Journal of Environmental Management 270 (2020) 110886

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

A bibliometric study of the Fenton oxidation for soil and water remediation

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ARTICLE INFO

Keywords:
Bibliometrics
Advanced oxidation processes
Fenton oxidation
Soil remediation
Water treatment
Wastewater treatment

ABSTRACT

Fenton based treatments have received tremendous attention in the recent decades as viable strategies for soil and water remediation. There exist different processes associated to the Fenton oxidation. Efficiency, reaction chemistry, and environmental consequences of these processes vary according to the iron (Fe) activation techniques such as soluble Fe(II) (homogeneous Fenton process), soluble Fe(II) and chelating agent (modified-Fenton), Fe minerals or solids (heterogeneous Fenton), iron and UV light (photo-Fenton) and electro-Fenton oxidation. Despite immense amount of research articles and reviews related to the Fenton oxidation, no bibliometric study of this topic has been published to our knowledge. Bibliometric studies provide a useful means to track research output and scholarly trends in a field. Here, we conducted a bibliometric study of the publications on this theme (>4000 documents) published during the past three decades available from the Science Citation Index Expanded (SCI-EXPANDED) database of the Web of Science Core Collection (Clarivate Analytics). Based on the bibliometric analysis of 4349 documents, various essential research indicators were described such as the type and language of publications, the most prominent authors in this theme, the most impactful articles, research categories, journals, institutions, and the countries, that have made the greatest contribution to this theme along with potential research hotspots. This bibliometric study allowed visualization of the current landscape and future trends in this field to facilitate the future collaborative research and exchange of knowledge.

1. Introduction

Advanced oxidation processes (AOPs) are emerging as viable strategies for the treatment of recalcitrant organic pollutants in contaminated soils and water/wastewater. The most common oxidants include ozone, permanganate, persulfate and H_2O_2 activated by Fe(II). Fenton oxidation is the most popular technique among AOPs due to its strong oxidation potential and effective remediation efficiency against a wide range of environmental pollutants (Usman et al., 2018).

Fenton oxidation is a complex catalytic process that describes the generation of hydroxyl radicals ($HO^•$) as a result of reaction of hydrogen peroxide (H_2O_2) with iron (mostly Fe(II) ion) at acidic pH. This process is based on Fenton's pioneering work which suggested the oxidation of tartaric acid by using solution of H_2O_2 and Fe(II) salt (termed as the Fenton's reagent) (Fenton, 1894). Provided below is the simplest and most-widely accepted reaction describing the traditional Fenton process (Fenton, 1894; Gligorovski et al., 2015):

$$\mathrm{Fe(II)} + H_2O_2 \rightarrow \mathrm{Fe(III)} + HO^- + HO^• \quad (1)$$

The $HO^•$ radical is among the most reactive chemical species with strong oxidation potential ($E^\circ = 2.8$ V) and, thus, have found widespread environmental applications especially for the remediation of contaminated environments (Gligorovski et al., 2015). There exist different processes associated to the Fenton oxidation with varying reaction chemistry, remediation efficiency and environmental consequences. For example, traditional Fenton oxidation (also termed as homogenous process) relies on soluble Fe(II) as a catalyst which, requires acidic conditions (pH < 4) to maintain catalyst solubility for an optimum treatment efficiency. This initial acidification is the major limitation of homogenous Fenton oxidation due to its detrimental impacts on native biota, cost of acidification and generation of Fe(III) sludge (Usman et al., 2016). To avoid this low pH, different alternative strategies have been suggested in literature. For example, soluble Fe(II) is applied with

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https://doi.org/10.1016/j.jenvman.2020.110886
Received 11 January 2020; Received in revised form 12 May 2020; Accepted 30 May 2020
Available online 6 June 2020

chelating agents that maintain Fe(II) in solution and enable the generation of HO• radicals at circumneutral pH. This process is usually described as modified Fenton oxidation. However, use of chelating agents is often linked to elevated treatment cost, higher toxicity and their involvement in non-productive consumption of oxidants decreasing oxidation efficiency (Xue et al., 2009; Pardo et al., 2014). Heterogeneous Fenton oxidation (also termed as Fenton-like process) is another alternative where instead of soluble Fe(II), solid iron catalysts (e.g. iron minerals) are used to catalyze generation of HO• radicals at circumneutral pH (Usman et al., 2012, 2016). The UV–vis radiation can also be applied with Fenton's reagent (H_2O_2 and Fe(II)) where additional reactions (e.g. photo-reduction of iron catalyst and peroxide photolysis) are involved to generate extra HO• radicals and the process is termed as photo-Fenton oxidation (Zhu et al., 2018; Liu et al., 2018). Another major Fenton based process is the electro-Fenton process that involves in-situ formation of H_2O_2 at a cathode with O_2 or air feeding with an iron-based catalyst (Fe(II), Fe(III) or iron minerals) in the reaction medium (Liu et al., 2018). On the other hand, electro-assisted Fenton process involves the catalyst regeneration by Fe(III) electrochemical reduction or the iron catalyst generation on the anode to form peroxi-coagulation process (Zhou et al., 2017).

Fenton oxidation has received tremendous attention in the recent decades to remediate contaminated soils and water/wastewater. Despite the immense amount of recent research as well as large number of review articles on the Fenton oxidation, no bibliometric analysis of this topic has been published to our knowledge.

Bibliometrics allows researchers to analyze, interpret, and develop indicators on the evolution and dynamics of scientific information in a particular field. This technique analyzes the characteristics of the existing literature on a subject to recognize the future research directions and to improve decision making by reducing the margin of error (Vanzetto and Thomé, 2019; Colares et al., 2020). These indicators can point out the latest state of a topic and are particularly helpful for researchers initiating a new research in a field.

Present study consists of a bibliometric study of 4349 publications related to the Fenton oxidation for the remediation of contaminated soil and water/wastewater available from Science Citation Index Expanded (SCI-EXPANDED). This database was chosen because it is the most efficient database to represent search results and, therefore, its use is recommended to search for journals and references (Vanzetto and Thomé, 2019). A SCI-EXPANDED-based analysis was performed to evaluate the search results according to the type and language of publications, the most prominent authors in this theme, the most cited articles, and the countries, institutions, and scientific journals (and research categories) that have made the greatest contribution to this theme. This would allow the identify the potential research hotspots and latest trends in this field which are discussed in last section of this article.

2. Methodology

Data used in the present study were retrieved on July 12, 2019 from the Clarivate Analytics Web of Science Core Collation, the online version of the Science Citation Index Expanded (SCI-EXPANDED). This databased was searched for the studies related to the remediation of contaminated soils and water/wastewater by employing Fenton oxidation. However, several variations of this term, remediation, exist in literature including remediation, treatment, degradation, removal. Therefore, database was searched by using the following parameters: Web of Science TOPIC (title, abstract, author keywords, and *KeyWords Plus*): ("Fenton" and ("groundwater" or "wastewater" or "wastewaters" or "water" or "waters" or "soil" or "soils" or "aqueous") and ("remediation" or "remediations" or "remediating" or "remediate" or "remediated" or "remediative" or "degrade" or "degradation" or "degrading" or "removal" or "remove" or "removed" or "removing" or "treatment" or "treated" or "treat" or "treating" or "treatments")) and year published: 1991–2018. It was pointed out that use of quotation marks (" ") is necessary to find the exact phrases and to avoid lemmatization and synonym features of Web of Science (these features are by default ON in search settings of this database) (Vanzetto and Thomé, 2019). Owing to this search feature, it was necessary to find different expressions and therefore, Boolean operator "or" was used which ensured the appearance of at least one term. To summarize, search terms were connected by using "and" and "or" which ensured that words Fenton, soil/water and remediation appeared in the TOPIC.

