Bibliometric analysis of wastewater treatment with microalgae in the period 1985-2023

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ABSTRACT

Objective. To indicate the condition of the wastewater treatment with microalgae (WTwM) research.

Methodology. The words treatment, wastewater, and microalgae, were entered as keywords in a search under "article title" in SCOPUS. The documents found were saved and exported as a file with a .bb extension. From R Studio, the BIBLIOMETRIX interface was linked to R Statistics. The interface was opened from MOZILLA to import the .bb file.

Results. There is a significant increase in the number of papers published since 2013, up to 68 articles in 2022. The authors with the highest number of contributions on the subject are Ivet Ferrer and Joan García. The countries most involved in this issue are China, Spain, India and Brazil; China is the one with the highest number of publications. The WTwM studies in 2023 are concerned with investigating biomass accumulation and nutrient removal as a way to make sustainable use of the process.

Conclusions. WTwM is a research topic that is studying and disseminating knowledge since the 80's. The author who stands out the most is Ivet Ferrer. China has little collaboration with scientists from other countries. The most recent WTwM studies address issues related to biodiesel production and biogas production. The topics to be addressed in future research will be related to the study of temperature, osmotic capacity, pH and O_2 levels.

Keywords: biological wastewater treatment, biomass, biodiesel, biogas.

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INTRODUCTION

Literature analysis is a way of identifying the development and growth of knowledge. And it is an alternative to evaluate scientific activity through the documents published on a particular topic. The importance of carrying out an exhaustive, representative and up-to-date bibliographic analysis lies in the assessment and selection of the information in a scientific database, through the appropriate use of bibliometric indicators, as a tool that measures the impact of the information.

At the international scale, SCOPUS and Web of Science (WoS) propose some indicators to determine the quality of scientific information (González-Sanabria, 2019). However, a bibliometric analysis is capable of analyzing the evolution, the degree of progress, as well as the scientific imperfection of a particular subject, as well as allowing to determine the rate of productivity, dispersion and scientific rigor with which knowledge is developed.

On this basis and considering that the scarcity of fresh water is currently a cause for concern; although various actions are carried out for the treatment of wastewater, most of these require large amounts of fossil energy, produce greenhouse gases and there is little use of the products obtained, it becomes necessary to search alternatives which would lead the scope of research efforts. In this regard, Atif *et al.* (2023) pointed out that the use of microalgae is a sustainable method for the production of biomass from wastewater (W). For this reason, the objective of this study was to indicate the current state of research on wastewater treatment with microalgae (WTwM); through bibliographic indicators that allow us to know the growth and development of the subject, when biological processes are studied as a sustainable alternative response to the increase in volumes of wastewater (W) worldwide.

MATERIALS AND METHODS

The keywords "treatment, wastewater, microalgae" were entered for a search in the SCOPUS database. This search only considered the words in "article title". It was sorted by document type ("DOCTYPE"), publication stage ("PUBSTAGE"), font type ("SRTYPE") and language ("LANGUAGE"). Documents found were saved in the "My Scopus" folder, which was exported as a .bb extension file using the "BibTex" tab of SCOPUS.

At R Studio with the "bibliometrix" library active, it was requested to run the "biblioshiny" command to link the BIBLIOMETRIX interface with R Statistics. The BIBLIOMETRIX interface was opened at MOZILLA, where a tab was opened in which the file with a .bb extension was imported using "DATA" "Load Data".

RESULTS AND DISCUSSION

Results generated from the search in SCOPUS showed 504 records that considered the words "treatment, wastewater, microalgae" in their title. Of these, 329 documents were selected filtered by document type (DOCTYPE), publication phase (PUBSTAGE), font type (SRTYPE) and language (LANGUAGE) which are shown in Table 1.

Main information analysed by BIBLIOMETRIX

As a result of the analysis, in the foreground BIBLIOMETRIX summarizes the main information obtained (Table 2).

Table 1. Results of the search of documents in the SCOPUS database, which in their title include the words "treatment, wastewater, with microalgae".

