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# A HALF-CENTURY OF RESEARCH ON MICROALGAE- BACTERIA FOR WASTEWATER TREATMENT

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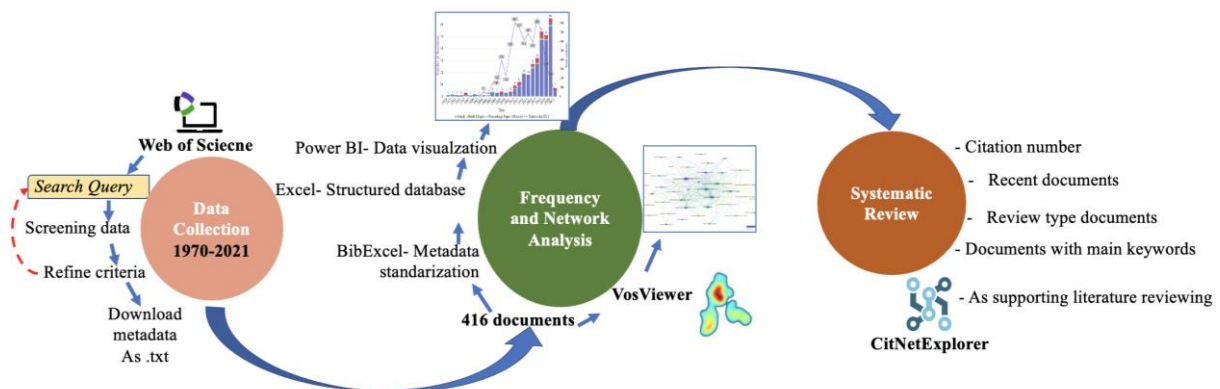
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## Abstract:

The use of microalgae-bacteria consortia (MBC) for wastewater treatment have received increasing attention because of its high capacity for nutrients and organic matter removal, using sunlight as an energy source, through self-sufficient oxygen production provided by photosynthesis. This review addresses the research hotspots and main challenges of this emerging technology, using bibliometric analysis. The evolution of MBC-related literature from 1970 to 2021 was analyzed, identifying of the main research topics explored, based on the frequency of the keywords. This document develops the following topics identified as research hotspots: **1)** The factors that influence the complex interactions between microalgae and bacteria (e.g., pH, incident light, dissolved oxygen), and the removal mechanisms of nutrients and organic matter, which are still relevant issues still requiring significant research efforts. **2)** The new enhanced pathways of total nitrogen and phosphorus removal, such as short cut nitrogen removal, algammox, and phosphorus luxury uptake, which have been explored during the last decade. **3)** The application of mathematical models to represent the behavior of MBC, as a tool for prediction and optimization of MBC systems. And **4)** The biomass retention technologies, such as biofilms, membrane bioreactors, and granular sludge; that allows the uncoupling of HRT from SRT, a condition required for high-rate wastewater treatment.

## Graphical Abstract:



**Keywords:** Bibliometric analysis, decentralized system, microalgae-bacteria consortia, nutrients removal, wastewater treatment

## 1. INTRODUCTION

Nowadays, about 80% of the produced wastewater (WW) worldwide is discharged into the environment without prior treatment. In developing countries, this number reached up to 90% in 2010 [1,2]. This situation promotes social, environmental, and public health problems, mainly in rural or small communities [3,4]. In this context, the most widely used wastewater treatment process worldwide is the conventional activated sludge (CAS) [5,6]. However, the application of this technology in small communities could be limited due to the high energy demand associated with mechanical aeration [7,8]. In fact, mechanical aeration in CAS represents between 50 and 90% of total energy demand [9–11]. In addition, CAS entails a high CO<sub>2</sub> footprint and a waste of nutrients (i.e., nitrogen and phosphorous).

Microalgae-bacteria consortia (MBC) based treatment systems are considered a promising bioremediation platform due to the self-sufficient production of oxygen, provided by microalgae in the presence of light (photooxygenation), which reduces the operational costs associated with mechanical aeration [12,13]. This O<sub>2</sub> production supplies the requirements of heterotrophic bacteria (HB) for the oxidation of chemical oxygen demand (COD) and of nitrifying bacteria (NB) for the oxidation of ammonium into NO<sub>3</sub><sup>-</sup> during the nitrification process. Meanwhile, CO<sub>2</sub> is produced by HB, which is subsequently used as a carbon source by microalgae and NB [14–16]. Moreover, MBC systems have shown a high capacity for nutrients removal. This is the result of the ability of microalgae to assimilate nutrients, and the mechanisms associated with nitrifying bacteria [17–20].

Use of MBC has the potential to transform the way wastewater treatment is conventionally conceived, by using sunlight as an energy source driving the biological process. Thus, operational costs are reduced, and potentially valuable products could be obtained from wastewater through the further biomass transformation in biofertilizer, biofuels, and/or bioproducts [21]. In addition, when compared to CAS, a reduction of CO<sub>2</sub> emissions is expected, mediated by the capture of CO<sub>2</sub> by microalgae [22–24]. Additionally, the treated effluent from MBC is expected to meet the wastewater discharge and reuse standards [25,26].

However, despite the advances and the knowledge acquired in the past 70 years in the application of MBC, there is still a lack of fundamental knowledge regarding the complex interactions between microorganisms, and substantial challenges associated with biomass separation. In fact, the poor settling properties of biomass is one of the main limitations of the application of MBC [27]. Although some researchers have addressed this limitation by applying different biomass retention technologies (e.g. biomass immobilization, membrane bioreactors, etc.), more research is still required [28].

On the other hand, several works published in the last decade dealing with MBC are devoted to treating different types of wastewaters, and literature on MBC keeps on growing steadily. In this context, a comprehensive analysis of the existing literature seems necessary to understand the current state of this research field, its advances, challenges, and opportunities.

To go beyond a standard state of the art review, the objective of this paper is to quantify and analyze reported research using bibliometric analysis. This tool has proven useful to analyze a scalable body of research literature, providing means for assessing and evaluating output of scientists, collaboration between groups and identification of key or emerging topics [29,30]. Then, this work is intended to provide a deep analysis of available literature dealing with the application of MBC to wastewater treatment, offering an in-depth synthesis of the most challenging topics.

## 2. MATERIAL AND METHODS

Bibliometric analysis enables the identification of the structure, characteristics, and trends for a given topic by exploring different bibliographic characteristics such as the number and type of documents, countries, institutions, keywords, citation analysis and using descriptive, impact, or/and relational indicators [31,32]. The input data to perform bibliometric analysis in scientific fields is typically provided by referential databases such as Web of Science (WoS). Based on our experience [33,34], a bibliometric analysis procedure was established, which is described in this section, along with the software tools used to generate diverse bibliometric results and trends.

### 2.1 Data collection

Data were collected up to December 2021, using the WoS Core Collection database, including the SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC. WoS database was selected since it is considered as a source of high-quality scientific data and frequently used for bibliometric analysis [35–37].

### 2.2 Search strategy

The bibliometric analysis involves a search query (SQ) that includes the use of keywords, boolean operators, and wildcards. In this work, the SQ used was “**TOPIC: (((\*alga\*\$(bacteri\* OR activated sludge) AND (consort\* OR symbio\*) and (\*wastewater OR sewage)))) NOT TITLE: (((\*hydrogen OR “fuel cell” OR \*ferment\* OR \*ethan\*))**””. Keywords involved in the SQ were searched in the fields title, abstract and keywords of the documents, using WoS database. In addition, the following document types were excluded from the analysis: early access, meeting abstract and editorial material, since they are not expected to provide a significant contribution to our research. The SQ used in this work was developed in order to provide documents related to MBC for wastewater treatment, excluding those that use the algal-based consortia for other purposes, such as the production of biofuels or biochemicals.

### 2.3 Frequency and network analysis and systematic review

After performing the SQ in WoS, metadata of all documents were obtained in the so-called local database. The following indicators and software were used to perform the bibliometric analysis.

- Bibexcel [38] was used for metadata standardization and the estimation of the local h-index impact indicator for countries [39,40]. The h-index was proposed by Hirsch [41] to characterize the scientific output of a researcher or country. It is defined as follows: “a scientist has index h if h of his/her N papers have at least h citations each and the other (Np - h) papers have  $\leq$  h citations each”. Thereby, the importance and broad impact of scientists’ or country’s cumulative research contribution could be addressed by using both the quantity (total documents) and quality (citation number) of publications. Moreover, the h-index was normalized (NH) as the ratio between the h-index and total documents. The NH ranges from 0 to 1 to describe the influence and impact of publications of each country. A value of 0 means that the country has an h-index equal to 0, i.e., none of its documents were cited. A value of 1 entail that the country has reached the maximum h-index.
- Microsoft Excel v.16.40 and PowerBI<sup>®</sup> v.2.87.762.0 were used to create a structured database for visualization purposes [42,43]. Descriptive indicators used in this work were the annual distribution of documents and citations, the performance of most productive countries, and normalized h-index (SH).

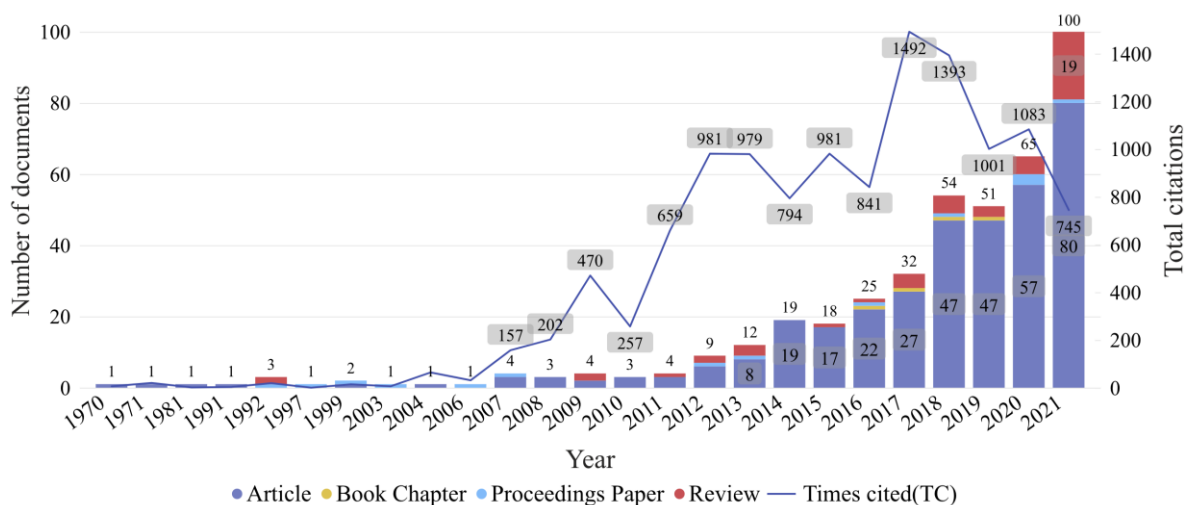
- VOSviewer v.1.6.16. was used to study the collaborative network of countries, and to elaborate the co-occurrence map of all keywords (author-defined keywords and keyword plus), using a frequency of 3 co-occurrences and a thesaurus file. The co-occurrence keyword map was performed using overlay visualization, with a weight or size of the circle representing the co-occurrence value and the color representing the average publication year. The clusterization in VOSviewer was performed by similarity [44].
- CitNetExplorer was used to analyse cited documents in the database and to facilitate systematic literature by identifying publications that are closely connected in terms of citation [45].