Using this strategy to search the database yielded 9490 documents including 9049 articles. *KeyWords Plus* yields additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes in the Clarivate Analytics database, which substantially increases the title-word and author-keyword indexing (Garfield, 1990). Despite its use for bibliometric analyses, SCI-EXPANDED is mainly designed to help researchers to find literature and is not meant directly for bibliometric studies (Ho, 2018). Therefore, use of SCI-EXPANDED for bibliometric studies requires an accurate bibliometric method because relying only on *KeyWords Plus* for search could lead to documents which are irrelevant to the theme being searched (Fu and Ho, 2015). This has been avoided by using "front page" (including the article title, the abstract, and the author keywords) as a filter which can improve the bibliometric studies as firstly proposed by Ho's group (Fu et al., 2012). Therefore, only documents with the searched keywords in their "front page" were considered. This improved method using the "front page" as a filter resulted in 4349 documents (46% of 9490) which were used for further analyses.

The *Journal Citation Reports* in 2018 were used to determine the impact factor of a journal (IF_{2018}). The obtained records were reorganized using Microsoft Excel 2016 as demonstrated elsewhere (Ho and Fu, 2016). The SCI-EXPANDED database designated the corresponding author as the "reprint author" but we retained the term "corresponding author" (Chiu and Ho, 2007). Single author in articles with unspecified authorship were both the first as well as corresponding author. Similarly, single institution articles were classified the institution as both of the first author and corresponding author. Moreover, we considered only the first corresponding author in articles having multiple corresponding authors. Addresses of the authors were used to determine the type of collaborations. Affiliations in England, Scotland, Northern Ireland, and Wales were reclassified as being from the United Kingdom (UK) (Chiu and Ho, 2005). Similarly, Plataforma Solar Almeria CIEMAT, CIEMAT Plataforma Solar Almeria, Plataforma Solar Almeria PSA CIEMAT, PSA CIEMAT, and CIEMAT were grouped as Centre for Energy, Environment and Technology (CIEMAT) in Spain. Univ Almeria, Univ Almeria CIEMAT, Univ Almeria CIESOL were grouped as Univ Almeria in Spain. Tsinghua Univ, China and Tsing Hua Univ, China were grouped as Tsinghua Univ in China.

To investigate the citations of publications, following three citation indicators were applied:

i) C_{year}: the number of citations in a particular year. For example, C_{2018} denotes the number of citations in 2018 (Ho, 2012).
ii) TC_{year}: the total citations received since publication till the end of the most recent year which is 2018 (TC_{2018}) in the present study).
iii) CPP_{year}: citations per publication ($CPP_{2018} = TC_{2018}/TP$) (Ho, 2012).

3. Results and discussion

Following sections describe general characteristics of the related publications in different categories.

3.1. Document type and language of publication

A relationship between type of document and their citations per publication in a research field was firstly proposed in 2004 (Hsieh et al., 2004). A total of 4349 publications in this theme was found which are categorized into seven document types indexed in the WoS (Table 1). Among these document types, article category ranked 1st (95% of 4349 publications) followed distantly by proceedings papers (6.6%) and reviews (4.3%). Article category denotes reports of research on original works where reviews can also be included and this bias in WoS cannot be avoided. A total of 288 proceedings papers were published in 68 journals in which *Water Science and Technology* published the most proceedings papers with 62 (22% of 288 proceedings papers). A total of 32 meeting abstracts were published in three journals in which *Abstracts of Papers of the American Chemical Society* published the highest number, 28, of meeting abstracts (88% of 32 meeting abstracts). *Chemical Engineering Journal* published the most reviews (11 reviews representing 5.9% of 187 reviews) followed by *Chemosphere* and *Applied Catalysis B-Environmental* with 10 reviews (5.3%) respectively.

The document type of reviews had the highest CPP_{2018} of 121 which can be attributed to the six classic reviews with $TC_{2018} \geq 1000$ including that by Pignatello et al. (2006), Neyens and Baeyens (2003), Malato et al. (2009), Pera-Titus et al. (2004) and Martínez-Huitle and Brillas (2009), and Gogate and Pandit (2004) with TC_{2018} of 1,598, 1,413, 1, 412, 1,317, 1,116, and 1,092, respectively. Review article by Pignatello et al. (2006) discussed fundamental and practical aspects of Fenton based chemistry for soil and water applications. It is worth mentioning that an erratum of this most-cited review has been published that highlighted the need to reinterpret the reactivity of Fe(II) species towards the oxidant (Pignatello et al., 2007). Neyens and Baeyens (2003) reviewed the overall kinetic scheme of reactions of the Fenton's reagent and role of different factors affecting the efficiency of Fenton oxidation. Further, they discussed the applications of the Fenton's reagent to improve sludge dewaterability. Malato et al. (2009) reviewed various developments in the use of solar photocatalysis for the degradation of organic contaminants and for disinfection in water. Pera-Titus et al. (2004) discussed the treatment of chlorophenols by different AOPs based on Fenton oxidation (traditional, Fenton-like, photo-Fenton), ozone, photocatalysis and photolysis. Review article by Martínez-Huitle and Brillas (2009) described various electrochemical technologies with an emphasis on electro-Fenton oxidation to remove organic dyes in contaminated wastewater. Gogate and Pandit (2004) evaluated treatment of refractory water pollutants by using five different oxidation processes at ambient conditions including Fenton oxidation, H_2O_2, ozonation, photocatalytic oxidation, and cavitation.

Regarding number of authors per publication (*APP*) for document types, it varied from 2.6 for meeting abstracts to 5.0 for editorial materials. It should be noted that some publications can be classified in two different document types in WoS, as is the case for 288 proceedings papers which were also classified as articles and, thus, the sum of individual percentages was higher than 100%.

Articles category is based mostly on reports of research on original works and, therefore, this category composed of 4118 articles was subjected to further analysis. Language of publication in a research field is one of basic concern in bibliometric studies (Wang and Ho, 2011). In searched theme, English was the most prominent publication language with 98% of the articles published in English with CPP_{2018} of 26 and *APP* of 4.5. There were 12 non-English languages including Polish (24 articles; $CPP_{2018} = 2.5$; $APP = 3.0$), Portuguese (23 articles; $CPP_{2018} = 5.6$; $APP = 3.8$), Chinese (20 articles; $CPP_{2018} = 4.9$; $APP = 5.0$), Spanish (6 articles; $CPP_{2018} = 0.67$; $APP = 4.8$), Turkish (6 articles; $CPP_{2018} = 3.3$; $APP = 2.5$), Japanese (5 articles; $CPP_{2018} = 1.4$; $APP = 2.6$), Czech (2 articles; $CPP_{2018} = 12$; $APP = 2.5$), German (2 articles; $CPP_{2018} = 4.0$; $APP = 3.5$), and one article for each of Croatian, French, Rumanian, and Serbian. One article was published in a bilingual journal of Serbo-Croatian.

Table 1
Citations and authors according to document type in Fenton oxidation for soil and water remediation.

Document type	*TP*	%	*AU*	*APP*	TC_{2018}	CPP_{2018}
Article	4118	95	18,328	4.5	106,848	26
Proceedings paper	288	6.6	1244	4.3	8297	29
Review	187	4.3	667	3.6	22,603	121
Meeting abstract	32	0.74	84	2.6	3	0.094
Correction	5	0.11	24	4.8	0	0
Letter	5	0.11	15	3.0	159	32
Editorial material	2	0.046	10	5.0	29	15

TP: number of articles; *AU*: number of authors; *APP*: number of authors per publication (*APP*); CPP_{2018}: citations per paper (TC_{2018}/TP); TC_{2018}: total citations from Web of Science Core Collection since publication to the end of 2018.