Data base	Search	Records	Documents
Scopus	TITLE (treatment AND wastewater AND with AND microalgae) AND PUBYEAR > 1987 AND PUBYEAR < 2023 AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))	503	329

* "DOCTYPE": type of document; "ar": article; "PUBSTAGE": publication phase; "final": final; "SRCTYPE": font type; "j": journal; "LANGUAGE": language; "English": English.

Table 2. Main information of the documents found in BIBLIOMETRIX.

Main information	Results
Artícle	329
Journals	109
Autors	1,305
Average documents per year	4.77
Average citation per document	34.73

Annual scientific production

The analysis showed that of the total number of articles identified and related to the topic since 1985 to 2012, less than one document (0.75) was published on average per year (Figure 1). From 2013 onwards, the number of documents shows a positive trend, as the publication of articles related to WTwM increased, from seven documents in that year to 68 in 2022 for a total of 293 articles. In 2017, the trend dropped, as only 19 papers were published, two fewer articles than in 2016.

Average number of citations per article

In this regard, Figure 2 shows a positive trend and two negative trends. The positive trend goes from six average citations in 1985 to 84 citations in 1996. On the other hand, the first negative trend went from 161 citations in 2001 to 12.67 in 2009; while the second negative trend is observed from 2011 to 2022, when it dropped from 105.33 to 8.35 average citations, respectively. The maximum average number of citations per document was observed in 2001, with a value of 161; while the average minimum was three in 1998.

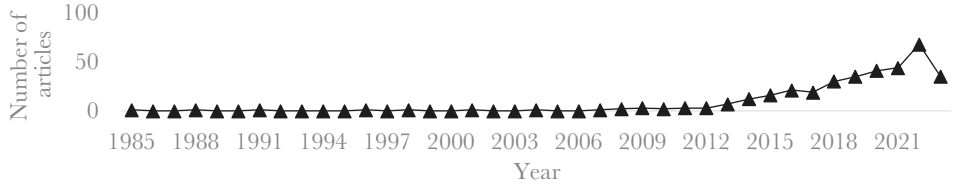


Figure 1. Behavior of scientific production in the period 1985-2023.

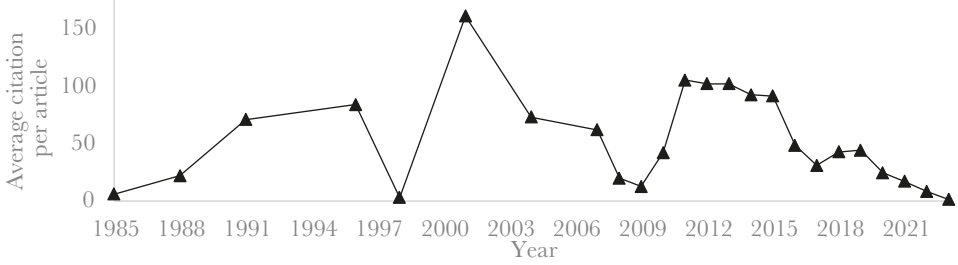


Figure 2. Behavior of the average number of citations per article in the period 1985-2023.

Most cited documents

The ten most cited documents are shown in Figure 3; those published by the authors Víctor Matamoros, Jyoti Prakassh Mayty, Sunja Cho, Annelies Beuckels and Esther Posadas stand out with more than 200 citations.

The paper "Capability of microalgae-based wastewater treatment systems to remove emerging organic contaminants: A pilot-scale study" by Matamoros *et al.* (2015), published in Journal of Hazardous Materials, is the most cited with 292 citations. It is followed by the article "Microalgae for third generation biofuel production, mitigation of greenhouse gas emissions and wastewater treatment: Present and future perspectives – A mini review" by Maity *et al.* (2014), published in Energy, which is cited 278 times.

The authors Cho *et al.* (2011) published the paper "Reuse of effluent water from a municipal wastewater treatment plant in microalgae cultivation for biofuel production" in Bioresource Technology, which is cited 239 times. On the other hand, Beuckels *et al.* (2015) and Posadas *et al.* (2015) with their articles "Nitrogen availability influences phosphorus removal in microalgae-based wastewater treatment" and "Influence of pH and CO_2 source on the performance of microalgae-based secondary domestic wastewater treatment in outdoors pilot raceways"; the first one published in Water Research and the second in Chemical Engineering Journal, these have 235 and 212 citations, respectively.