Based on the results provided by bibliometric data, publication trends, keywords co-occurrence evolution, and collaboration network were determined. Then, technical aspects related with the application of MBC for wastewater treatment were discussed.

### 3. BIBLIOMETRIC ANALYSIS

#### 3.1 Annual distribution of documents and citations

In total, 416 documents were found in the local database, including reports from 1970 to 2021. The documents considered were articles (350 documents, corresponding to 84%), review articles (48 documents, corresponding to 12%), and proceeding papers or book chapters (18 documents, corresponding to 4 %). The distribution of documents by year is shown in Figure 1, along with their number of citations.



**Figure 1.** Yearly distribution of type of documents and number of citations dealing with the application of MBC for wastewater treatment from 1970 to 2021

The data presented in Figure 1 shows a growing interest in the study of MBC during the last decade. Three stages can be identified for bibliographic production and knowledge development. The first stage ranges from 1970 to 2012 and involves 40 documents (10 %) with an average annual frequency below 5 documents. Interestingly, the bibliographic production during this period is not continuous, as can be observed in Figure 1, which may be attributed to the use of microalgae in other research contexts (e.g., bioproducts or biofuels). The second stage ranges from 2013 to 2017 and involves 106 documents (25 %). Despite the shorter period

involved, the second stage includes 2.7 times more documents than stage 1. The cumulative average growth rate is about 5 documents per year, only including a slight drop in 2015. The third stage ranges from 2018 to 2021. It involves 270 documents, corresponding to 65% of all the documents, showing that the use of MBC for wastewater treatment is becoming an attractive technology, attracting growing research efforts. The average frequency of review production increased from an average of 0.16 documents per year in the first stage to 1.8 in the second stage, and to 8 in the third stage. This increase may be interpreted as the result of a rapid build-up of knowledge on the subject during recent years. Similar trends were obtained by Qi et al. [46], highlighting the growing interest in applying MBC for wastewater treatment.

Several relevant reports that have contributed to the development of MBC-based wastewater treatment were identified by CitNetExplorer, based on their high citation score. The document with the highest citation score was published in 2006 by Muñoz and Guieysse [16], with 875 total citations, with 121 of them from documents included in the local database used in this bibliometric analysis. Review article from Muñoz and Guieysse [16] has contributed to conceptualize the potential use of MBC and photooxygenation for the removal of different pollutants during wastewater treatment. In addition, the application of different operational conditions and bioreactor configurations were discussed, as well as the promising use of microalgae as a feedstock to produce high-value chemicals or biogas. The second most cited article, with 240 citations (75 of them by documents included in the local database), was published in 2012 by Su et al. [47], who investigated the synergistic cooperation between algae (wastewater-born) and activated sludge, at different algae/sludge inoculation ratios. This paper revealed that an algae/sludge ratio of 5:1 showed the highest ammonium and phosphorus removal, assimilation being the main removal mechanisms of  $\text{NH}_4^+$  in the consortia.

Several documents published during the third stage also deserve to be highlighted, based on the relevant number of citations received in such a short period of time. The most cited article is the one from Sepehri et al. [48] published in 2020, with 221 citations, reporting that aeration in the conventional nitrification process could be replaced by photo-oxygenation, achieving 100% of  $\text{NH}_4^+$  removal at the ratio of 10% of microalgae (*Chlorella Vulgaris*) and 90% of nitrifying activated sludge (w/w) at a low C/N ratio. On the other hand, Su et al. (2012), reported that the removal mechanism of  $\text{NH}_4^+$  was mainly governed by biomass assimilation. Therefore, several factors, such as wastewater characteristics and dominant microbial species, could change the mechanisms of removal as well as the optimal ratio of algae and bacteria.

The second most cited article during third stage is the one published by Mohsenpour et al. [49], with 117 citations. The authors reviewed the incorporation and importance of microalgae in wastewater treatment, as well as the cellular and metabolic mechanisms involved in nitrogen, phosphorus and organic matter removal. The third most cited article in the third stage was the one from Renuka et al. [50], with 115 citations. It reviews the potential of microalgae as biofertilizers in agriculture and how cultivation using waste-substrates is emerging as an economically viable strategy. The article also highlighted that future efforts should be directed to the validation and commercialization of the biofertilizer. The fourth most cited article was the one from Ji et al. [51], with 88 citations. It studies the capacity of coexisting *Chlorella Vulgaris* and *Bacillus Licheniformis* for the removal of nitrogen, phosphorus and COD. Finally, the fifth most cited article corresponds to the published by Zhang et al. [52], with 87 citations, who explored the advances in granulation and how this process is enhanced by MBC (i.e., providing granular stability, improving nutrient removal efficiency, and biomass settleability). These reports and their high citation level provide an insight into the relevance and importance of topics involving MBC systems behavior, such as microalgae/bacteria ratio, granulation, biomass recovery, and valorization.

A comprehensive analysis of the citations showed low values until 2007, when a gradual rise

was observed. The highest number of citations occurred in 2017 and 2012, with 1492 and 981, respectively. Unusually, a topic that has been researched for more than 50 years presents the largest number of citations in the last 10 years. The observed citations evolution could be considered as an indicator of two phenomena: First, the popularization of MBC for wastewater treatment by the end of the first stage, resulting in fast consolidation of knowledge [27,53], and second, the application, improvement, and valorization of biomass from MBC, especially during the third stage [50,54,55].

### 3.2 Most productive and collaborative countries

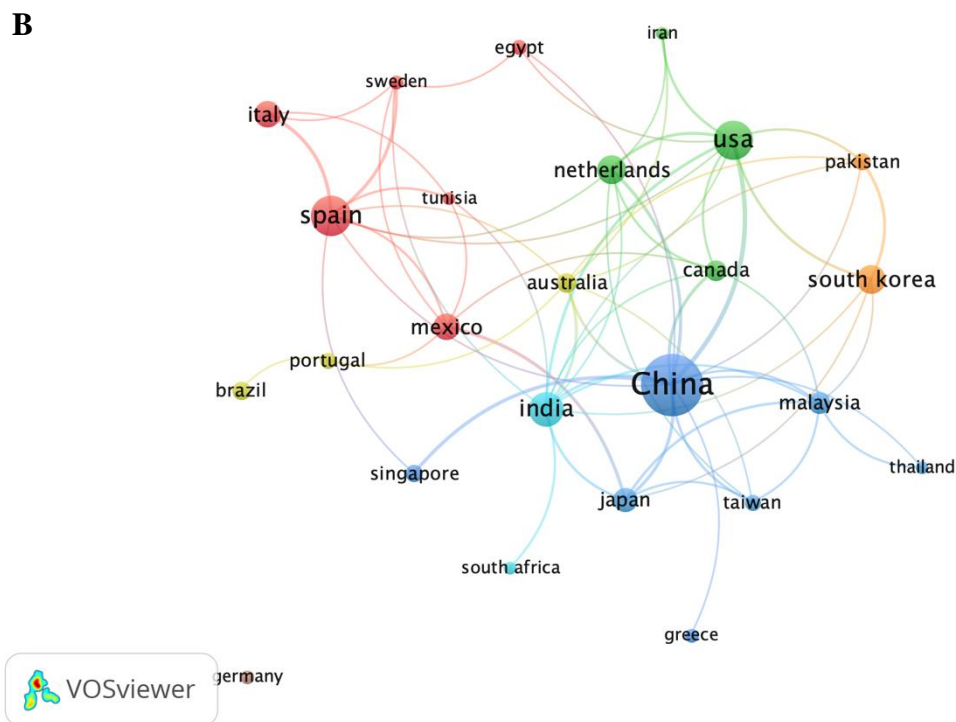
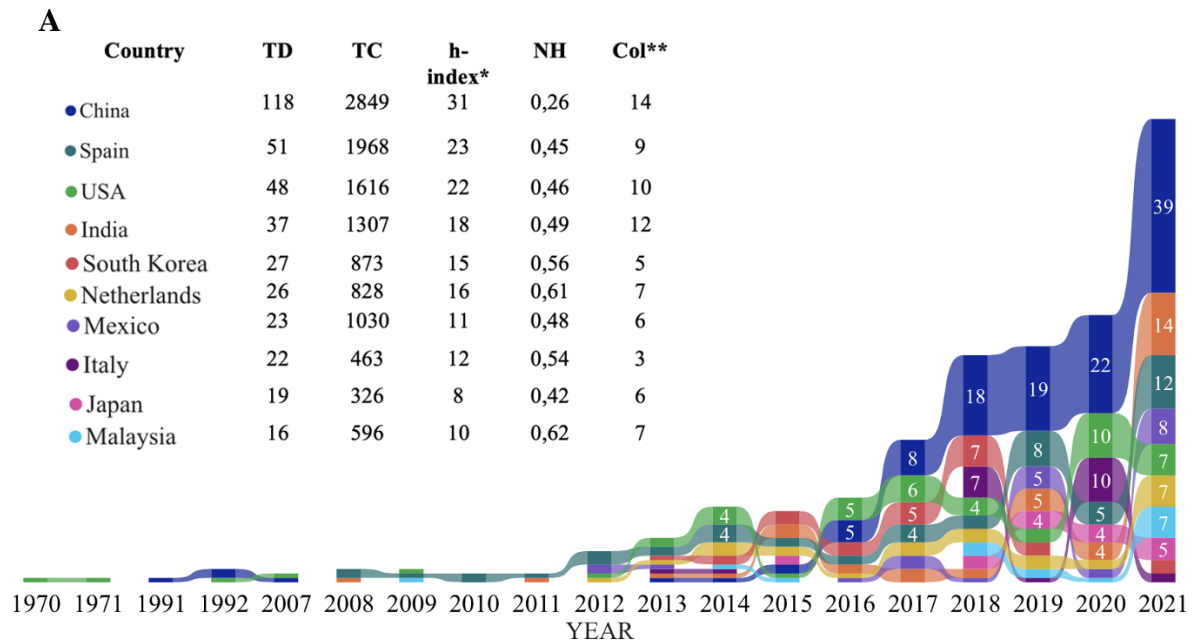
A total of 60 countries have contributed to the available literature in MBC for wastewater treatment, between 1970 and 2021. Figure 2 (A) shows the performance of the 10 countries showing the highest productivities from 1970 to 2021. Information on total documents (TD), total citations (TC), international collaboration (Col), h-index and normalized h-index (NH) is provided. The countries that have the largest contribution are China, USA, and Spain, with 118 (28,3%), 51 (12,3%), and 48 (11,5%) documents, respectively.