3.2. Trends in articles related to Fenton oxidation for soil and water remediation

It has been recognized that a publication's life in scientific literature is correlated to the number of the citations it receives (Chiu and Ho, 2005). Publications and their citation trends can be better explained by the relationship between citations per publication (CPP_{2018}) and article life (Chuang et al., 2007). Generally, CPP_{2018} of articles sharply increases to attain its peak values after publication year followed by a gradual decrease (Chuang et al., 2007). However, present study shows that citations per publication sharply increased to reach a plateau with CPP_{2018} of about 4.2 (Fig. 1).

To better understand the publications and their impact trends in a research field, a relationship has been proposed by Ho between total number of publications (*TP*) in a year and their citations per publication ($CPP_{year} = TC_{year}/TP$) by the decades (Ho, 2012) and years (Ho, 2013) which has been used as a unique indicator for research topics. The annual number of articles in this theme in SCI-EXPANDED and their CPP_{2018} were counted and are displayed in Fig. 2. Obtained data indicates that <30 articles were published each year in period of 1991–1998. However, after 1998 (with 19 articles), annual number of articles started to gradually increase to 198 in 2011 followed by a sharp increase since 2011 (465 articles in 2018) which shows the increasing amount of scientific interest in this field.

3.3. Most productive Web of Science categories and journals

Distributions of WoS category and journal are basic part of a bibliometric study (Chiu and Ho, 2005). Articles in this field were published in journals that belonged to in 93 WoS categories in SCI-EXPANDED.

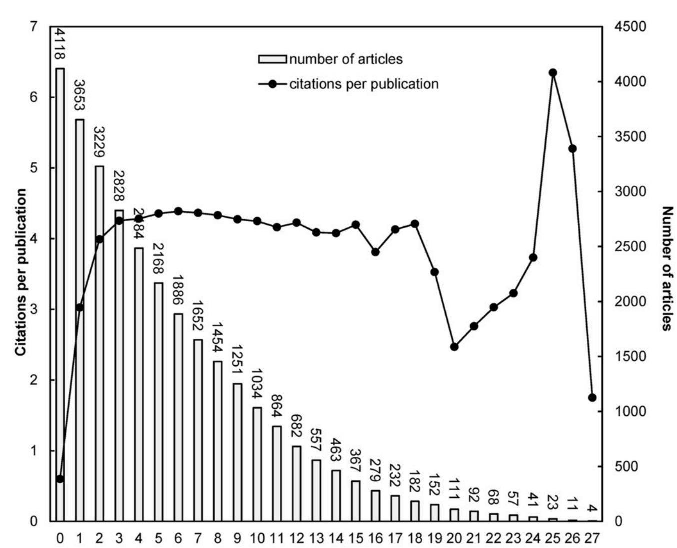

Fig. 1. Number of articles and citations per publication by article age on Fenton oxidation for soil and water remediation.

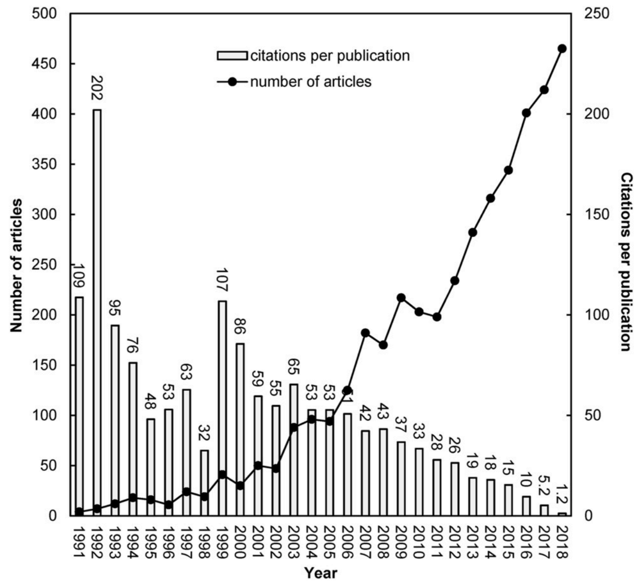

Fig. 2. Trends of articles on Fenton oxidation for soil and water remediation in SCI-EXPANDED and citations per publication from 1991 to 2018.

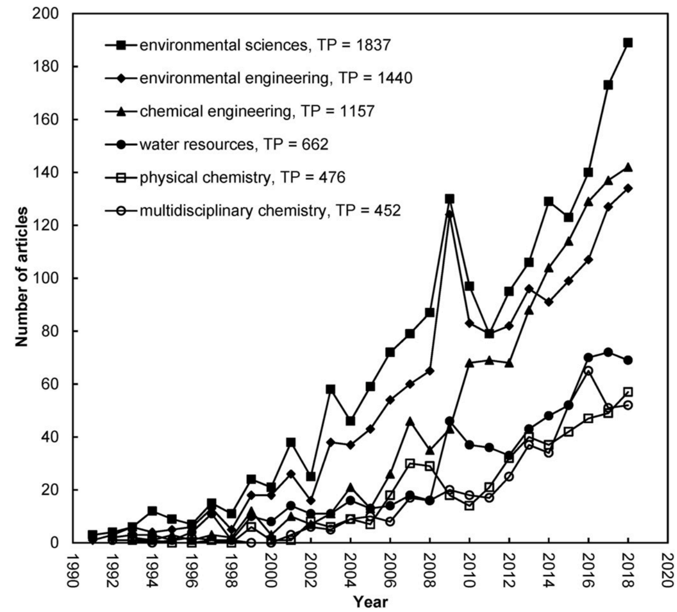

Fig. 3. Trends of the top six categories in field of Fenton oxidation for soil and water remediation.

The top 15 productive WoS categories with at least 50 articles are shown inTable S1 (Supplementary material). Following are the four leading categories where 3018 articles (73% of total articles) were published: environmental sciences, environmental engineering, chemical engineering, and water resources. It should be noticed that journals could fit in multiple categories in WoS. For example, *Water Research* was listed in categories of environmental sciences, environmental engineering, and water resources thus the sum of percentages is higher than 100%. The percentages of the top categories were high, which indicated the research focused on specific research areas including 'engineering' and 'environmental sciences and ecology'. Trends of the top six categories are presented in Fig. 3. In total, 4118 articles in this theme were published in 517 journals in SCI-EXPANDED. Furthermore, we analyzed the main scientific journals that have published in this subject in order to facilitate the researchers working on this theme. The top 10 most productive journals on this theme with their IF_{2018} and CPP_{2018} are listed in Table 2. Six of the top 10 productive journals belong to WoS category of environmental sciences; five in environmental engineering; four in chemical engineering; three in water resources; and one in physical chemistry. *Journal of Hazardous Materials* ($IF_{2018} = 7.650$), categorized in environmental sciences and environmental engineering published the most articles (307 articles; 7.5% of 4118 articles) followed by *Chemical Engineering Journal* ($IF_{2018} = 8.355$) with 241 articles and *Chemosphere* ($IF_{2018} = 5.108$) with 219 articles. Considering journal's impact factor, *Energy & Environmental Science* stood first with the highest IF_{2018} of 33.250 (one article), followed by *Advanced Functional Materials* ($IF_{2018} = 15.621$, three articles), *Applied Catalysis B-Environmental* ($IF_{2018} = 14.229$, 138 articles), *ACS Nano* ($IF_{2018} = 13.903$, two articles), *Journal of Materials Chemistry A* ($IF_{2018} = 10.733$, 16 article), and *Biomaterials* ($IF_{2018} = 10.273$, one article). Comparing the top ten productive journals (Table 2) revealed that articles published in *Water Research* had the highest CPP_{2018} of 71 followed by those in *Applied Catalysis B-Environmental* ($CPP_{2018} = 52$) and *Journal of Hazardous Materials* ($CPP_{2018} = 49$). Articles published in *Desalination and Water Treatment* had the lowest CPP_{2018} of 4.0.