The most relevant Journal in 2023

Of the 109 journals analyzed, Figure 4 shows that Bioresource Technology, Algal Research, Journal of Environmental Management, and Water Science and Technology are those with the highest number of documents related to the topic of WTwM in 2023, with 52, 21, 13 and 11 respectively. The journals Environmental Science and Pollution Research, Journal of Water Process Engineering, Science of the Total Environment and Water Research have 10 published papers each.

Chemosphere has eight publications related to WTwM. In addition, Biochemical Engineering Journal and Journal of Environmental Chemical Engineering have seven published papers each.

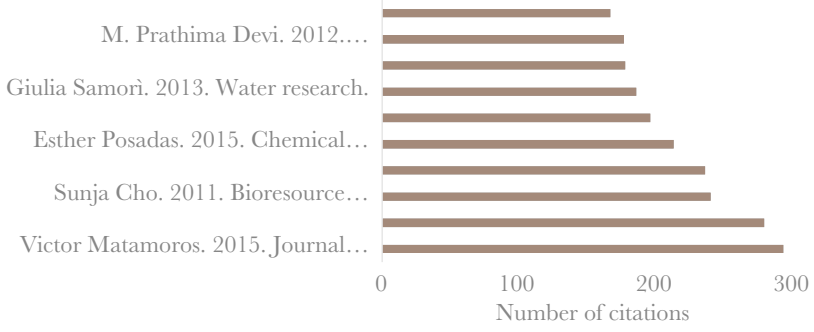


Figure 3. Number of citations included per article, which are related to Wastewater treatment with microalgae (WTwM).

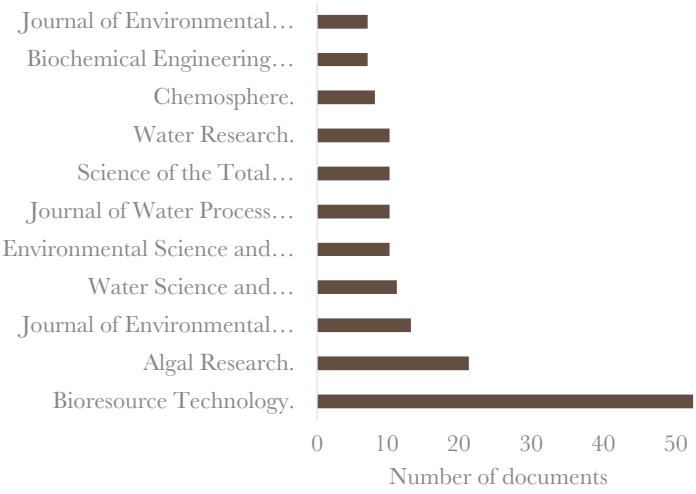


Figure 4. Behavior of journals that publish articles related to WTwM in 2023.

Journal production over time

Regarding the frequency of publication, Figure 5 shows that the journal Water Research has frequently published documents related to WTwM since 1988, with a cumulative number of 130 articles. While Bioresouce Technology, despite started publising in 1996, it has 334 articles on the subject to date.

On the other hand, of the journals with a recent incursion into the publication of related articles about wastewater treatment with microalgae (WTwM), Science of the Total Environment stands out, which began to be published in 2018 with a cumulative number of 29 papers. Environmental Science and Pollution Research, and Journal of Water Process Engineering have been publishing since 2019 with a cumulative number of articles 35 and 33 respectively. In addition, Journal of Environmental Management, publising since 2016, has 35; Algal Research with 109 published papers since 2016, and Water Science and Technology, publising since 2009, has a cumulative number of 75 articles.