However, when considering the most productive countries during 2020 and 2021, few emerging countries appear: Italy with 10 documents during 2020, India with 14 documents during 2021 and Mexico with 8 documents during 2021. Despite China ranking 1<sup>st</sup> place in bibliographic production from 1970 to 2021, it has the lowest NH (0.26), suggesting a modest impact. On the other hand, HS values for Spain, USA, Italy, and India are 0.45, 0.46, 0.54, and 0.49 respectively. Meanwhile, countries with lower productivity, such as Malaysia, Mexico, Netherlands, and South Korea, have the most significant impact (high NH), probably due to their collaboration with the most productive countries.

The topic of MBC for wastewater treatment is being developed in a collaborative network, as it is shown in **Figure 2 (B)**, where the 25 most productive countries were grouped into 8 clusters, using VOSviewer. All clusters show interconnection, except for Germany, which appears isolated. The closer each cluster and country are located to each other, the stronger their collaboration relatedness. China shows the highest international cooperation, showing interaction with 14 of the 25 countries included in the collaboration network (**Figure 2 A, col**). USA and China have the highest joint collaboration, with 12 documents, followed by Spain-Italy (6) China-Singapore (6), Canada-Sweden (5), and Japan-Mexico (5). A strong collaboration between USA and countries with low productivity but high impact (high NS) is observed (for example with The Netherlands and South Korea) (**Figure 2 B**). Although an interconnected network can be identified, collaboration could be considered low, if the total number of documents and countries contributing to MBC research is considered. Improving the collaboration between countries with different levels of experience and productivity would undoubtedly promote the transfer of knowledge and technology, positively impacting and enhancing research.

The analysis also reveals another interesting aspect of the processes for wastewater treatment involving microalgae: the topics on which each country has focused. China has studied lipid and biomass production using aerobic granular biomass [56–58], biofilm bioreactors [59,60], and membrane bioreactors [61–63]. China was the first country to conduct studies combining membranes and MBC for wastewater treatment, addressing membrane performance and fouling [63,64]. USA has researched the effect of parameters such as biomass inoculation, carbon-nitrogen ratio (C/N), and incident light on MBC-based wastewater treatment [48,65,66]. Italy has focused on photosynthesis and respiration models [67,68], respirometry tests to evaluate the activity of consortia [69,70], mixotrophic metabolism of microalgae [71], and studies involving sewage and outdoor pilot raceways [72,73].





**Figure 2.** Contribution of countries on MBC field from 1970 to 2021 (A) Information of the 10 countries showing the highest bibliographic productivity: Total documents (TD), total citations (TC), h-index, NH and international collaboration (Col). \* Local h-index calculated using BibExcel. \*\*International collaboration determined using VOSviewer (B) Collaboration network between countries presented using VOSviewer. Each circle represents one country, and its size is proportional to the number of published documents

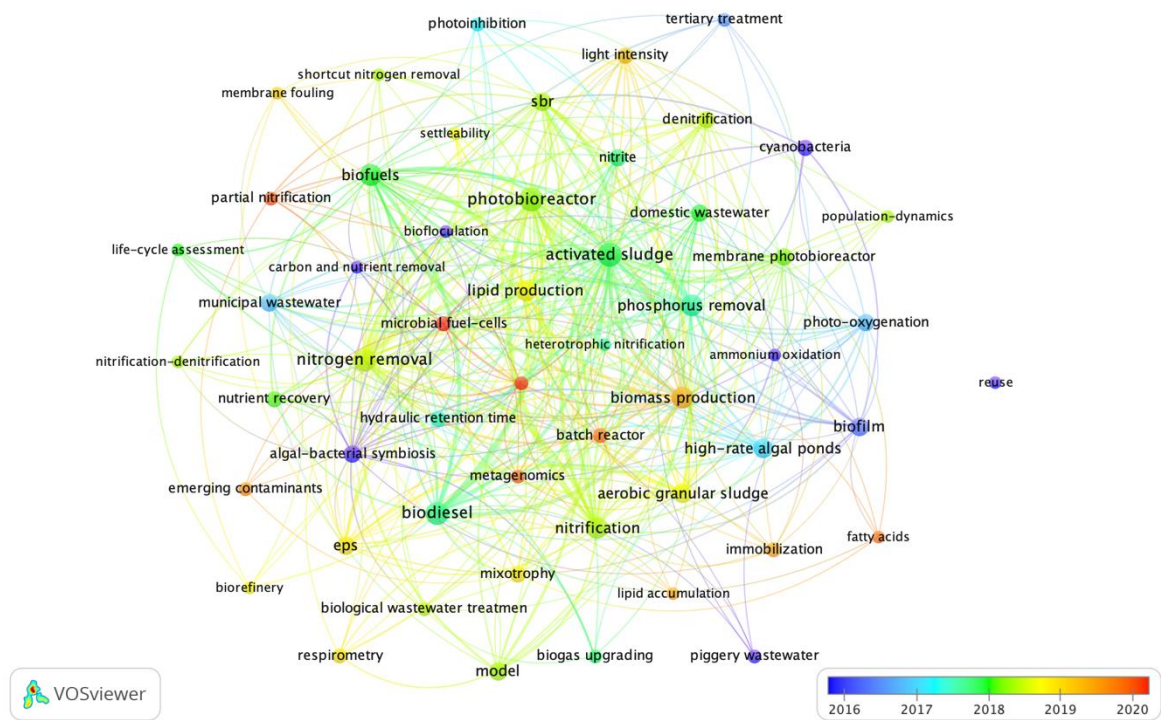
(TD). Clusters are identified by different colors.

Data shows a low presence of Latin American countries on the revised scientific literature dealing with MBC for wastewater treatment. This region contributed with only 12% of the bibliographic production (50 documents) and included countries such as Brazil, Nicaragua, Bolivia, Chile, Honduras, Argentina, and Colombia. Interestingly, Latin America is a region where the application of MBC for wastewater treatment may represent an alternative to cope with the lack of access to proper sanitation in medium and small communities. One could expect the rapid development of research in this geographic area in the future, which may be enhanced by the opportunities provided by collaborative work.

### 3.3 Evolution of MBC research for wastewater treatment

The evolution of the research on MBC for wastewater treatment was addressed using all keywords co-occurrence network map over time. CitNetExplorer was used to analyze the cited documents. A total of 1932 keywords were found, which were reduced to 49, using a thesaurus and a minimum of co-occurrence of 5 times, as is shown in **Figure 3**. CitNetExplorer showed how studies on MBC for wastewater treatment dated back more than 60 years. The keywords “*activated sludge*”, “*carbon and nutrient removal*”, “*high-rate algal ponds (HRAPs)*”, and “*photo-oxygenation*” are strongly related to the oldest author cited. Oswald and his research group proposed the use of HRAPs already in 1957 [74]. They proposed for the first time the symbiosis of MBC as a platform for wastewater treatment, reporting COD, nitrogen, and phosphorus removals in the range of 70-90%, 50-90%, and 60-99%, respectively [75–81].

Between 2014 and 2017, the use of MBC was intensified. The emergence of keywords such as “*piggery wastewater*”, “*municipal wastewater*”, and “*domestic wastewater*” shows a speciation of the scientific community towards different technologies depending on the wastewater [82–84]. In the last decade, some strategies have been adopted to address the low settleability of microalgae. This has been identified as one of the most significant limitations of MBC, resulting in unclarified effluents and the need for high HRT and footprints [14,85]. The keywords “*bioflocculation*”, “*biofilm photobioreactor*” [86,87], “*aerobic granular sludge*” [58,88]), “*immobilization*” [89,90], “*membrane photobioreactor*” and “*EPS*” [62,63] refer to reactor configuration, biomass recovery and biomass structure to improve the “*settleability*” of biomass.



**Figure 3.** All keyword co-occurrence network map from 1970 to 2021, elaborated using VOSviewer software. Each circle represents one keywords, its size is related to the number of co-occurrences and the color represent the publication year average.

**Figure 3** shows how the keywords “*biodiesel*”, “*biofuels*”, “*phosphorus removal*”, and “*nutrient recovery*” reinforce the established structure of the second stage (2013-2017): interactions between microorganisms leading to nutrients removal and biofuels production. This is well fitted with the work published by Olguín [27], with 277 citations at the end of the first stage (Figure 1), where the author defined the dual purpose of microalgae-bacteria based systems to treat wastewater and concomitantly produce biodiesel and chemical products within a biorefinery concept.

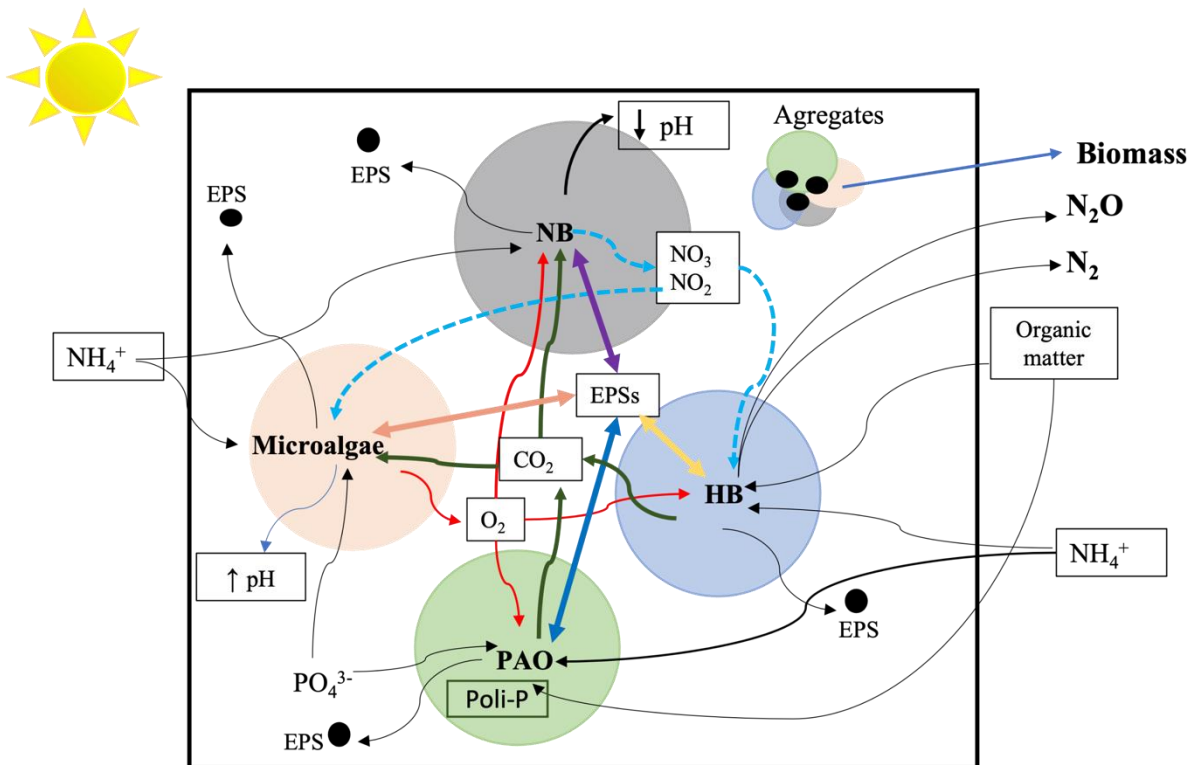
The main topics characterizing the current research streams can be identified using the co-occurrence of the keywords for the articles published during stage 3 (2018-2021). Keywords such as “*metagenomic*” [91,92], “*model*” [93–96] and “*respirometry*” [67,69] are related with the efforts oriented to analyze the diversity of microbial consortium, the use of mathematical models describing the complexity of the involved biological processes, and the use of respirometry-based techniques to obtain kinetics parameters of the consortium. In addition, “*membrane bioreactor*”[97,98], “*nitrification-denitrification*” [99], “*shortcut nitrogen removal*” [100], and “*partial nitrification*” keywords are related to emergent bioreactor configurations using physical biomass retention, and nutrient removal mechanisms. On the other hand, keywords such as “*biogas upgrading*” [101,102] and “*microbial fuel cells*” [103] highlight the new directions of the potential use of microalgae, coupling wastewater treatment with other processes, such as CO<sub>2</sub> sequestration and bioelectricity production.