Table 2
The top 10 productive journals that have published the most on Fenton oxidation for soil and water remediation.

Journal	*TP* (%)	IF_{2018}	Web of Science category	CPP_{2018}
Journal of Hazardous Materials	307 (7.5)	7.650	environmental engineering environmental sciences	49
Chemical Engineering Journal	241 (5.9)	8.355	environmental engineering chemical engineering	27
Chemosphere	219 (5.3)	5.108	environmental sciences	40
Desalination and Water Treatment	174 (4.2)	1.234	chemical engineering water resources	4.0
Water Science and Technology	157 (3.8)	1.624	environmental engineering environmental sciences water resources	13
Water Research	154 (3.7)	7.913	environmental engineering environmental sciences water resources	71
Applied Catalysis B-Environmental	138 (3.4)	14.229	physical chemistry environmental engineering chemical engineering	52
Environmental Science and Pollution Research	133 (3.2)	2.914	environmental sciences	9.1
Separation and Purification Technology	77 (1.9)	5.107	chemical engineering	30
Environmental Technology	72 (1.7)	1.918	environmental sciences	11

TP: number of total articles; IF_{2018}: journal impact factor in 2018; CPP_{2018}: citations per paper (TC_{2018}/TP).

3.4. Countries that have published the most in this field

The contributions provided by different countries were estimated by the affiliation of at least one author of articles related to this theme. These 4113 articles with author affiliations in SCI-EXPANDED were published by authors from 89 countries. Among them, 3167 articles (77% of 4113 articles) were country-independent publications from 66 countries and 946 (23%) articles were internationally collaborative publications from 86 countries. Research performance for different countries was evaluated on the basis of six publication indicators including total (*TP*), country independent (*IP*), internationally collaborative (*CP*), first author (*FP*), corresponding author (*RP*), and single author (*SP*) articles, as well as a citation indicator (CPP_{2018}) (Zhai and Ho, 2018). Table 3 shows the top 15 productive countries which include seven Asian countries, six European countries, and two American countries. Five of the seven major industrialized countries of the world (G7) including USA, France, Italy, Germany, Japan were ranked in the top 15 while UK (83 articles; ranked 18th) and Canada (62 articles; ranked 21st), do not appear in this list. China is the most prominent country having *TP* of 971 articles (24% of 4113 articles), *IP* of 785 articles (25% of 3167 country independent articles), *FP* of 938 articles (23% of 4113 first author articles), and *RP* of 929 articles (23% of 4095 corresponding author articles). Spain had the highest *CP* of 244 articles (26% of 946 internationally collaborative articles) while Turkey had the highest *SP* of 16 articles (21% of 77 single author articles). USA and France had the highest CPP_{2018} which is 41 for both countries. Iran and Poland share the lowest CPP_{2018} (11) in this list of top 15 countries. It is worth mentioning that Tunisia (62 articles; ranked 21st) published the most articles in Africa.

3.5. Institutions that have published the most on Fenton oxidation

Institution's articles were compared on the basis of six publication indicators and a citation indicator (CPP_{2018}) (Table 4) derived from a previous study (Hsu and Ho, 2014). Among total 4113 articles, 1955 articles (48%) were single institution articles and 2158 (52%) articles were the result of inter-institutional collaborations. The top 15 institutions are shown in Table 4 with their total articles and other indicators associated to this theme. Among them, six are located in Spain, five in China, and one in each Brazil, France, Portugal, and Switzerland. University of Barcelona in Spain ranked top with 144 articles (3.5% of 4113 articles) including 48 institutional independent articles (2.5% of 1955 articles), 88 first-authored articles (2.1% of 4113 articles), and 101 corresponding author articles (2.5% of 4095 articles) while Centre for Energy, Environment and Technology (CIEMAT) in Spain has the most institutional independent articles with 119 (5.5% of 2158 articles). L'Ecole Polytechnique Fédérale de Lausanne in Switzerland was the only one which published single-author articles in this list of institutions. Apart from this list, Mutah University in Jordan, Uludag University in Turkey, Northeast Petroleum University in China, and Silesian University of Technology in Poland published the most of single author articles with three. A bias could appear here because the Chinese Academy of Sciences has branches in different cities (Li et al., 2009) whereas its publications were pooled as of one organization at present. However, division of publications according to its branches could result in different rankings (Li et al., 2009). Furthermore, University of Chinese Academy of Sciences in China ranked 12th with three first and corresponding author articles but none of the institute independent and single author articles. Identifying the dominating institutions in this field can facilitate the researchers to identify the potential venues suitable for their knowledge exchange activities, research, study tours, postdoctoral studies etc. (Vanzetto and Thomé, 2019).

3.6. Highly impactful and highly cited articles related to the Fenton oxidation

Number of citations of a study represent perhaps its most important bibliometric quality because it represents the relevance and importance of a study in the academic world. However, Ho and Hartley (2016) recommended that researchers should pay more attention to the recent highly impactful articles considering citations in the most recent year (C_{year}) instead of relying solely on total citations since publication (TC_{year}). This recommendation was based on their observation that certain recent highly impactful articles with high C_{year} have not yet had comparable citations with older articles with high TC_{year} which can undermine their significance (Ho and Hartley, 2016). Therefore, C_{year} emerged as a better citation indicator to assess the impact of an article (Ho and Hartley, 2016). We used two citation indicators C_{2018} and TC_{2018} to identify the top ten highly impactful articles categorized (Table 5). The citation histories of the top ten articles were compared in Fig. 4. Four of these top 10 highly cited articles with $TC_{2018} \geq 412$ in this theme still have a strong impact in the most recent year with $C_{2018} \geq 46$ (ranked top 10). These articles are detailed below:

1) "Advanced oxidation processes (AOP) for water purification and recovery"

This article was published by Andreozzi et al. (1999) from University of Naples and National Research Council and is ranked 1st in both parameters of C_{2018} (139) and TC_{2018} (1196). They critically evaluated different features of the following AOPs: Fenton oxidation, photo-assisted Fenton, photocatalysis and ozone. These processes showed prominent abatement capacity against a wide range of toxic and/or refractory organic pollutants at laboratory scale while studies at upscaled/field level were found to very few. They also examined the working procedures and experimental setups for wastewater application along with treatment economics. Cost evaluation of these AOPs revealed

Table 3
Top 15 productive countries regarding Fenton oxidation for soil and water remediation.