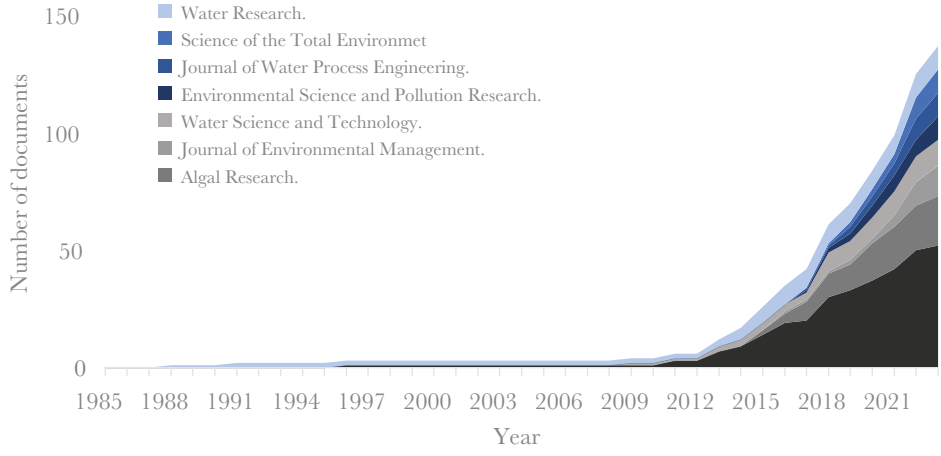


Figure 5. Trend in the production of articles per journal in the period 1985–2023.

Most relevant authors

Regarding this, Figure 6 shows that out of 1305 authors, those who have worked the most on the subject are Ivet Ferrey and Joan García, each with 10 articles published. They are followed by Liu Y., with nine publications (which initial includes either Yang Liu, Yu Liu, Yuhuan Liu, Yanbo Liu or Yuanqi Liu, as it was observed in the review of articles). Afterwards, Zhang Y., with eight published papers (the initial aggregates Yulei Zhang, Yaping Zhang, Yakun Zhang, Yifeng Zhang; Yalei Zhang, Yangguo Zhang, as it was observed in the review of those articles).

It is also noted that Uggetti Enrica published seven papers. Marianna Garfí, Raúl Muñoz and Li X (initial includes either Xiang Li, Xuyang Li, Xiangxing Li, Xunzhou Li, Xin Li or Xue Li; as it was observed in the review of articles) is a group of authors who participated in the publication of six papers each.

In another group, with five published documents each, we found mentioned Germán Buitrón, Chen X (several authors), Raquel Gutiérrez, Li Z (several authors) and Fabiana Passos.

Authors' production over time

Figure 7 shows that the authors Ivet Ferrer, Joan García and Raúl Muñoz have been publishing almost consistently since 2014; however, Ferrer did not publish in 2019 and 2021, García did not publish from 2019 to 2021, neither did Muñoz in 2017, 2020 and 2021.

Enrica Uggetti behaves similarly to the previous mentioned authors; however, this author started publishing in 2015 and did not publish from 2019 to 2021. In turn, Raquel Gutiérrez only published from 2015 to 2017. On the other hand, the authors Mariana Garfí and German Buitrón, who have been publishing since 2017 and 2016 respectively, are authors who also have recently published.

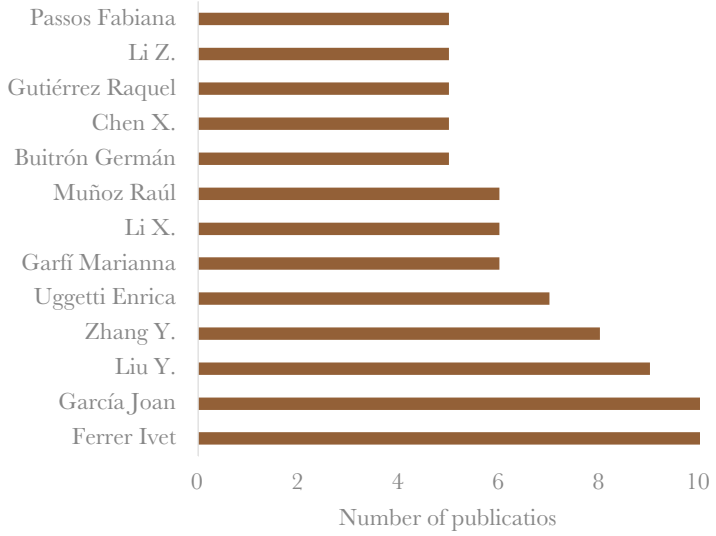


Figure 6. Behavior of the trend on most relevant authors.