Finally, this bibliometric analysis offers a general perspective of the topics explored during the last 4 years, that were clustered into 4 main categories: microbial interactions, nutrient removal mechanisms, mathematical modelling, and biomass retention technologies. The next sections

synthesise the state of the art along these four cross-cutting research streams.

#### 4. INTERACTIONS BETWEEN MICROALGAE AND BACTERIA

Interactions between microalgae and bacteria have been explored for over 70 years [12,81] when terms such as "*photo-oxygenation*" were introduced. As shown in **Figure 4**, the microbial metabolisms coexisting in MBC are photoautotrophic, heterotrophic, and autotrophic [104,105]. The most characteristic interaction between algae and bacteria is the  $O_2/CO_2$  transfer. Microalgae produce  $O_2$  (photo-oxygenation) as a consequence of the photosynthetic process, which is then used by HB and NB to oxidize organic matter and ammoniacal nitrogen, respectively [13,16]. The photo-oxygenation drives, therefore, the availability in the culture broth of  $O_2$ , a key electron acceptor during nitrogen and organic matter oxidation [12,106]. Moreover, HB releases  $CO_2$  that is later used by microalgae and AB as a carbon source [14].



**Figure 4.** Interactions within MBC. Adapted from Yang et al. [28]

In addition to the above-mentioned  $O_2/CO_2$  exchange, soluble metabolite exchange also plays an essential role in the removal of pollutants. Nitrogen in domestic wastewater is typically found as urea, and ammonia ( $NH_4^+$  and  $NH_3$ ) and is further oxidized to  $NO_2^-$  and  $NO_3^-$  by NB. The nitrogen forms that microalgae can assimilate are  $NO_3^-$ ,  $NO_2^-$  and  $NH_4^+$ . They are catalysed by different enzymatic transformations from  $NO_3^-$  to  $NH_4^+$  and finally to the organic nitrogen present in amino acids. The enzymes that act in the nitrogen assimilation process in microalgae are nitrate and nitrite reductase to transform  $NO_3^-$  into  $NO_2^-$  and into  $NH_4^+$ , respectively, and glutamine synthetase to convert  $NH_4^+$  into organic nitrogen [20,107,108]. Nitrate and nitrite reductase enzymes are inhibited at high ammonium concentrations since microalgae prefer  $NH_4^+$  as a nitrogen source due to the lower energy required for its assimilation [53,109]. On the other hand, the activity of denitrifying heterotrophic bacteria has been evidenced under conditions of low  $O_2$  concentration (typically during the dark phase and for low oxygen transfer

rate) [60,93,99,100,110]. Phosphorus ( $\text{PO}_4^{3-}$ ) can also be removed from wastewater by both microalgae and bacteria through assimilation in the biomass [111,112].

Cell to cell communication has also been reported as a relevant mechanism for microbial interaction. It involves the intracellular exchange of small signal compounds between bacteria, and the response of microalgae to these signals have been recently also reported in MBC cultures [113]. This cell to cell communication mechanism is normally referred to as quorum sensing, and it is density-cell dependent [114,115]. In MBC, the quorum sensing signals play a crucial role since it can determine the stimulation or inhibition of microorganisms present in the consortium [116–119], the formation of biofilm or aggregates [120–122], the processing and transformation of nutrients [123,124], and lipid synthesis [125,126]. The secretion by microalgae or bacteria of toxic substances, such as algicidal or bactericidal compounds, could be non-beneficial for the culture [21,91,127,128]. For instance, it has been reported that a concentration of  $19,45 \mu\text{g L}^{-1}$  of urocanic acid, excreted by bacteria, negatively affects the activity of microalgae *P. Globosa*, *P. Donghaiense*, *H. Akashiwo*, and *S. Costatum* [59]. The secretion of algicidal substances by bacteria are triggered by bacterial cell concentration rather than the detection of microalgae by bacteria [114]. Some reported algicidal compounds are amylase, 2-undecen-1'-yl-4-quinolone, 2-undecyl-4-quinolone indole-3-acetic acid and octadecenoic acid [128]. Moreover, bactericidal substances such as chlorellin, secreted by microalgae, exhibit an inhibitory effect on both Gram-positive and Gram-negative bacteria [21,116,129]. Others compounds reported as relevant for cell to cell communication are indole-3-acetic acid (phytohormone) that stimulate the metabolism of microalgae, enhancing the interaction between microalgae and bacteria [118,130,131]. Likewise, vitamins produced by bacteria such as thiamine pyrophosphate and 4-amino-5-hydroxymethyl-2-methylpyrimidine were found to promote the growth, lipid content, and glucose uptake of *A. Protothecoides* [132]. Moreover, vitamins secreted by bacteria such as B12, B1 and B7 are required for supported the growth of microalgae in the MBC culture [133,134].

Excretion of extracellular polymeric substances (EPS) has been reported as a relevant factor triggering floc formation in MBC, acting as a biological glue, promoting the agglomeration of microalgae and bacteria, and thus improving its settleability [92,135]. The secretion of EPS have also been correlated with quorum sensing acyl-homoserine lactones secreted by bacteria [120,136]. For example, Zhou et al. 2017 [121] reported self-aggregation of *Chlorophyta sp* in  $200 \mu\text{m}$  bioflocs by secreting 460–1000 kDa of aromatic proteins, upon interacting with N-acetyl-homoserine lactones.

Gene transfer is another mechanism of microbial that may play a role in the development of MBC. It implies the change on gene expression of individual organisms during the interaction in the consortia. These changes may play a role in microalgae adaptation to changes on environmental conditions [133,137].

Thus, studying the interactions between microalgae and bacteria is of utmost importance to explore and investigate how to better manage their dynamics, and enhance the pollutant removal mechanisms efficiency as well as the quality and quantity of sludge generated during wastewater treatment [118,138].

## 5. NUTRIENT REMOVAL MECHANISMS

The keywords “*Phosphorus removal*” and “*nitrogen removal*” were identified as relevant terms when analyzing available literature on the application of MBC municipal wastewater treatment (**Figure 4**). MBC can provide a simultaneous removal of carbon, phosphorus, and nitrogen in a single-step process. Many authors agree that the removal of nutrients provided by

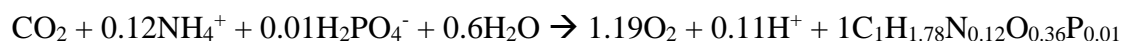
MBC are higher than those provided by algae and bacteria alone [139,140]. Nutrient removal has been approached in different ways. Several mechanisms for the removal of phosphorus and nitrogen in MBC have been identified. Such variety can be considered as an advantage since it provides options or alternatives. However, it also represents a challenge since it involves complexity for understanding, controlling, or simulating the process.

### 5.1 Phosphorus removal

The mechanisms reported for phosphorus removal in MBC are precipitation and assimilation by microalgal and/or bacterial biomass. Phosphorus precipitation is an indirect removal mechanism induced at high pH values (pH>8), where the pH increase is mainly attributed to the microalgal activity. In this context, some authors have highlighted the importance of Ca<sup>++</sup> availability in phosphorus precipitation, Mg<sup>++</sup> playing a minor role in the precipitation process [75,141].

Phosphorus removal through assimilation in microalgae could be limited by unbalanced nitrogen/phosphorus (N/P) ratio in wastewaters. *Equation 1* shows the stoichiometric growth of microalgae on NH<sub>4</sub><sup>+</sup>, PO<sub>4</sub><sup>-</sup> and CO<sub>2</sub>, assuming a biomass composition of C<sub>1</sub>H<sub>1.78</sub>N<sub>0.12</sub>O<sub>0.36</sub>P<sub>0.01</sub> [142]. Then, it could be expected that wastewater with an N/P ratio close to 12 would be required for N and P removal without nutrient limitation.

Nonetheless, some authors have observed an optimal N/P ratio between 5 and 12 for nutrient removal, using municipal wastewater [76,142]. The range of N/P can vary since the optimal N/P ratio in microalgae biomass is flexible, according to the cell stoichiometry and strongly depends both on the species of microalgae and their capacity of performing luxury phosphorus uptake [63,143,144]. When the N/P ratio is lower than the optimal maximum for biomass production, phosphorus removal decreases due to nitrogen limitation [79,145,146]. Thus, in MBC systems where the nutrients are shared (Figure 5), since many nitrogen removal mechanisms can take place (e.g., nitrification or ammonia volatilization), it is of utmost importance to guarantee the availability of NH<sub>4</sub><sup>+</sup> for efficient PO<sub>4</sub><sup>-</sup> removal [147].



#### *Equation 1*

Concerning the microalgae luxury uptake of phosphorus, it has been reported that during light conditions and a preceding phosphorus starvation, the accumulation of larger polyphosphate granules is triggered [148]. The maximum content of phosphorus in microalgae can be up to 3.8 mg P mg<sup>-1</sup> of dry biomass, about four times the maximum standard content under balanced microalgal metabolism (Equation 1) [149,150]. The most common microalgae performing luxury uptake in waste stabilization ponds and HRAPs have been reported to be *Chlamydomonas/Cryptomonas*, *Micractinium/Microcystis*, and *Scenedesmus* [149,151]. However, the luxury phosphorus uptake mechanisms must be further explored, considering their complexity.

Another mechanism for PO<sub>4</sub><sup>3-</sup> removal is the one involving the activity of polyphosphate-accumulating organisms (PAOs), which has not been widely explored in MBC systems (Figure 5.). The accumulation of phosphate through PAOs is achieved in two environments, one anaerobic followed by one aerobic/anoxic. The PAOs uptake and store organic carbon such as acetate and propionate anaerobically as polyhydroxyalkanoate (PHA), with polyphosphate as the energy source [152]. In anaerobic environments, organic carbon decreases while soluble PO<sub>4</sub><sup>3-</sup> increases. In the subsequent aerobic/anoxic environment PAOs oxidize the stored PHA, which is used as energy for growth and restore internal polyphosphate. During aerobic/anoxic environment, the PO<sub>4</sub><sup>3-</sup> decreases; through this cyclical process, more P is stored than was released, resulting in the net removal of phosphorus [153,154]. In MBC systems, Huang et al.