Country	*TP*	*TPR* (%)	*IPR* (%)	*CPR* (%)	*FPR* (%)	*RPR* (%)	*SPR* (%)	CPP_{2018}
China	971	1 (24)	1 (25)	2 (20)	1 (23)	1 (23)	3 (12)	17
Spain	616	2 (15)	2 (12)	1 (26)	2 (12)	2 (12)	N/A	38
USA	358	3 (8.7)	3 (6.2)	3 (17)	3 (5.4)	3 (5.5)	4 (6.5)	41
Brazil	246	4 (6.0)	6 (5.1)	5 (8.9)	5 (4.9)	6 (4.6)	N/A	23
India	220	5 (5.3)	4 (5.8)	15 (3.7)	4 (5.0)	4 (5.0)	N/A	21
France	215	6 (5.2)	14 (1.9)	4 (16)	8 (3.2)	7 (3.7)	7 (3.9)	41
Turkey	207	7 (5.0)	5 (5.5)	17 (3.4)	6 (4.7)	5 (4.8)	1 (21)	28
Italy	163	8 (4.0)	9 (2.7)	6 (8.4)	10 (2.8)	10 (2.8)	10 (2.6)	34
Iran	155	9 (3.8)	7 (4.4)	28 (1.8)	7 (3.6)	8 (3.6)	7 (3.9)	11
Taiwan	140	10 (3.4)	8 (3.4)	17 (3.4)	9 (3.1)	9 (3.3)	4 (6.5)	37
Portugal	130	11 (3.2)	12 (2.1)	8 (6.8)	11 (2.7)	11 (2.7)	N/A	29
South Korea	110	12 (2.7)	11 (2.1)	12 (4.5)	12 (2.1)	12 (2.0)	10 (2.6)	26
Germany	94	13 (2.3)	19 (0.92)	7 (6.9)	16 (1.3)	17 (1.3)	10 (2.6)	38
Japan	90	14 (2.2)	13 (2.0)	22 (2.9)	15 (1.7)	15 (1.7)	10 (2.6)	23
Poland	89	15 (2.2)	10 (2.6)	43 (0.85)	13 (2.0)	12 (2.0)	2 (13)	11

TP: total number of articles; *TPR* (%), *IPR* (%), *CPR* (%), *FPR* (%), *RPR* (%), *RPR* (%), *SPR* (%): the rank and percentage of total articles, country independent articles, internationally collaborative articles, first author articles, corresponding author articles, and single author articles among their total articles, respectively; CPP_{2018}: citations per paper (TC_{2018}/TP); N/A: not available.

Table 4
Top 15 productive institutions regarding Fenton oxidation for soil and water remediation.

Institute	*TP*	*TPR* (%)	*IPR* (%)	*CPR* (%)	*FPR* (%)	*RPR* (%)	*SPR* (%)	CCP_{2018}
University of Barcelona, Spain	144	1 (3.5)	1 (2.5)	3 (4.4)	1 (2.1)	1 (2.5)	N/A	52
Centre for Energy, Environment and Technology (CIEMAT), Spain	127	2 (3.1)	41 (0.41)	1 (5.5)	3 (1.4)	4 (1.6)	N/A	45
Chinese Academy of Sciences, China	123	3 (3.0)	4 (1.2)	2 (4.6)	2 (1.9)	2 (1.9)	N/A	21
University of Almeria, Spain	87	4 (2.1)	81 (0.26)	4 (3.8)	8 (0.83)	8 (0.83)	N/A	42
University of Paris-Est, France	81	5 (2.0)	81 (0.26)	5 (3.5)	4 (1.4)	3 (1.6)	N/A	46
University of Porto, Portugal	67	6 (1.6)	5 (1.2)	6 (2.0)	5 (1.3)	5 (1.3)	N/A	26
Harbin Institute of Technology, China	59	7 (1.4)	7 (1.1)	8 (1.7)	6 (1.0)	6 (1.1)	N/A	17
L'Ecole Polytechnique Fédérale de Lausanne, Switzerland	55	8 (1.3)	18 (0.77)	7 (1.9)	7 (0.85)	9 (0.78)	9 (1.3)	40
University of Sao Paulo, Brazil	52	9 (1.3)	10 (1.0)	10 (1.5)	10 (0.75)	15 (0.68)	N/A	19
Tsinghua University, China	45	10 (1.1)	18 (0.77)	11 (1.4)	10 (0.75)	7 (0.85)	N/A	21
Tongji University, China	38	11 (0.92)	18 (0.77)	13 (1.1)	14 (0.71)	14 (0.71)	N/A	31
University of Chinese Academy of Sciences, China	37	12 (0.90)	N/A	8 (1.7)	264 (0.073)	253 (0.073)	N/A	8.5
University of Extremadura, Spain	36	13 (0.88)	2 (1.4)	93 (0.37)	10 (0.75)	11 (0.76)	N/A	35
University of Granada, Spain	36	13 (0.88)	31 (0.51)	12 (1.2)	23 (0.51)	23 (0.54)	N/A	23
University of Vigo, Spain	36	13 (0.88)	8 (1.1)	29 (0.70)	10 (0.75)	11 (0.76)	N/A	16

TP: total number of articles; *TPR* (%), *IPR* (%), *CPR* (%), *FPR* (%), *RPR* (%), *SPR* (%): the rank and percentage of total articles, single-institution articles, inter-institutionally collaborative articles, first-author articles, corresponding-author articles, and single author articles among their total articles, respectively; CPP_{2018}: citations per paper (TC_{2018}/TP); N/A: not available.

Table 5
Top ten most impactful articles in 2018 with two citation indicators C_{2018} and TC_{2018}.

Rank (C_{2018})	Rank (TC_{2018})	Article title	Reference
1 (139)	1 (1196)	Advanced oxidation processes (AOP) for water purification and recovery	Andreozzi et al. (1999)
2 (111)	3 (586)	Degradation of organic contaminants in water with sulfate radicals generated by the conjunction of peroxymonosulfate with cobalt	Anipsitakis and Dionysiou (2003)
3 (64)	29 (235)	Green synthesis of iron nanoparticles and their application as a Fenton-like catalyst for the degradation of aqueous cationic and anionic dyes	Shahwan et al. (2011)
4 (62)	274 (85)	Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: A critical review	Ahmed et al. (2017)
5 (54)	6 (412)	Rates of hydroxyl radical generation and organic compound oxidation in mineral-catalyzed Fenton-like systems	Kwan and Voelker (2003)
5 (54)	33 (230)	Self-propelled micromotors for cleaning polluted water	Soler et al. (2013)
7 (51)	218 (98)	A review of the influence of treatment strategies on antibiotic resistant bacteria and antibiotic resistance genes	Sharma et al. (2016)
8 (50)	33 (230)	Fenton-like degradation of 2,4-dichlorophenol using Fe_3O_4 magnetic nanoparticles	Xu and Wang (2012)
9 (48)	227 (96)	Coupling of membrane filtration and advanced oxidation processes for removal of pharmaceutical residues: A critical review	Ganiyu et al. (2015)
10 (46)	5 (437)	Decolorization of the azo dye Reactive Black 5 by Fenton and photo-Fenton oxidation	Lucas and Peres (2006)

C_{2018}: total citations from Web of Science Core Collection in 2018; TC_{2018}: total citations from Web of Science Core Collection since publication to the end of 2018.

that these overall costs of these processes are comparable to that of well-established remediation techniques.

2) "Degradation of organic contaminants in water with sulfate radicals generated by the conjunction of peroxymonosulfate with cobalt"

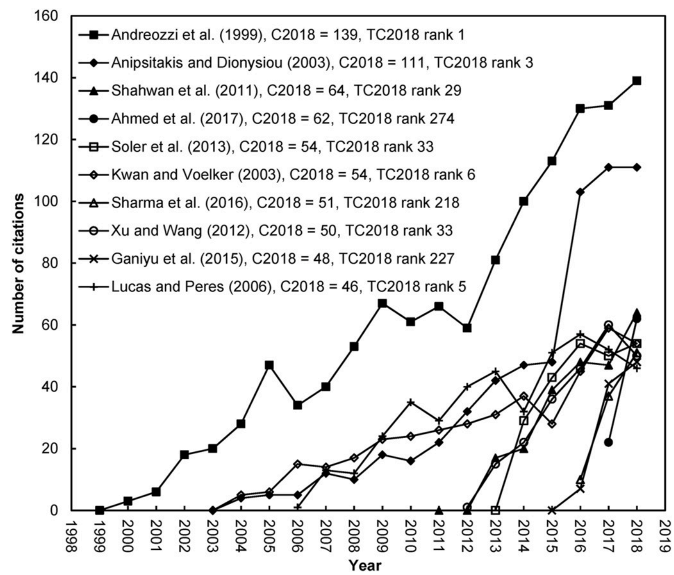

Fig. 4. The citation histories of the top ten articles (with C_{2018}) on Fenton oxidation for soil and water remediation.