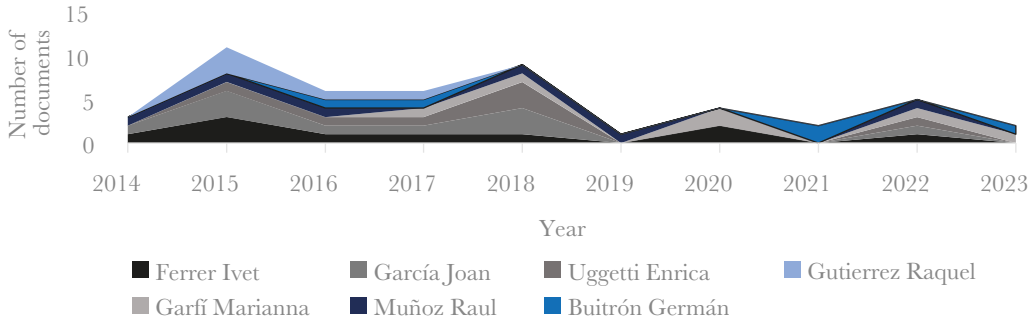


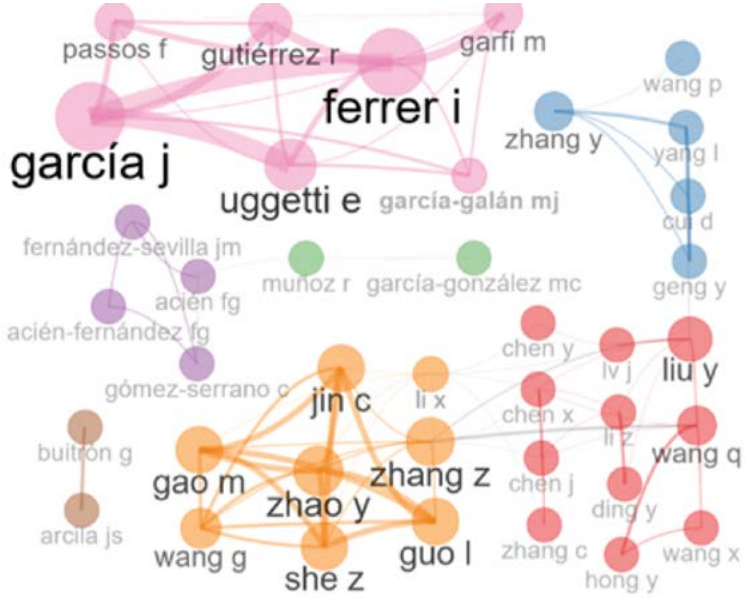
Figure 7. Trend in the production of articles per author in the period 2014-2023.

Collaborative network among authors

The analysis shows that there are seven networks of researchers who have worked with WTwM, of these, there are two groups that collaborate with each other; while two networks do not collaborate with any other network (Figure 8).

In the first group of networks with mutual collaboration (purple and green), seven authors participate in the first one, and Francisco Gabriel Ascíen stands out, who is the nexus with Raúl Muños of the second network (green) with only two authors. In the second group there are three collaborative networks, Zhang Z (orange) is Liu Y's nexus (red), who in turn is Geng Y's nexus (blue). Authors in these networks are eight in the first one (orange), 12 in the second, and five in the third (blue).

The first collaboration network without any nexus to other (pink) is made up of seven authors, including Joan Garcia, Ivet Ferrer and Enrica Uggetti. In the second no-nexus network (brown) only Germán Buitrón and Juan S. Arcila participate.



Source: BIBLIOMETRIX with the SCOPUS database.
Figure 8. Behavior of collaboration networks among authors.