[155] studied the effect of algae growth on aerobic granulation and nutrient removal. They observed inhibition of PAOs due to free nitrous acid (FNA) accumulation ( $6.3\text{--}9.8 \times 10^{-3}$  mg  $\text{HNO}_2\text{-N L}^{-1}$ ), obtaining a total phosphorus removal not higher than 44%. Furthermore, PAOs activity may be limited due to the high  $\text{NO}_3^-$  concentrations typically found in MBC systems, which hamper the occurrence of anaerobic conditions affecting the release of  $\text{PO}_4^{3-}$  and subsequently the uptake of phosphate [156].

In addition, recent works have reported indicating that a low carbon/nitrogen ratio will provide low organic carbon to HB growth, including PAOs [58,157]. Then, just under some specific environmental conditions, PAOs may play a significant role in phosphorus removal when the MBC system is used [158]. Due to the complex environmental condition where PAOs act as the main actor in phosphorus removal, some researchers have found them playing a role as phosphorus assimilation and growth promoters in microalgae [139,159].

## 5.2 Nitrogen Removal

During the first and second stages illustrated in **Figure 1**, the most common nitrogen removal mechanisms reported were the assimilation by microalgal biomass, nitrification/denitrification, and  $\text{NH}_3$  volatilization. García et al. [160] reported 73% of total nitrogen (TN) removal at HRT of 10 days and 57% at HRT of 4 days. In both systems, ammonia stripping was the dominant mechanism over microalgal assimilation on TN removal. Moreover, denitrification was not considered, and nitrification was identified mainly in the HRAP working at lower HRT (4 days), contributing to  $\text{NH}_4^+$  removal. Nurdogan and Oswald (1995) reported 90% of TN removal, which was mainly attributed to volatilization, especially in summer, when pH reached a maximum value of 11. The predominance of ammonia stripping mechanism has generally been found in HRAP systems as a result of high pH, usually higher than 9, due to the activity of microalgae [161,162]. In addition, some authors have highlighted that controlling pH at a lower level by supplying  $\text{CO}_2$  can reduce the ammonia stripping in HRAP by favoring the ammonium form. Moreover, reducing inorganic carbon limitation, enhanced nitrogen recovery [26,163–165]. However, Ruas et al. [26] evaluated the domestic wastewater treatment with the supply of synthetic gas mixture (30% v/v  $\text{CO}_2$ ), and the pH was maintained in the system between 6.8 to 7.7. The TN removal obtained was below 40% due to high nitrification activity combined with a lower pH, preventing ammonia stripping. Similarly, Karya et al. [13] reported low TN removal when treating synthetic wastewater using activated sludge and *Scenedesmus Quadricauda* as inoculum (pH-controlled at 7.5). Under the tested conditions, nitrification was the most relevant ammonia removal mechanism (81% - 85%), contributing to the low the TN removal obtained.

Furthermore, pH has indirect effects on the availability of toxic compounds such as free ammonia (FA) and FNA, where the role of pH indirectly determines the magnitude of inhibition by establishing the degree of dissociation of non-toxic  $\text{NH}_4^+$  to toxic  $\text{NH}_3$ . For example, Valdivelu et al. [168] found that *Nitrobacter* was more sensitive than *Nitrosomonas* to FA. For *Nitrobacter*, the growth was completely inhibited at above  $6.0$  mg  $\text{NH}_3\text{-N L}^{-1}$ , and the capacity to oxidize  $\text{NO}_2^-$  to  $\text{NO}_3^-$  was reduced by 12 % at concentration of  $6.0\text{--}10$  mg  $\text{NH}_3\text{-N L}^{-1}$ ; meanwhile, *Nitrosomonas* did not experience any inhibition at FA up to  $16$  mg  $\text{NH}_3\text{-N L}^{-1}$ . Indeed, nitrification process ( $\text{NO}_2^-$  to  $\text{NO}_3^-$ ) seems to be the more sensitive to ammonia concentrations. Meanwhile, FA can also affect photosynthetic activity. For instance, a FA concentrations of  $73$  mg  $\text{NH}_3\text{-N L}^{-1}$  in MBC with dominant species of *Chlorella sp.* and *Scenedesmus sp.* can generate 50% inhibition of the photosynthetic activity and photooxygenation [169,170].

Likewise, FNA has a greater impact on *Nitrobacter* by completely stopping the growth process at concentrations of 0.02 mg HNO<sub>2</sub>-N L<sup>-1</sup> and inhibiting the energy yielding metabolisms at concentrations greater than 0.024 mg HNO<sub>2</sub>-N L<sup>-1</sup> [168]. Huang et al. [155] found that microalgae inhibit NB growth by competing for NH<sub>4</sub><sup>+</sup> substrate, which led to an accumulation of NO<sub>2</sub> and FNA (>28 mg HNO<sub>2</sub>-N L<sup>-1</sup>) in the effluent, thus limiting the nitrification and denitrification process. This resulted in low levels of TN removal (40.7% - 45.4%).

The key role of the influent alkalinity regulation to avoid strong inorganic carbon limitation has been recently highlighted in MBC systems [171]. CO<sub>2</sub> is the substrate of the Calvin cycle and strongly determines the microalgal growth rate [48,166,167]. It also determines growth of NB, since it is also their carbon source. Inorganic carbon limitation can affect nitrogen removal and is more often observed for wastewaters characterized by low biodegradable organic carbon contents (e.g., digestate). A low biodegradability will limit HB growth, reducing the CO<sub>2</sub> production [48,157]. Conditions of very low alkalinity results in intense competition for inorganic carbon between algae and nitrifiers (limited growth of photoautotrophic microorganisms), incomplete nitrification (high level of ammoniacal nitrogen in the effluent) and favorable conditions for N<sub>2</sub>O production and emissions [171,174–176]. N<sub>2</sub>O is a very potent greenhouse gas (GHG), with a global warming potential about 298 times higher than that of CO<sub>2</sub> [173].

A well-known mechanism for the oxidation of ammonium nitrogen by bacteria is complete or partial nitrification (nitritation), which requires further denitrification to achieve an effective total nitrogen removal. New processes have been identified in MBC when nitrogen removal is considered, starting by the end of the second stage (**Figure 1**). Keywords such as “*nitrification-denitrification*” and “*shortcut nitrogen removal*” were the most representative in the same time-lapse. Wang et al. [100] developed a novel shortcut nitrogen removal in a photo-sequencing batch reactor (PSBR) using an HRT of 4 days. Researchers obtained a TN removal of 90% without external aeration. As a result of the high concentrations of FA (2.4 mg L<sup>-1</sup>) and FNA (0.013 mg L<sup>-1</sup>) and low O<sub>2</sub>, 80% of the TN removal was achieved by nitritation/denitrification with the addition of acetate as an external carbon source (ECS) during the dark period. Other researchers have used methanol as ECS for the same purpose [95]. In addition, Alcantará et al. [177] reported a new anoxic-aerobic photobioreactor process with biomass recycling that provided TN removal in the range 68-79%, when treating synthetic wastewater at an HRT of 2 days. In this system, the authors found that NH<sub>4</sub><sup>+</sup> nitritation was dominant in the aerobic photobioreactor reaching concentrations up to 20 mg NO<sub>2</sub>-N L<sup>-1</sup> at constant pH of 7.7. TN removal was mainly attributed to nitritation in the photobioreactor and denitrification in the anoxic tank. This unusual NO<sub>2</sub><sup>-</sup> accumulation and inhibition of NO<sub>3</sub><sup>-</sup> production was probably due to the high incident light (400 μmol m<sup>-2</sup>L<sup>-1</sup>), which might have partially inhibited bacterial nitrifiers [178]. Manser et al. [179] proposed the “algamox” process, which consisted of TN removal through the conventional Anaerobic Ammonium Oxidation (anammox) process. The anammox process is based on the anaerobic oxidation of ammonia using nitrite as an electron acceptor, giving molecular nitrogen N<sub>2</sub> as a final product. The algamox process differs from conventional anammox in that the oxygen for NO<sub>2</sub><sup>-</sup> production is provided by microalgae [179,180]. The algamox process was carried out in a photo-sequencing batch reactor, alternating periods of light and dark, favouring low DO concentrations, since anammox is inhibited by DO above 1.5 mg L<sup>-1</sup> [181]. The results showed that ammonia was converted to nitrite during periods of light at a rate of 168 mg NH<sub>4</sub> L<sup>-1</sup>d<sup>-1</sup>, and subsequently, an average of 82% of nitrite was reduced to N<sub>2</sub> during the dark (anoxic) period due to anammox activity.



## 6. MODELLING OF MICROALGAE BACTERIA CONSORTIA

Recently, mathematical modelling has taken an essential role in describing and predicting biological processes such as the MBC system, as we found in the analysis of the frequency of all keywords in Figure 3. Mathematical models are extremely powerful instruments that can be applied for managing existing biotechnologies processes, but also for studying, understanding, and optimizing new processes. Mathematical models have become increasingly attractive since, once calibrated and validated on a long-time scale, they make feasible the investigation of several scenarios and operational conditions. Therefore, the design and operation of MBC systems using models may involve several advantages, such as the reduction of operating costs, the increase in nutrients removal, and the valorization of the nutrients and energy contents of wastewaters.

The classic reference models describing biological processes for waste treatment are Activated Sludge Models (ASMs) [182] and the Anaerobic Digestion Model n°1 (ADM1) [183], which have been widely implemented [184,185]. To date, a large number of models describing microalgae-based bioprocess are available in the literature [186]. However, only a minority of them were developed to represent microalgae and bacteria behavior for wastewater treatment. International Water Association (IWA) introduced a standardized notation for models, including the use of a Petersen matrix. This standardized notation could favor the integration of MBC models with those describing existing water resource recovery facilities (ASMs and ADM) [187]. However, among the microalgae/bacteria reported models, there are only 10 that follows this standardized notation [93,94,96,188–195]. **Table 1** summarizes a comparison between the most recent MBC models available in the literature, for wastewater treatment. Some of the proposed models were developed with the purpose of estimating the biofuels/bioproducts production [196–202]. Among these models, only a few implemented both the phototrophic and heterotrophic metabolisms for the algal biomass, such as the ones proposed by Adesanya et al. [203] and Figueroa-Torres et al. [204]

On the other hand, the calibration and validation of mathematical models are crucial steps to produce reliable simulation results [186,205]. However, there is a lack of long-term validation dataset covering yearly seasonal variation (temperature, incident light, etc.) when working with MBC models for wastewater treatment. Only two works involves long-term seasonal study, the works published by Broekhuizen et al. [192] and by Casagli et al. [93].