This article was published by Anipsitakis and Dionysiou (2003) from University of Cincinnati in USA with C_{2018} of 111 (ranked 2nd) and TC_{2018} of 586 (ranked 3rd). This study was based on the comparison of the cobalt activated peroxymonosulfate with traditional Fenton oxidation to degrade three model pollutants including 2,4-dichlorophenol, atrazine, and naphthalene. Traditional Fenton oxidation was found more effective than cobalt/peroxymonosulfate at acidic pH. However, its activity diminished at circumneutral pH whereas cobalt/peroxymonosulfate showed higher degradation efficiency at neutral pH. Higher efficiency of cobalt/peroxymonosulfate systems was associated to the formation of sulfate radicals as the primary oxidizing species in the system.

3) *"Rates of hydroxyl radical generation and organic compound oxidation in mineral-catalyzed Fenton-like systems"*

This article was published by Kwan and Voelker (2003) from Massachusetts Institute of Technology (MIT) in USA with C_{2018} of 54 (ranked 5th) and TC_{2018} of 412 (ranked 6th). This article was aimed to identify the factors controlling the generation rate of HO• radicals and to check if its use can possibly aid to predict the oxidation rate of organics. Use of different iron minerals (ferrihydrite, goethite, hematite or a natural iron oxide-coated quartz in aquifer sand) revealed that generation rate of HO• radicals was proportional to the product of the contents of H_2O_2 and mineral's surface area though radicals were formed at different rates with different solids. They provided a reasonable mechanism for generation of HO• radicals via Fenton-like oxidation catalyzed by pure form or dispersed iron minerals on aquifer sand.

4) *"Decolorization of the azo dye Reactive Black* 5 by *Fenton and photo-Fenton oxidation"*

This article was published by Lucas and Peres (2006) from University of Trás-os-Montes and Alto Douro in Portugal with C_{2018} of 46 (ranked 10th) and TC_{2018} of 437 (ranked 5th). This study consisted of batch experiments to investigate the oxidative removal of an azo dye (reactive black 5) by using traditional Fenton (H_2O_2/Fe(II)) and photo-Fenton oxidation (H_2O_2/Fe(II)/UV). Both processes resulted in effective decolorization of the target dye with removal efficiency of >97% at optimum conditions. However, TOC removal was significantly higher by H_2O_2/Fe(II)/UV (46% removal) than H_2O_2/Fe(II) (21% removal) which indicates that role of UV lamp is particularly important in dye mineralization than dye decolorization.

3.7. Research hotspots and their trends in this theme related to the Fenton oxidation

The distribution of words in article titles, abstracts, author keywords, and *KeyWords Plus* can be informative when evaluating trends in research topics because they provide the most significant information which authors want to convey to their readers (Wang and Ho, 2016). Considering this, we examined words in article titles, abstracts, author keywords, and *KeyWords Plus* and ranked them according to the whole study duration and 6-year study period. Table 6 represents the 25 most frequently used author keywords according to their ranking. Overall (1991–2018), photo-Fenton emerged as the most-frequently used author keyword (appeared in 364 articles representing 10% of total articles in 1991–2018) followed by electro-Fenton (8.0%). It is interesting to note that for the last six years (Table 6, 2012–2018 *R* (%)), electro-Fenton occupies the first position with slightly higher appearance (9.2%) than photo-Fenton oxidation (9.0%). There exist another keyword "photocatalysis" (19th position) which could signify even higher amount of research in the photo-Fenton oxidation. Analysis of the words in article title (Table S2, supplementary material) reveals a higher ranking of "photo"-Fenton (7th) than "electro"-Fenton (13th). Apart from these two processes in author keywords, "Fenton-like" oxidation occupies 25th place. Fenton-like oxidation relies on the use of solid iron or iron minerals to catalyze the chemical oxidation at neutral pH (Usman et al., 2018). These processes are intended to address the limitations associated with traditional (homogeneous) Fenton oxidation (discussed in introduction of this manuscript). Traditional Fenton oxidation relies on catalytic ability of soluble Fe(II) which can precipitate at neutral pH. However, iron minerals have iron immobilized within interlayer spaces of their mineral structure which prevents their oxidation and aids to maintain the catalytic ability at circumneutral pH (Usman et al., 2012; Munoz et al., 2015).

We also employed the word cluster analysis where a serious synonymic single word and congeneric phrases from results of words analysis, were summed up, which could represent the possible research hotspots related to a field (Fu et al., 2013). Each word cluster is composed of several supporting words. For example, words like electro-Fenton, electro-Fenton degradation, electro-Fenton process could constitute a word cluster for electro-Fenton oxidation. Growth trends related to the development and application of electro-Fenton, photo-Fenton (photo-Fenton, photo-Fenton-like, heterogeneous photo-Fenton, photo-Fenton degradation, photo-Fenton oxidation, photo-Fenton process, photo-Fenton reaction, solar photo-Fenton), and heterogeneous Fenton oxidation (Fenton-like, Fenton-like degradation, Fenton-like oxidation, Fenton-like process, Fenton-like reaction, heterogeneous Fenton, heterogeneous Fenton process, heterogeneous Fenton reaction) are shown in Fig. 5 which clearly represent the growing research interest in this field particularly in electro-Fenton oxidation.

Use of heterogeneous oxidation is gaining significant attention in the recent decades with a particular emphasis on development of effective catalysts as evident from word "catalyst" on 24th position in article title. Particular interest in catalysis is also evident from the word cluster analysis where growth trends related to catalysis occupies much higher ranking than other potential research hotspots (Fig. 6). Four major

Table 6
Top 25 author keywords in publications related to Fenton oxidation for soil and water remediation.