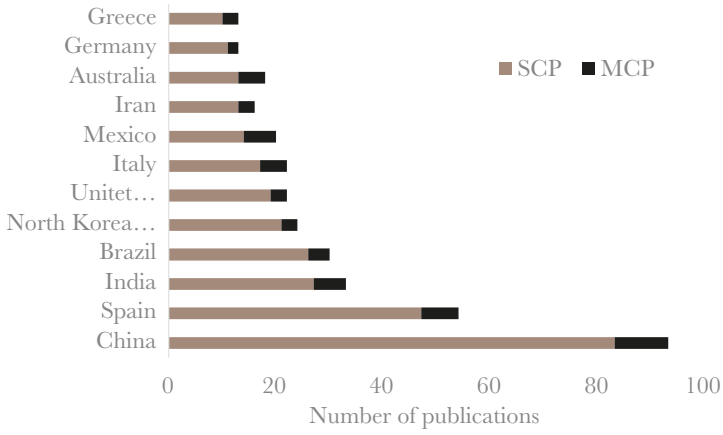
Production per country

The analysis showed that China is the country with the highest number of documents published regarding WTwM (Figure 9). Of these, 83 were published independently and 10 were published in collaboration with other countries. On the other hand, Spain published 47 articles independently and seven in collaboration, India 27 independently and six in collaboration, Brazil 24 independently and four were collaborative.

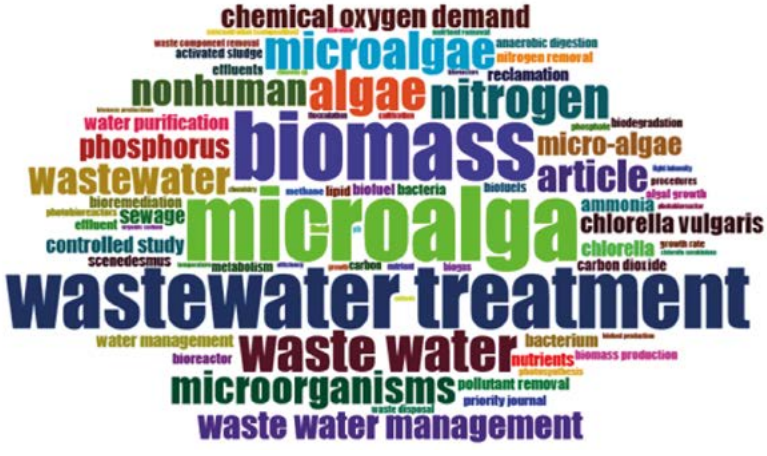
The list also considers South Korea, the United States, Italy, Mexico, Iran, Australia, Germany, and Greece with 21, 19, 17, 14, 13, 13, 11 and 10 documents published independently (3, 3, 5, 6, 3, 5, 2 and 3 in collaboration), respectively. Therefore, one outstanding point is that most countries publish in collaboration with other countries.

Keyword cloud

The bibliometric analysis shows in Figure 10 a cloud of keywords among which the word "biomass" stands out with a frequency of occurrence of 340. Other important words



* MCP: multiple country publications; SCP: single country publications.
Figure 9. Number of publications per country, with and without collaboration.



Source: BIBLIOMETRIX with the SCOPUS database.
Figure 10. Keyword cloud.

are "nitrogen" and "phosphorus" with frequencies of 200 and 119. Also, words related to species and genus of microalgae appear in the cloud, these are *Chlorela vulgaris* and *Scenedesmus* with frequencies of 100 and 57, respectively.

Reference content analysis

Biomass accumulation, through the removal of nutrients present in W through the use of microalgae, was the objective of researchers such as Fan *et al.* (2023), Paulenco *et al.* (2023), Liu *et al.* (2023), Zhuang *et al.* (2023), Zuo *et al.* (2023), Li *et al.* (2023), Qy *et al.* (2023) and Muthuraman *et al.* (2023). The microalgae species used were *Chlorella* sp., *Nannochloris* sp., Hybrid, Chlorella FACHB-30, Chlorella FACHB-5, *Chlorella vulgaris*, *Chlorella sorokiniana* and *Coelastrella* sp.; mostly pre-grown in BG11 medium at 25 °C and light: dark periods of 12:12 h by using microbial consortium, Li *et al.* (2023) and Liu *et al.* (2023) obtained biomass values of 6.22 and 1.79 mg L^{-1}. In turn, Paulenco *et al.* (2023) and Fan *et al.* (2023) obtained values of 1600 and 375 mg L^{-1} without using the consortium.