**Table 1.** comparison between the most recent algae-bacteria models available in the literature for wastewater remediation

	RWQM1	PHOBIA	Modified RWQM1 <sup>(D)</sup>	Modified ASM3	Bioalgael	Bioalgae2	ALBA <sup>(D)</sup>	ABACO
<b>Reference</b>	[189]	[190]	[192]	[195]	[188]	[94]	[93]	Z[96]
State variable (n°)	24	16	24	16	19	19	17	19
Biological processes (n°)	22	13	22	21	18	18	19	18
Parameters (n°)	120	75	138	47	94	108	72*	108
Growth kinetic type	Multiplicative	Minimum	Multiplicative	Multiplicative	Multiplicative	Multiplicative	Multiplicative/ Minimum**	Multiplicative
Dependence on organic and inorganic carbon	C <sub>ORG</sub>	C <sub>ORG</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup>	C <sub>ORG</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup> , CO <sub>3</sub> <sup>2-</sup>	C <sub>ORG</sub>	C <sub>ORG</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup>	C <sub>ORG</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup>	C <sub>ORG</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup> , CO <sub>3</sub> <sup>2-</sup>	C <sub>ORG</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup>
Considered N-forms	NH <sub>3</sub> , NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> , NO <sub>2</sub> <sup>-</sup>	NH <sub>3</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup>	NH <sub>3</sub> , NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> , NO <sub>2</sub> <sup>-</sup> , N <sub>2</sub>	NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> , NO <sub>2</sub> <sup>-</sup>	NH <sub>3</sub> , NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> , NO <sub>2</sub> <sup>-</sup>	NH <sub>3</sub> , NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> , NO <sub>2</sub> <sup>-</sup>	N <sub>org</sub> , NH <sub>3</sub> , NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> , NO <sub>2</sub> <sup>-</sup> , HNO <sub>2</sub> , HNO <sub>3</sub> , NO <sub>2</sub> <sup>-</sup>	NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> , NO <sub>2</sub> <sup>-</sup>
Considered P-forms	H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> , HPO <sub>4</sub> <sup>2-</sup>	-	H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> , HPO <sub>4</sub> <sup>2-</sup>	-	SPO4 (***)	SPO4 (****)	H <sub>3</sub> PO <sub>4</sub> , H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> , HPO <sub>4</sub> <sup>2-</sup> , PO <sub>4</sub> <sup>3-</sup>	SPO4 (****)
Continuity check (mass conservation)	C, O, N, P	(n.s.)	C, O, N, P	(COD, N, P.)	(n.s.)	(n.s.)	C, H, O, N, P, COD	(n.s.)
Algal biomass composition	C <sub>100</sub> H <sub>232</sub> O <sub>26</sub> N <sub>14</sub> P <sub>4</sub>	(n.s.)	C <sub>100</sub> H <sub>232</sub> O <sub>26</sub> N <sub>14</sub> P	C <sub>106</sub> H <sub>181</sub> O <sub>45</sub> N <sub>16</sub> P	C <sub>100</sub> H <sub>232</sub> O <sub>26</sub> N <sub>14</sub> P	C <sub>100</sub> H <sub>232</sub> O <sub>26</sub> N <sub>14</sub> P	C <sub>100</sub> H <sub>183</sub> O <sub>48</sub> N <sub>11</sub> P	C <sub>100</sub> H <sub>232</sub> O <sub>26</sub> N <sub>14</sub> P
Bacterial biomass composition	C <sub>150</sub> H <sub>335</sub> O <sub>13</sub> N <sub>30</sub> P <sub>0</sub>	(n.s.)	C <sub>150</sub> H <sub>335</sub> O <sub>13</sub> N <sub>30</sub> P	C <sub>5</sub> H <sub>7</sub> O <sub>2</sub> N	C <sub>150</sub> H <sub>335</sub> O <sub>13</sub> N <sub>30</sub> P	C <sub>150</sub> H <sub>335</sub> O <sub>13</sub> N <sub>30</sub> P	C <sub>60</sub> H <sub>87</sub> O <sub>23</sub> N <sub>12</sub> P	C <sub>150</sub> H <sub>335</sub> O <sub>13</sub> N <sub>30</sub> P
PAR model	Steele	Eilers & Peters	Smith	Poisson	Eilers & Peters	Eilers & Peters	Bernard & Remond	Molina
pH model	NH <sub>4</sub> <sup>+</sup> , NH <sub>3</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup> , CO <sub>3</sub> <sup>2-</sup> , H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> , HPO <sub>4</sub> <sup>2-</sup> , Ca <sup>2+</sup> , H <sup>+</sup> , OH <sup>-</sup>	NH <sub>4</sub> <sup>+</sup> , NH <sub>3</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup> , CO <sub>3</sub> <sup>2-</sup> , H <sup>+</sup> , OH <sup>-</sup> , Δ <sub>CAT,AN</sub>	NH <sub>4</sub> <sup>+</sup> , NH <sub>3</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup> , CO <sub>3</sub> <sup>2-</sup> , H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> , HPO <sub>4</sub> <sup>2-</sup> , Ca <sup>2+</sup> , H <sup>+</sup> , OH <sup>-</sup>	-	NH <sub>4</sub> <sup>+</sup> , NH <sub>3</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup> , CO <sub>3</sub> <sup>2-</sup> , H <sup>+</sup> , OH <sup>-</sup>	NH <sub>4</sub> <sup>+</sup> , NH <sub>3</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup> , CO <sub>3</sub> <sup>2-</sup> , H <sup>+</sup> , OH <sup>-</sup>	NH <sub>4</sub> <sup>+</sup> , NH <sub>3</sub> , CO <sub>2</sub> , HCO <sub>3</sub> <sup>-</sup> , CO <sub>3</sub> <sup>2-</sup> , H <sub>3</sub> PO <sub>4</sub> , H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> , HPO <sub>4</sub> <sup>2-</sup> , PO <sub>4</sub> <sup>3-</sup> , NO <sub>2</sub> <sup>-</sup> , NO <sub>3</sub> <sup>-</sup> , HNO <sub>2</sub> , HNO <sub>3</sub> , H <sup>+</sup> , OH <sup>-</sup> , Δ <sub>CAT,AN</sub> , TA	-

Experimental setup	pH growth dependence	-	-	Gaussian law	-	-	CPMI	CPM	CPMI
	Temperature simulation/growth dependence	-/Arrhenius	-	-/Arrhenius	-	-/Arrhenius	-/CTMI	✓/CTMI	-/CTMI
	Ammonification	-	-	-	-	-	-	✓	-
	DO inhibition	-	-	-	-	✓	✓	✓	✓
	NH <sub>3</sub> inhibition	-	-	-	-	-	-	✓	-
	Gas-liquid mass transfer	O <sub>2</sub>	-	O <sub>2</sub>	-	O <sub>2</sub> , CO <sub>2</sub> , NH <sub>3</sub>	O <sub>2</sub> , CO <sub>2</sub> , NH <sub>3</sub>	O <sub>2</sub> , CO <sub>2</sub> , NH <sub>3</sub> , evaporation	-
	Reactor type	River environment	Laboratory incubator	Raceway	Column PBR	Raceway	Column PBR	Raceway	Column PBR
	Reactor installation/Volume	Outdoor	Indoor(Lab)/3L	Outdoor/8 m <sup>3</sup>	Indoor(Lab)/2 L	Outdoor/1 m <sup>3</sup>	Indoor(Lab)/4 L	Outdoor/17 m <sup>3</sup> , 1 m <sup>3</sup>	Indoor(Lab)/1 L
	Influent	Wastewater discharge	MM	MWW	DSC	MWW	MWW	SWW, DSC	DSC
	Calibration dataset	-	-	365 d	✓ (24 h)	✓ (4 d)	✓ (8 d)	✓ (30 d)	✓ (14 d)
	short-term dynamics	-	-	-	✓ (24 h)	✓ (4 d)	n.s.	✓ 3, 14 d	✓ (14 d)
	long-term dynamics	-	-	330 d	-	✓ (175 d)	-	✓ (413 d, 189 d)	-
	Sensitivity analysis	✓	✓	-	✓	✓	-	✓	-
	Seasonal analysis	-	-	-	-	-	-	✓	-
Validation	Parameter Uncertainty	✓	-	-	✓	-	-	✓	-
	Confidence intervals for model predictions	✓	-	-	-	-	-	✓	-

**Abbreviations:** ✓: implemented; (n.s.) not specified or provided in the relative publications; IC: Inorganic Carbon; DSC: Diluted Swine Centrate; MM: Mineral Medium; MWW: Municipal Wastewater; SWW: Synthetic Municipal Wastewater; TA: Total Alkalinity; CTMI: Cardinal Temperature Model with Inflection; CPMI: Cardinal pH Model with Inflection; CPM: Cardinal pH Model. Notes: (D) demonstrative scale reactors (> 5 m<sup>3</sup>); (\*) not including chemical constants, their temperature dependence, and stoichiometric coefficients); (\*\*) in the ALBA model, only the Monod limitation terms relative to nutrients availability were implemented in the minimum function, while the dependence on inhibitory and environmental factors are multiplied for the minimum term (in the PHOBIA model, all the multiplicative terms considered are included in the minimum function); (\*\*\*) P limitation term only on algae; (\*\*\*\*) P limitation term on algae and bacteria

## 7. BIOMASS RETENTION TECHNOLOGIES

The bibliometric analysis highlights two factors driving the research oriented towards the development or application of biomass retention technologies:

1. The low settling capacity of microalgae, which still represents a major challenge when they are used as a technological platform, due to the high separation and recovery costs, and the need to guarantee a good effluent quality during wastewater treatment [27].
2. The consolidation of solid retention time (SRT) as a key operational parameter, since it affects the type of microorganisms developing in the system, and consequently the nutrient removal [99,195,206].

As shown in **Figure 3**, the research targeting the development of new reactor configurations has boosted from 2014 onwards, mainly to address biomass retention [62,86]. MBC biomass is typically separated by a secondary settler or by applying the sequential batch operation mode, as highlighted by the keywords “SBR,” which showed the highest average frequency in 2018. Indeed, biomass is separated from the liquid phase through gravity sedimentation during a non-aerated or non-mixed phase under SBR operation mode. However, a higher level of automation is required in SBR systems, and separation strongly depends on the biomass aggregation level (flocs). Keywords such as “biofilm”, “immobilization”, “membrane photobioreactor”, and “aerobic granular sludge” increased during the last years, thus resulting in new reactor designs (**Figure 3**). De Godos et al. [176] explored a new configuration based on the concept of denitrification-nitrification CAS with a low C/N ratio, internal recycling ( $\text{NO}_3^-$ ), and external recycling (biomass) that allowed the decoupling of the HRT and SRT. The system consisted of two interconnected tanks: an anoxic tank followed by an aerobic photobioreactor inoculated with cyanobacteria-bacteria. Results showed high organic carbon (>95%) and TN (>90%) removal using the photobioreactor alone at HRT of 3.5 days and SRT of  $31 \text{ d}^{-1}$ , and using the two-stage anoxic-aerobic configuration at HRT 4.5 days and SRT of  $20 \text{ d}^{-1}$ . Furthermore, the settler system located after the photobioreactor led to an effluent with  $25 \pm 19 \text{ mg L}^{-1}$  of volatile suspended solids, concentration below the European discharge limits. On the other hand, Steen et al. [207] also applied the concept of the CAS, coupling a mixed photobioreactor inoculated with microalgae-bacteria with a settler, providing biomass recirculation to the reactor. The system was able to remove 85% of the applied ammonium load ( $66 \text{ mg L}^{-1} \text{ d}^{-1}$ ) at HRT of 1 day and SRT of 15 d.