Author keywords	*TP*	1991–2018 *R* (%)	1991–1997 *R* (%)	1998–2004 *R* (%)	2005–2011 *R* (%)	2012–2018 *R* (%)
photo-Fenton	364	1 (10)	8 (7.1)	5 (8.6)	1 (13)	2 (9.0)
electro-Fenton	290	2 (8.0)	N/A	26 (2.6)	3 (7.5)	1 (9.2)
Fenton	284	3 (7.8)	N/A	7 (7.2)	3 (7.5)	3 (8.3)
hydrogen peroxide	239	4 (6.6)	1 (21)	2 (17)	5 (6.6)	5 (4.7)
advanced oxidation processes	198	5 (5.5)	15 (3.6)	3 (9.2)	6 (6.0)	6 (4.7)
Fenton's reagent	195	6 (5.4)	2 (16)	1 (17)	2 (8.2)	23 (2.1)
degradation	174	7 (4.8)	44 (1.8)	17 (3.9)	10 (4.7)	4 (5.0)
Fenton reaction	167	8 (4.6)	4 (13)	11 (5.3)	9 (4.8)	8 (4.2)
wastewater treatment	164	9 (4.5)	15 (3.6)	11 (5.3)	10 (4.7)	7 (4.3)
wastewater	158	10 (4.4)	10 (5.4)	9 (5.9)	12 (4.2)	8 (4.2)
Fenton process	150	11 (4.1)	N/A	50 (1.3)	7 (5.8)	11 (3.8)
mineralization	147	12 (4.1)	44 (1.8)	50 (1.3)	7 (5.8)	13 (3.6)
hydroxyl radical	144	13 (4.0)	4 (13)	3 (9.2)	12 (4.2)	16 (2.9)
water treatment	136	14 (3.7)	15 (3.6)	11 (5.3)	17 (3.2)	11 (3.8)
Fenton oxidation	128	15 (3.5)	10 (5.4)	6 (7.6)	26 (2.4)	14 (3.5)
advanced oxidation process	127	16 (3.5)	44 (1.8)	28 (2.3)	19 (2.9)	10 (4.0)
oxidation	123	17 (3.4)	7 (8.9)	8 (6.9)	16 (3.5)	17 (2.7)
hydroxyl radicals	99	18 (2.7)	44 (1.8)	20 (3.0)	19 (2.9)	18 (2.6)
photocatalysis	94	19 (2.6)	10 (5.4)	15 (4.9)	25 (2.5)	21 (2.2)
biodegradability	93	20 (2.6)	N/A	17 (3.9)	15 (3.7)	27 (1.9)
toxicity	91	21 (2.5)	N/A	20 (3.0)	19 (2.9)	20 (2.3)
adsorption	90	22 (2.5)	15 (3.6)	34 (2.0)	40 (1.5)	15 (3.0)
phenol	89	23 (2.5)	N/A	50 (1.3)	14 (3.8)	25 (2.0)
Fenton reagent	78	24 (2.1)	6 (11)	11 (5.3)	18 (3.0)	45 (1.1)
Fenton-like	76	25 (2.1)	N/A	196 (0.33)	34 (1.7)	19 (2.6)

TP: total number of articles; *R*: rank; N/A: not available.

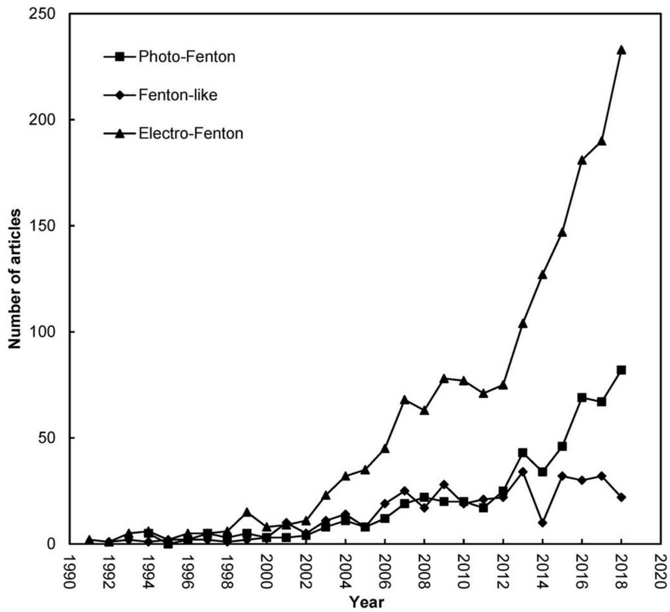

Fig. 5. Growth trends of three major Fenton based oxidation processes during 1991–2018 revealed by word cluster analyses where electro-Fenton (electro-Fenton, electro-Fenton degradation, electro-Fenton), photo-Fenton (photo-Fenton, photo-Fenton-like, heterogeneous photo-Fenton, photo-Fenton degradation, photo-Fenton oxidation, photo-Fenton process, photo-Fenton reaction, solar photo-Fenton), and Fenton-like oxidation (Fenton-like, Fenton-like degradation, Fenton-like oxidation, Fenton-like process, Fenton-like reaction, heterogeneous Fenton, heterogeneous Fenton process, heterogeneous Fenton reaction) processes are shown.

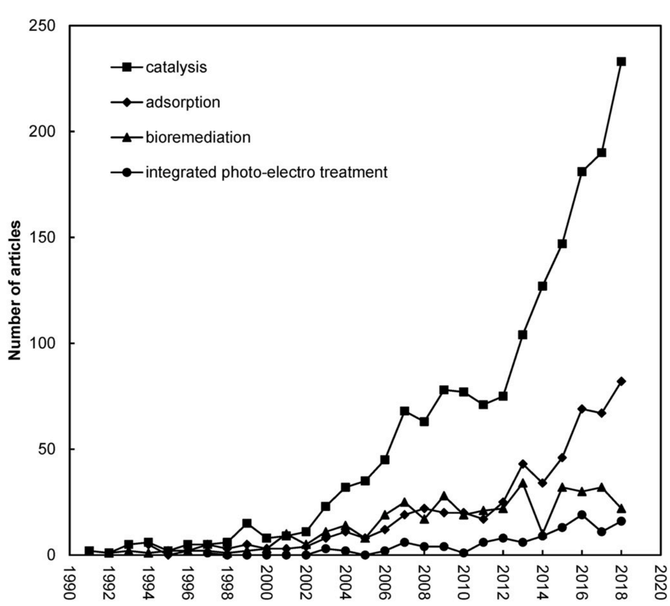

Fig. 6. Growth trends of major research focuses during 1991–2018 revealed by word cluster analysis where catalysis (catalysis, catalyst, catalysts, catalytic, electrocatalytic, heterogeneous catalysis, heterogeneous catalyst, mineral-catalyzed, nanocatalyst, photo-catalytic, photocatalysis, photocatalyst, photo-catalytic, solar photocatalysis, sonocatalyst), adsorption (adsorption, sorption, desorption, physisorption, biosorption, and chemisorption), bioremediation (bioremediation, biodegradation, biological treatment), and integrated photo-electro treatments (photo-electro-Fenton, photoelectro-Fenton, solar photoelectro-Fenton) were classified.

research hotspots with the most articles in Fenton oxidation for soil and water remediation were catalysis, adsorption, bioremediation and integrated photo-electro treatments (general but frequently-used word clusters based on degradation, advanced oxidation processes were ignored). Growth trends related to these topics are illustrated in Fig. 6 where catalysis (catalysis, catalyst, catalysts, catalytic, electrocatalytic, heterogeneous catalysis, heterogeneous catalyst, mineral-catalyzed, nanocatalyst, photo-catalytic, photocatalysis, photocatalyst, photo-catalytic, solar photocatalysis, sonocatalyst), adsorption (adsorption, sorption, desorption, physisorption, biosorption, and chemisorption), bioremediation (bioremediation, biodegradation, biological treatment), and integrated photo-electro treatments (photo-electro-Fenton, photoelectro-Fenton, solar photoelectro-Fenton) were classified. It should be noted that the word "iron" occupies the 14th place in the words in article titles, 24th in *KeyWords Plus,* and 21st in abstract words indicating the greater interest in iron-based catalysts. Catalytic ability of different iron-based catalysts has been explored in literature. Owing to the presence of structural Fe(II), Fe(II) bearing minerals (e.g. magnetite) are gaining particular attention to catalyze the Fenton-like oxidation for soil and water applications (Munoz et al., 2015; Usman et al., 2018). Focus of large amount of the current research is to develop effective iron catalysts with greater stability but without compromising the treatment ability. Different strategies are used to design effective catalysts such as development of composite materials, use of different stabilizers or supports to anchor iron on catalyst surface and coupling with other remediation strategies etc. (Nidheesh, 2015; Usman et al., 2018). Similarly, use of different chemical activation agents has been proposed to enhance the reactivity of heterogeneous Fenton oxidation by tuning the redox chemistry of iron minerals (Sun et al., 2020).