Several authors studied the behavior of microalgae to remove W nutrients, through the use of microalgae strains in a simple and combined way. Nandini *et al.* (2023), Paulo de Sousa *et al.* (2023), Wang *et al.* (2023), and Krasaesueb *et al.* (2023) used *Chlorella vulgaris*, *Scenedesmus* sp., Chlorococcus AY122332.1, and Synechocystis ΔSphU (mutant cyanobacteria), respectively, as simple strains. On the other hand, Gu *et al.* (2023) did not specify the strain of microalgae used. The NH_4^+ removal was 100%, 94%, 91%, 45%, and 98%, respectively; while that of PO_4^{-3} varied from 71 to 97%.

Nutrient removal, by microbial consortium and the combination of strains from *Chlorella vulgaris*, *Scenedesmus* sp., *Chlorococcum* sp., and *Oscilatoria* sp., was performed by Nagabalaji *et al.* (2023) and removed 86.6% of NH_4^+. Soroosh *et al.* (2023) also experimented with a consortium and the combination of strains from *Chlorella* sp., *Desmodesmus* sp., and *Tribonema* sp., those authors obtained a removal of NH_4^+ and PO_4^{-3} of 88 and 98%.

The production of biodiesel through the biomass accumulated in microalgae by the removal of nutrients present in W was the objective established by Zhao *et al.* (2023), El-Sheekh *et al.* (2023), Vasistha *et al.* (2023) and Khalaji *et al.* (2023). El-Sheekh *et al.* (2023) managed to accumulate 98.2% fatty acids with the microalgae *Chlamydomonas reinhardtii* from a biomass of 48.62 mg L^{-1}, which originated from the removal of 69.2 and 7% of NH_4^+ y PO_4^{-3}, respectively in W. On the other hand, Khalaji *et al.* (2023) with an inoculum of 13 million mL^{-1} cells of *Chlorella vulgaris* in a 25% dilution of W from the dairy industry, observed the accumulation of 23.3% of palmitic acid.

In turn, Satheesh *et al.* (2023) experimented with the production of biohydrogen from the culture of *Chlorella pyrenoidosa*, *Scenedesmus obliquus* and *Chlorella sorokiniana*; *Scenedesmus obliquus* was able to produce 45.5 mL of H_2 g^{-1} VS, from the accumulation of 25.34% lipids in 710 mg L^{-1} of biomass. While Oliveira *et al.* (2023) produced 8175.7 N mL^{-1} Gsv^{-1} with a Chlorophycea-class microalgae.

In the analysis, the average number of articles published per year (4.77) shows little importance in WTwM research. From 1985 to 2012, the average annual publication was only 0.75, where the maximum number of articles published per year was three in 2009. In addition, in 15 years of this period, no publication was reported. In this way, the

analysis shows that WTwM research started growing from 2013 onwards. In this regard, in 2007 the United Nations updated Millennium Development Goal number Seven, which established as number 7c, "for 2015, to reduce by-half the percentage of people who did not have sustainable access to safe drinking water and basic sanitation services in 1990". WTwM is currently investigated as a way to reduce greenhouse gas emissions intending to limit global warming by producing sustainable biofuels (CEPAL, 2015; Paddock, 2019).

The average number of citations per article in the analysis indicates that, in the first years, the number of citations increases as the years go by, reaching a maximum in 2001. In turn, there has been a decrease in the average number of citations from 2001 to date. However, the average number of citations an article has over time is 52.82. In this sense, Price (1973) pointed out that the number of queries made about a work is a measure that indicates its scientific importance. On the other hand, Cañedo (1999) mentioned that citations are a way of evaluating scientific publications, but dependent on the stage in which the research topic is in relation to time.