Several biofilm-based microalgal bacterial cultivation systems have been reported in recent years, for environmental remediation and biofuel production purposes [208–210]. De Godos et al. [87] engineered an innovative enclosed tubular biofilm photobioreactor inoculated with *Chlorella Sorokiniana* and activated sludge to treat pre-treated swine slurry (7 days of HRT). The system supported removal efficiencies for nitrogen and phosphorus ranging from 94% to 100% and 70% to 90%. The retained biomass was greater than 92% of the generated biomass. Interestingly, *Chlorella Sorokiniana* was dominant throughout the entire experiment. On the other hand, designs such as the rocker system using polystyrene foam as support material [210], the rotating algal disk [211], the rotating rope reactor with spool harvester partially submerged in wastewater [212] and the attached cultivation reactor using glass plate and filter paper as a substratum [213] are among the biofilm-based system’s configuration described in the literature. The

49 biofilm approach seems to improve the sustainability and the productivity of the  
50 microalgae production systems [214]. Compared to conventional open ponds, enhanced  
51 biomass productivities have been shown using biofilm-based microalgal cultivation. For  
52 instance, Christenson and Sims [212] reported the tertiary wastewater treatment in an  
53 enhanced raceway bioreactor using five rotating biological contactors (RBC), close to the  
54 paddlewheel of the bioreactor. The five RBC used cotton cords as biofilm support and  
55 were 40% submerged in the reactor. With an HRT ranging from 3 to 6 days, an average  
56 removal of TN and total phosphorus were 76 % and 23 %, respectively. The achieved  
57 biomass productivity was 5.5 g m<sup>-2</sup> d<sup>-1</sup> at laboratory scale and 31 g m<sup>-2</sup> d<sup>-1</sup> at pilot scale,  
58 values higher than those for conventional raceway ponds. In addition, other studies that  
59 explored the configuration of biofilm-based systems have reported productivities up to  
60 302% [208], 697% [215] and 700% [216] of the ones expected for traditional raceway  
61 ponds.

62  
63 Researchers from Brazil have worked with hybrid HRAP systems, consisting of the  
64 combination of HRAP with a biofilm unit [217,218]. In hybrid HRAP systems, additional  
65 carbon source supplementation (CO<sub>2</sub>) was not necessary since biofilm provided better  
66 conditions for atmospheric CO<sub>2</sub> capture [217]. In addition, hybrid systems followed by a  
67 settling tank provided a biomass production 2.6 greater than that of a conventional HRAP  
68 followed by a settling tank. Moreover, biomass harvesting in the hybrid system was  
69 facilitated [218]. Recently, attached biofilms in carriers have been explored for MBC  
70 [59,60,112]. Gou et al. [59] observed a 90% COD and ammonia removal, reducing the  
71 HRT to 12 hours, applying a three-dimensional carrier that improved the efficiency by  
72 promoting the mass transfer from the wastewater to the biofilm.

73  
74 Microalgal-bacterial granules have been lately explored to improve biomass settleability  
75 and enhance biomass harvesting. Granules formation depends on several factors, such as  
76 the inoculum, the composition and concentration of EPS as polysaccharides and proteins,  
77 wastewater characteristics, and environmental factors such as seasonal variability that  
78 contributes to the change of incident light and temperature [55,219,220]. For instance,  
79 Quijano et al. [219] evaluated the influence of light on EPS and granules formation while  
80 treating municipal wastewater, at an HRT of 10 days. Low irradiances levels (< 3800 Wh  
81 m<sup>-2</sup> d<sup>-1</sup>) promoted the formation of microalgae-bacteria flocs and granules with high  
82 settleability (432 m d<sup>-1</sup>) and relatively high removal efficiencies of TN (60 %) and total  
83 COD (89 %). Conversely, phosphorus removal did not experience the same trend at low  
84 irradiances, exhibiting removals of 92 % at 6213 Wh m<sup>-2</sup> d<sup>-1</sup> and 28% at incident light  
85 lower than 3800 Wh m<sup>-2</sup> d<sup>-1</sup>. Ji et al. (2020) used microalgal-bacterial granules for  
86 synthetic wastewater treatment and reported removal efficiencies of 93 %, 97% and 87%  
87 for organic matter, ammonia, and phosphorus, respectively; operating in cycles of 6 hours  
88 under non-aeration conditions. The most abundant microalgae found in this system was  
89 *Pantanalinema Rosaneae*.

90  
91 The most recent bioreactor configuration explored for MBC is membrane bioreactors  
92 (MBR) [145]. MBRs have been widely explored for aerobic wastewater treatment as an  
93 alternative to biomass settling. In MBRs, the cultivation and removal of contaminants are  
94 carried out in a reactor, with a membrane system providing complete solids retention and  
95 providing a clarified effluent. HRTs as low as 8-24 hours have been reported, with fluxes  
96 in the range of 168-360 L m<sup>-2</sup> d<sup>-1</sup>, achieving high pollutant removal. In addition, easier  
97 operation, amelioration of microbial activity, and better pollutants removal have been  
98 achieved in MBR systems inoculated with microalgae and bacteria than in MBR systems

99 inoculated with only activated sludge [62,63]. Furthermore, lower membrane fouling has  
100 been reported when operating with microalgae and bacteria consortia, in comparison with  
101 a system worked only with activated sludge [98]. In fact, the presence of microalgae in  
102 the inoculum is used to improve the biomass quality by transforming the EPS composition  
103 and thus improving floc filterability and also decreasing the cake-layer formation in the  
104 membrane [63,98].

105  
106 All these biomass retention technologies have become an essential issue for efficient  
107 microalgae valorization. Regardless of the technology used for biomass retention in MBC  
108 systems, some researchers have emphasized the importance of carefully selecting the SRT  
109 and subsequently the biomass concentration, avoiding growth limitation by self-shading  
110 and thus low light availability for microalgae in the reactor [48,206].

## 111 112 **8. FUTURE PERSPECTIVES**

113 MBC has been already studied for more than 70 years, and the knowledge consolidation  
114 is getting faster. This literature research identified the current trends in the main research  
115 streams in MBC for wastewater treatment. The first identified trend is the elucidation of  
116 nutrient removal mechanisms in the MBC, under the influence of factors such as incident  
117 light, pH, temperature, and dissolved oxygen (DO). Future research studies should not  
118 only focus on the conditions that can guarantee the removal of nutrients and organic  
119 matter, but also establish the fluxes and symbiotic mechanisms determining process  
120 performance. For instance, the environmental and operational conditions that promote  
121 nitrogen assimilation over nitrification, and vice versa. In addition, more research is  
122 needed in new nitrogen removal mechanisms such as the “shortcut nitrogen removal” or  
123 “algammox”. Likewise, more attention should be paid to the removal mechanisms that  
124 promote “luxury” uptake of phosphorus by microalgae or the proliferation of PAOs. On  
125 the other hand, although MBC has the potential to reduce the direct and indirect emission  
126 of CO<sub>2</sub>, microalgal-bacterial photobioreactors can lead to the release of NH<sub>3</sub> or the  
127 production of N<sub>2</sub>O, because of inorganic carbon competition between nitrifiers and  
128 microalgae. Thus, these removal mechanisms must further be understood and evaluated  
129 together with the potential emissions of GHG.

130 Mathematical modeling represents an extremely powerful tool for studying,  
131 understanding, and optimizing microalgae-bacteria processes. The application of  
132 mathematical models must be promoted, since models are especially useful for managing  
133 the complexity and nonlinearities arising from the interactions among microalgae and  
134 bacteria and physical-chemical processes. involved in nutrients removal mechanisms and  
135 GHG emissions. On the other hand, long-term dataset validation must become a standard,  
136 to promote reliable mathematical representations that can represent the process over a  
137 wide range of potential scenarios and operational conditions.

138 Low microalgae settling capacity is another issue identified during literature analysis.  
139 This issue can hinder biomass separation by settling, which is the most used solid-liquid  
140 separation operation in wastewater treatment. Combination of membranes and  
141 photobioreactors is expected to bring new opportunities for biomass retention and an  
142 effluent clarification. Moreover, the evaluation of biomass properties affecting membrane  
143 fouling membrane is key issue. Furthermore, the use of photosynthetic biofilms  
144 represents an interesting alternative to facilitate biomass harvesting and valorization.  
145 Moreover, the application of different biofilm-based reactor configurations has shown  
146 potential for wastewater treatment and the enhancement of biomass productivity. Future

147 works must focus on the strategies and operational conditions of these systems. Finally,  
148 more studies are necessary for both membrane and biofilm photobioreactors, optimizing  
149 the design and operating strategy and implementing these technologies at pilot and/or full  
150 scale.

151

152

## 153 **9. CONCLUSIONS**

154 • The mechanisms involved in the removal of nutrients and COD depend mainly on  
155 the interactions of microorganisms and, at the same time, on factors affecting  
156 these interactions, such as pH, light, dissolved oxygen, C/N/P ratio. These factors  
157 directly impact the chemical equilibria of pollutants and the presence of toxic  
158 compounds (e.g., free NH<sub>3</sub>, HNO<sub>2</sub>), and inhibitors. Further research is needed to  
159 assess the influence of these factors on interactions and removal mechanisms.

160 • Novel nutrient removal mechanisms such as "short-cut nitrogen removal,"  
161 "algammox," and "phosphorus luxury uptake" have been proposed in the past  
162 decade. These could present an alternative to improve nutrients removal during  
163 wastewater treatment. However, more research is needed to evaluate the specific  
164 conditions in which these mechanisms are predominant.

165 • The application of mathematical modelling has been explored in MBC systems.  
166 This tool presents a high potential for the optimization of MBC systems. However,  
167 models need to be correctly calibrated and validated.

168 • Different reactor configurations have been explored to decouple HRT from SRT,  
169 and to keep slow-growing microorganisms such as nitrifiers in the reactor. The  
170 membrane bioreactor and biofilm photobioreactors have shown high potential,  
171 presenting high removal levels of nutrients and organic matter, while facilitating  
172 biomass harvesting and reducing systems footprint. These emerging technologies  
173 must be thoroughly explored and evaluated, to determine potential full-scale  
174 applicability.

175 • More research efforts must be devoted to assessing the performance of MBC for  
176 wastewater treatment at a large scale, including the revalorization of biomass and  
177 reuse of treated water, along with its socio-environmental and economic  
178 implications.

179 • MBC has been highlighted as a prominent wastewater technology that could  
180 compete with conventional systems. However, the main challenges associated are  
181 a high footprint, harvesting costs, and biomass processing to produce high-value  
182 products.

183

## 184 **Declaration of Conflicting Interests**

185 The author(s) declared no potential conflicts of interest concerning the research,  
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187

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195

## 196 **Author contribution statements**

197 Jineth Arango conceived the structure, wrote the manuscript, designed the SQ and the  
198 analysis with permanent feedback from David Jeison. Francesca Casagli, contributed to  
199 the structure of modelling section. Olivier Bernard, Francesca Casagli, Raúl Muñoz, and  
200 Andrés Donoso contributed to the technical aspects and the critical review of the  
201 document, as well as contributed to the structure and conceptualization of the document.  
202 All authors provided critical feedback and helped shaping the research, analysis, and  
203 manuscript writing.

