocatalytic reduction on alkali-decorated graphitic carbon nitride. Appl Cat B. 2017;216:146-55. doi: 10.1016/j.apcatb.2017.05.064.
59. Akple MS, Chimmikuttanda SP, Takyi GKS, Elloh VW. Fabrication and density functional theory calculations of bromine doped carbon nitride nanosheets with enhanced photocatalytic reduction of CO_2 into solar fuels. Biointerface Res Appl Chem. 2021;11(6):14602-19. doi: 10.33263/BRIAC116.1460214619.
60. Kumar A, Prajapati PK, Aathira MS, Bansiwal A, Boukherroub R, Jain SL. Highly improved photoreduction of carbon dioxide to methanol using cobalt phthalocyanine grafted to graphitic carbon nitride as photocatalyst under visible light irradiation. J Colloid Interface Sci. 2019;543:201-13. doi: 10.1016/j.jcis.2019.02.061, PMID 30802767.
61. Zhao X, Fan Y, Zhang W, Zhang X, Han D, Niu L, *et al.* Nanoengineering construction of Cu_2O nanowire arrays encapsulated with g-C_3N_4 as 3D spatial reticulation all-solid-state direct Z-scheme photocatalysts for photocatalytic reduction of carbon dioxide. ACS Catal. 2020;10(11):6367-76. doi: 10.1021/acscatal.0c01033.
62. Mishra A, Mehta A, Basu S, Shetti NP, Reddy KR, Aminabhavi TM. Graphitic carbon nitride (g–C_3N_4)–based metal-free photocatalysts for water splitting: A review. Carbon. 2019;149:693-721. doi: 10.1016/j.carbon.2019.04.104.
63. Li X, Xiong J, Gao X, Huang J, Feng Z, Chen Z, *et al.* Recent advances in 3D g-C_3N_4 composite photocatalysts for photocatalytic water splitting, degradation of pollutants and CO_2 reduction. J Alloys Compd. 2019;802:196-209. doi: 10.1016/j.jallcom.2019.06.185.
64. Rhimi B, Wang C, Bahnemann DW. Latest progress in g-C3N4 based heterojunctions for hydrogen production via photocatalytic water splitting: A mini review. J Phys Energy. 2020;2(4). doi: 10.1088/2515-7655/abb782.
65. Ismael M, Wu Y, Wark M. Photocatalytic activity of ZrO_2 composites with graphitic carbon nitride for hydrogen production under visible light. New J Chem. 2019;43(11):4455-62. doi: 10.1039/C8NJ06507A.
66. Lei W, Mi Y, Feng R, Liu P, Hu S, Yu J, *et al.* Hybrid 0D–2D black phosphorus quantum dots–graphitic carbon nitride nanosheets for efficient hydrogen evolution. Nano Energy. 2018;50:552-61. doi: 10.1016/j.nanoen.2018.06.001.
67. Zhang Z, Zhang Y, Lu L, Si Y, Zhang S, Chen Y, *et al.* Graphitic carbon nitride nanosheet for photocatalytic hydrogen production: The impact of morphology and element composition. Appl Surf Sci. 2017;391:369-75. doi: 10.1016/j.apsusc.2016.05.174.
68. Da Silva ES, Moura NMM, Neves MGPMS, Coutinho A, Prieto M, Silva CG, *et al.* Novel hybrids of graphitic carbon nitride sensitized with free-base meso-tetrakis (carboxyphenyl) porphyrins for efficient visible light photocatalytic hydrogen production. Appl Cat B. 2018;221:56-69. doi: 10.1016/j.apcatb.2017.08.079.
69. Ismael M, Wu Y, Taffa DH, Bottke P, Wark M. Graphitic carbon nitride synthesized by simple pyrolysis: Role of precursor in photocatalytic hydrogen production. New J Chem. 2019;43(18):6909-20. doi: 10.1039/C9NJ00859D.
70. Zou Y, Shi JW, Ma D, Fan Z, Cheng L, Sun D, *et al.* WS_2/graphitic carbon nitride heterojunction nanosheets decorated with CdS quantum dots for photocatalytic hydrogen production. ChemSusChem. 2018;11(7):1187-97. doi: 10.1002/cssc.201800053. PMID 29400001.
71. Sun J, Yang S, Liang Z, Liu X, Qiu P, Cui H, *et al.* Two-dimensional/one-dimensional molybdenum sulfide (MoS_2) nanoflake/graphitic carbon nitride (g-C_3N_4) hollow nanotube photocatalyst for enhanced photocatalytic hydrogen production activity. J Colloid Interface Sci. 2020;567:300-7. doi: 10.1016/j.jcis.2020.02.029, PMID 32065904.
72. Dong J, Zhao Y, Chen H, Liu L, Zhang W, Sun B, *et al.* Fabrication of pegylated graphitic carbon nitride quantum dots as traceable, pH-sensitive drug delivery systems. New J Chem. 2018;42(17):14263-70. doi: 10.1039/C8NJ02542H.
73. Zaboli A, Raissi H, Farzad F, Hashemzadeh H. Assessment of adsorption behavior of 5-fluorouracil and pyrazinamide on carbon nitride and folic acid-conjugated carbon nitride nanosheets for targeting drug delivery. J Mol Liq. 2020;301:112435. doi: 10.1016/j.molliq.2019.112435.
74. Zhang JR, Kan YS, Gu LL, Wang CY, Zhang Y. Graphite carbon nitride and its composites for medicine and health applications. Chem Asian J. 2021;16(15):2003-13. doi: 10.1002/asia.202100499, PMID 34121348.
75. Chu YM, Muhammad MH, Rauf A, Ishtiaq M, Siddiqui MK. Topological study of polycyclic graphite carbon nitride. Polycyclic Aromat Compd. 2020:1-13. doi: 10.1080/10406638.2020.1857271.
76. Rauf A, Ishtiaq M, Muhammad MH, Siddiqui MK, Rubbab Q. Algebraic Polynomial Based Topological Study of Graphite Carbon Nitride (g-) Molecular Structure. Polycyclic Aromatic Compounds. 2021:1-22. doi: 10.1080/10406638.2021.1934044.

Cite this article: Akple MS, Atombo C, Takyi GKS, Dumenya A. Scientometric Assessment and Mini Review of Graphitic Carbon Nitride (g-C_3N_4) for Photocatalytic CO_2 Reduction: An Evidence of Progress. Journal of Data Science, Informetrics, and Citation Studies. 2022;1(1):22-34.