Of the first 13 researchers, Ivet Ferrer Martí, a researcher in the Environmental Engineering and Microbiology Group of the Polytechnic University of Catalonia in Barcelona, Spain, leads the research line on anaerobic digestion and biogas production in the GEMMA Research Group. This author's research focuses on the recovery of waste streams to obtain bioproducts and bioenergy, within the framework of the circular bioeconomy. That author specializes in the fields of anaerobic digestion and algae biotechnology (UPC, 2023a).

From the same research centre, Joan García is the second author who stands out in this analysis.This scientist studies the development and improvement of environmental biotechnology in the treatment of W, mimics natural decomposition processes, and maximizes eco-efficiency. And is focused on the recovery of bioproducts and bioenergy in the context of the circular bioeconomy, nature-based solutions and water reuse (UPC, 2023b).

On his part, the scientist Raúl Muños is another of the expert co-authors in WTwM. This researcher is Professor in the Department of Chemical Engineering and Environmental Technologies at the University of Valladolid in Spain. His main field of research is biological gas treatment and wastewater treatment with algae and bacteria in photobioreactors (ResearchGate, 2023).

In the 329 papers analyzed, it was observed that the number of authors involved in co-authorship, which exceeds five individuals on average per paper, demonstrates that the research is carried out as a team. However, authors such as Sofia Chaudry, Hai-Ming Jiang, and Hee-Jeong Choi†, independently published their respective papers. In this sense, Wuchty *et al.*, (2007) mentioned that in the last five decades, the number of studies carried out by research teams is greater than those carried out by individual authors; this is, when the topics are related to science and engineering. However, the complexity of the study is the element that justifies the number of people involved (Repiso, 2020).

The analysis showed that most of the countries involved in WTwM research collaborate with other countries; and that China is the country with the largest number of documents related to the subject. Spain is the country with the most relevant authors in the research

and generation of knowledge in the WTwM. In this regard, Van Raan (1998) discussed the epistemic advantage of an international collaborative work that also provides them with influence and impact.

Regarding the most important keywords, "biomass" is directly related to the cultivation of microalgae in wastewater, and corresponds to the assimilation of nutrients, minerals and molecules (lipids, carbohydrates, polymers and pigments) by these (Viera *et al.*, 2023). In this regard, Atif *et al.* (2023) pointed out that microalgae use various biochemical processes to remove chemicals and nutrients such as nitrogen and phosphorus from the W to produce biomass.

El-Sheekh *et al.* (2023) pointed out that microalgae bioengineering should be aimed at increasing lipid production and fatty acid accumulation, in order to meet energy demand through the use of microalgae as feedstock in the production of third-generation biofuels. On the other hand, Atif *et al.* (2023) mentioned that future research would be directed to the study of parameters such as temperature, biomass production, osmotic capacity, pH and O_2 levels in the efficiency of WTwM to determine optimal culture conditions on a large scale and within an industrial environment.

CONCLUSIONS

The analysis indicates that WTwM is a research topic that has been studying and disseminating knowledge since the 80's; however, this has been generated intermittently to date. Among the authors who stand out the most in the publication of scientific articles on WTwM is Ivet Ferrer, who deals with the recovery of waste streams to obtain bioproducts and bioenergy, and specializes in the fields of anaerobic digestion and algae biotechnology.

China is the country with the highest number of WTwM publications; however, this country, as well as Spain, India, Brazil, among others, publish individually and their collaboration with groups of scientists from other countries is limited. The most recent WTwM studies address issues related to biomass accumulation, nutrient removal, biodiesel production and biogas production, as a way to make sustainable use of the process.

The topics to be addressed in future research on the efficiency of WTwM will be related to the study of parameters such as temperature, biomass production, osmotic capacity, pH and O_2 levels. The availability of scientific documents documenting processes associated with WTwM is limited, which evidences large gaps in knowledge regarding this subject. Regardless, the importance of this issue in relation to water supply facing climate vulnerability makes it relevant to be addressed.

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