Another process namely "adsorption" emerged in the word cluster analysis (Fig. 6) and top 25 words (19th for *KeyWords Plus*, and 22nd for author keywords). Its ranking further improved during the last six years (15th for both *KeyWords Plus* and author keywords) indicating recent research in this field. This could be related to the coupling of adsorption with Fenton oxidation which can be applied as pre- or post-Fenton oxidation (Zhang et al., 2018). In the recent decade, researchers have widely focused on the coupling of Fenton oxidation with other remediation strategies such as adsorption (Zhang et al., 2018), bioremediation (Sanchis et al., 2014), reduction (Rybnikova et al., 2016) etc. Coupling Fenton oxidation with suitable remediation strategies can improve the treatment efficiency and address the limitations associated with Fenton oxidation (highlighted in the introduction of this manuscript) (Usman et al., 2016). Biodegradability is another prominent keyword (20th in author keywords, Table 6) that has been used recently (no study with this keyword from 1991 to 1997). This word can describe the major necessity of coupling the Fenton oxidation with bioremediation. Fenton oxidation is widely used as a pretreatment to improve the biodegradability of a contaminant by subsequent biological treatment that can reduce the treatment cost (Loveira et al., 2019). Another word "toxicity", occupying the 21st place in author keywords (Table 6), can mainly ascribe reducing the toxicity of pollutants for subsequent biological treatments or in toxicity assessment of Fenton oxidation. Fenton oxidation reduces the contaminant load, but it could also negatively affect the environmental quality and microbial community. Exploring the impacts of various Fenton-based strategies have received significant attention recently particularly in terms of contaminated soils (Usman et al., 2016). However, most of the applications of Fenton based strategies have been evaluated in laboratory conditions and there exists limited amount of data in field conditions. Therefore, field experiments should be performed to evaluate the promising processes and their suitable applications with a focus on associated challenges and their potential solutions.

Apart from the information about the processes in top-25 author keywords, there are three keywords regarding application of Fenton oxidation in water including "wastewater treatment" (ranked 9th), "wastewater" (ranked 10th), and "water treatment" (ranked 14th) while

1^{st} keyword related to soil (entitled "soil remediation") appeared at 35^{th} position. A similar trend was observed in words in article titles ("wastewater", "water", "aqueous", "solution" and "soil" at 4^{th}, 10^{th}, 11^{th}, 23^{rd}, and 30^{th} position, respectively) (Table S2, supplementary material), words in abstracts ("wastewater", "water", "solution", "aqueous", and "soil" at 10^{th}, 15^{th}, 17^{th}, 19^{th}, and 130^{th} position, respectively) (Table S3, supplementary material) and *KeyWords Plus* ("waste-water", "aqueous-solution", "water", "waste-water treatment", "wastewaters", and "contaminated soils" at 5^{th}, 6^{th}, 9^{th}, 13^{th}, 15^{th}, and 96^{th}" (Table S4, supplementary material). This reveals that higher amount of research related to Fenton oxidation is being conducted in water medium (a prominent research hotspot) as compared to those in soil system. This might be associated to the complex nature of soil which makes it difficult to fairly assess the oxidation efficiency (Rybnikova et al., 2016; Monfort et al., 2019, 2020). Moreover, injection of oxidants and catalysts (even in nanosized) becomes problematic in soils and require thorough investigations of soil constituents' properties and their interactions with the pollutants (Usman et al., 2020). Aqueous solutions or water medium, however, offer greater flexibility and better control of reaction conditions and are therefore considered as a realistic choice especially for preliminary studies and mechanistic investigations. It is worth mentioning that owing to the complexity of the soil system, amount of research is even limited in historically contaminated soils as compared to that in sand/spiked soils (Usman et al., 2016, 2020). Artificially contaminated soils can offer ease in preliminary evaluations but are not the true representative of the real contaminated soils under field conditions. We, therefore, call researchers to target the real contaminated soils in their future studies to depict the true potential of proposed treatment.

This data also reveals the occurrence of two types of pollutants in this list including i) phenol (23^{rd} in author keywords as well as *KeyWords Plus*) and ii) dye/azo-dye (ranked 19^{th} for words in title and 21^{st} for *KeyWords Plus*). Higher amount of research has been devoted to these two pollutants because they are frequently used as model pollutants owing to their environmental relevance. Moreover, large amount of data is available in literature about their removal and degradation which facilitates the mechanistic investigations and data comparison especially for preliminary investigations. Strong relevance of using phenol as a model pollutant has been highlighted in a recent review on Fenton-based oxidation strategies (Brillas and Garcia-Segura, 2020).

4. Conclusion

This bibliometric study has brought together the knowledge on publications related to the application of Fenton oxidation for soil and water remediation that are available from the Web of Science database. Science citation index expanded analysis of 4349 publications was performed to visualize panorama of publications, the most prominent authors, institutions, countries, research categories, and journals. These indicators are intended to facilitate researchers in analysis of existing literature which could improve the research direction for better scientific contribution.

With regard to the articles, top three journals publishing on this subject were *Journal of Hazardous Materials*, *Chemical Engineering Journal* and *Chemosphere* with high impact factors that highlights the evident scientific interest in this theme. It is worth mentioning that *Energy & Environmental Science* stood first with the highest IF_{2018} of 33.250 (one article), followed by *Advanced Functional Materials* (IF_{2018} = 15.621, three articles) and *Applied Catalysis B-Environmental* (IF_{2018} = 14.229, 138 articles, which is also ranked at 7^{th} position in top-ten journals in this theme. Articles published in *Water Research* had the highest citations per publication (CPP_{2018} = 71) followed by *Applied Catalysis B-Environmental* (CPP_{2018} = 52) and *Journal of Hazardous Materials* (CPP_{2018} = 49). Most-impactful articles in this theme are also identified by using updated citation parameters where instead of relying only on total citations, we also considered the recent citations. Comparing total citations of an old article with a recent one can be misleading and, therefore, both parameters should be considered to identify the most-impactful articles.

China, Spain and USA were found as the leading countries in ranking according to the number of publications in this theme. Amongst the seven major industrialized countries of the world (G7), USA, France, Italy, Germany, Japan were ranked in the top 15 countries. However, UK (ranked 18^{th}) and Canada (ranked 21^{st}), do not appear in this list which indicates potential area for research and development on Fenton oxidation in these regions. Leading institutions working on this subject are recognized which can facilitate the researchers to identify the potential venues for knowledge exchange activities, joint research, study tours, postdoctoral studies etc.

Finally, research hotspots were identified on the basis of this bibliometric study especially after analyzing words in author keywords, article titles, abstract and *KeyWords Plus*. It has been found that photo-Fenton, electro-Fenton and heterogeneous Fenton oxidation are widely investigated. It is, however, challenging to develop effective iron-based catalysts with greater stability for an improved oxidation efficiency. Coupling of chemical oxidation with other remediation strategies such as adsorption, bioremediation etc., is also emerging as another avenue for potential research in this field. As focused largely in the current research, it would be highly rewarding to develop the iron catalysts having higher catalytic potential and stability under diverse experimental conditions. Higher amount of research work on this subject is being conducted in water/wastewater/aqueous solution than in soil system. Soil application of these processes requires thorough investigations of the soil constituents and their interactions with pollutants, mode of oxidant injection, fate of nano-catalysts and their toxicity assessment. Industrial application of Fenton oxidation for soil and water/wastewater treatment requires field experiments to evaluate the promising Fenton-based processes and their suitable applications with a focus on associated challenges and their potential solutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Muhammad Usman: Conceptualization, Methodology, Writing - original draft. **Yuh-Shan Ho:** Methodology, Data curation, Formal analysis, Writing - review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110886.

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