204

## 205 **REFERENCES**

- 206 [1] WWAP (United Nations World Water Assessment Programme), The United  
207 Nations World Water Development Report 2017. Wastewater: The Untapped  
208 Resource., París, UNESCO, 2017. [www.unwater.org](http://www.unwater.org).
- 209 [2] E. Corcoran, C. Nellemann, E. Baker, R. Bos, D. Osborn, H. Savelli, Sick Water?  
210 The Central Role of Wastewater Management in Sustainable Development. A  
211 Rapid Response Assessment, The Hague, UN-Habitat/ UNEP/GRID-Arendal,  
212 2010.
- 213 [3] P.M. Nyenje, J.W. Foppen, S. Uhlenbrook, R. Kulabako, A. Muwanga,  
214 Eutrophication and nutrient release in urban areas of sub-Saharan Africa - A  
215 review, *Sci. Total Environ.* 408 (2010) 447–455.  
216 <https://doi.org/10.1016/j.scitotenv.2009.10.020>.
- 217 [4] WWAP (UNESCO World Water Assessment Programme), The United Nations  
218 World Water Development Report 2019: Leaving No One Behind., Paris,  
219 UNESCO, 2019.
- 220 [5] A. Noyola, A. Padilla-Rivera, J.M. Morgan-Sagastume, F. Herna, Typology of  
221 Municipal Wastewater Treatment Technologies in Latin America, 40 (2012)  
222 926–932. <https://doi.org/10.1002/clen.201100707>.
- 223 [6] Y.J. Chan, M.F. Chong, C.L. Law, D.G. Hassell, A review on anaerobic-aerobic  
224 treatment of industrial and municipal wastewater, *Chem. Eng. J.* 155 (2009) 1–  
225 18. <https://doi.org/10.1016/j.cej.2009.06.041>.
- 226 [7] J. Drewnowski, A. Remiszewska-Skwarek, S. Duda, G. Lagod, Aeration Process  
227 in Bioreactors as the Main Energy Consumer in a Wastewater Treatment Plant .  
228 Review of Solutions and Methods of process optimization, *Processes.* (2019).
- 229 [8] Oilgae., Oilgae Guide to Algae-based Wastewater Treatment A Sample Report,  
230 Retrived from [http:// repository.uobabylon.edu.iq/2010\\_2011/4\\_6558\\_416.pdf](http://repository.uobabylon.edu.iq/2010_2011/4_6558_416.pdf),



- 231 Chennai, India, 2009.
- 232 [9] H.Y. Dong, Z.M. Qiang, W.D. Wang, H. Jin, Evaluation of rural wastewater  
233 treatment processes in a county of eastern China, *J. Environ. Monit.* 14 (2012)  
234 1906–1913. <https://doi.org/10.1039/c2em10976j>.
- 235 [10] I. Lee, H. Lim, B. Jung, M.F. Colosimo, H. Kim, Evaluation of aeration energy  
236 saving in two modified activated sludge processes, *Chemosphere.* (2015).  
237 <https://doi.org/10.1016/j.chemosphere.2014.03.086>.
- 238 [11] D. Rosso, L.E. Larson, M.K. Stenstrom, Aeration of large-scale municipal  
239 wastewater treatment plants: State of the art, *Water Sci. Technol.* (2008).  
240 <https://doi.org/10.2166/wst.2008.218>.
- 241 [12] W.J. Oswald, H.B. Gotaas, H.F. Ludwig, V. Lynch, S. Sewage, I. Wastes, N. Jun,  
242 I. Wastes, J. Oswald, F. Ludwig, *Algae Symbiosis in Oxidation Ponds : III .*  
243 *Photosynthetic Oxygenation*, 25 (1953) 692–705.
- 244 [13] N.G.A.I. Karya, N.P. van der Steen, P.N.L. Lens, Photo-oxygenation to support  
245 nitrification in an algal-bacterial consortium treating artificial wastewater,  
246 *Bioresour. Technol.* 134 (2013) 244–250.  
247 <https://doi.org/10.1016/j.biortech.2013.02.005>.
- 248 [14] F.J. Humenik, G.P. Hanna, P. Hanna, *Algal-Bacterial Symbiosis for Removal*  
249 *and Conservation of Wastewater Nutrients*, *Water.* 43 (1971) 580–594.
- 250 [15] G. Mujtaba, K. Lee, Advanced treatment of wastewater using symbiotic co-  
251 culture of microalgae and bacteria, *Appl. Chem. Eng.* 27 (2016).  
252 <https://doi.org/10.14478/ace.2016.1002>.
- 253 [16] R. Muñoz, B. Guieysse, *Algal – bacterial processes for the treatment of*  
254 *hazardous contaminants : A review*, *Water Res.* 40 (2006) 2799–2815.  
255 <https://doi.org/10.1016/j.watres.2006.06.011>.
- 256 [17] C.C. Tang, W. Zuo, Y. Tian, N. Sun, Z.W. Wang, J. Zhang, Effect of aeration  
257 rate on performance and stability of algal-bacterial symbiosis system to treat  
258 domestic wastewater in sequencing batch reactors, *Bioresour. Technol.* 222  
259 (2016) 156–164. <https://doi.org/10.1016/j.biortech.2016.09.123>.
- 260 [18] H. Khaldi, M. Maatoug, C.S. Dube, M. Ncube, R. Tandlich, H. Heilmeier, R.K.  
261 Laubscher, A. Dellal, Efficiency of wastewater treatment by a mixture of sludge  
262 and microalgae, *J. Fundam. Appl. Sci.* 9 (2017) 1454.  
263 <https://doi.org/10.4314/jfas.v9i3.13>.
- 264 [19] G. Gutzeit, D. Lorch, A. Weber, M. Engels, U. Neis, Biofloculent algal-bacterial  
265 biomass improves low-cost wastewater treatment, *Water Sci. Technol.* (2015).  
266 <https://doi.org/10.2166/wst.2005.0415>.
- 267 [20] D. Kang, K. Kim, Y. Jang, H. Moon, D. Ju, G. Kwon, D. Jahng, Enhancement of  
268 wastewater treatment efficiency through modulation of aeration and blue light on  
269 wastewater-borne algal-bacterial consortia, *Int. Biodeterior. Biodegrad.* 135  
270 (2018) 9–18. <https://doi.org/10.1016/j.ibiod.2018.07.008>.
- 271 [21] A.L. Gonçalves, J.C.M. Pires, M. Simões, A review on the use of microalgal  
272 consortia for wastewater treatment, *Algal Res.* 24 (2017) 403–415.  
273 <https://doi.org/10.1016/j.algal.2016.11.008>.
- 274 [22] T. Essam, M. ElRakaiby, A. Hashem, Photosynthetic based algal-bacterial

- 275 combined treatment of mixtures of organic pollutants and CO<sub>2</sub> mitigation in a  
 276 continuous photobioreactor, *World J. Microbiol. Biotechnol.* 29 (2013) 969–974.  
 277 <https://doi.org/10.1007/s11274-013-1254-z>.
- 278 [23] A. Anbalagan, A. Toledo-Cervantes, E. Posadas, E.M. Rojo, R. Lebrero, A.  
 279 González-Sánchez, E. Nehrenheim, R. Muñoz, Continuous photosynthetic  
 280 abatement of CO<sub>2</sub> and volatile organic compounds from exhaust gas coupled to  
 281 wastewater treatment: Evaluation of tubular algal-bacterial photobioreactor, *J.*  
 282 *CO<sub>2</sub> Util.* 21 (2017) 353–359. <https://doi.org/10.1016/j.jcou.2017.07.016>.
- 283 [24] Wang, Y. Li, N. Wu, C.Q. Lan, CO<sub>2</sub> bio-mitigation using microalgae, *Appl.*  
 284 *Microbiol. Biotechnol.* 79 (2008) 707–718. [https://doi.org/10.1007/s00253-008-](https://doi.org/10.1007/s00253-008-1518-y)  
 285 [1518-y](https://doi.org/10.1007/s00253-008-1518-y).
- 286 [25] Á. Robles, G. Capson-Tojo, A. Galès, M.V. Ruano, B. Sialve, J. Ferrer, J.P.  
 287 Steyer, Microalgae-bacteria consortia in high-rate ponds for treating urban  
 288 wastewater: Elucidating the key state indicators under dynamic conditions, *J.*  
 289 *Environ. Manage.* 261 (2020). <https://doi.org/10.1016/j.jenvman.2020.110244>.
- 290 [26] G. Ruas, M.L. Serejo, P.L. Paulo, M.Á. Boncz, Evaluation of domestic  
 291 wastewater treatment using microalgal-bacterial processes: effect of CO<sub>2</sub>  
 292 addition on pathogen removal, *J. Appl. Phycol.* 30 (2018) 921–929.  
 293 <https://doi.org/10.1007/s10811-017-1280-6>.
- 294 [27] E.J. Olguín, Dual purpose microalgae-bacteria-based systems that treat  
 295 wastewater and produce biodiesel and chemical products within a Biorefinery,  
 296 *Biotechnol. Adv.* 30 (2012) 1031–1046.  
 297 <https://doi.org/10.1016/j.biotechadv.2012.05.001>.
- 298 [28] J. Yang, W. Shi, F. Fang, G. Guo, Jinsong, L. Lu, Y. Xiao, X. Jiang, Exploring  
 299 the feasibility of sewage treatment by algal–bacterial consortia, *Crit. Rev.*  
 300 *Biotechnol.* 0 (2020) 1–11. <https://doi.org/10.1080/07388551.2019.1709796>.
- 301 [29] J.A. Moral-Muñoz, E. Herrera-Viedma, A. Santisteban-Espejo, M.J. Cobo,  
 302 Software tools for conducting bibliometric analysis in science: An up-to-date  
 303 review, *El Prof. La Inf.* 29 (2020) 1–20.
- 304 [30] Elaine Gauthier, *Bibliometric analysis of scientific and technological research: A*  
 305 *user’s guide th the methodology*, (1998) 81.
- 306 [31] Alan Pritchard, *Statistical Bibliography or Bibliometrics?*, *J. Doc.* (1969) 348–  
 307 349.
- 308 [32] L. Castell, Trends in scienti fi c research on climate change in agriculture and  
 309 forestry subject areas ( 2005 e 2014 ), 147 (2017) 406–418.  
 310 <https://doi.org/10.1016/j.jclepro.2017.01.112>.
- 311 [33] F. León-Vargas, J. Arango-Oviedo, H.J. Luna Wandurraga, Two Decades of  
 312 Research in Artificial Pancreas : Insights from a Bibliometric Analysis, *J. Dia.*  
 313 (2021). <https://doi.org/10.1177/19322968211005500>.
- 314 [34] D.C. Calvo, H.J. Luna Wandurraga, J. Arango-Oviedo, C.I. Torres, B.E.  
 315 Rittmann, Determining global trends in syngas fermentation research through a  
 316 bibliometric analysis, *J. Environ. Manage.* 307 (2022) 114522.  
 317 <https://doi.org/https://doi.org/10.1016/j.jenvman.2022.114522>.
- 318 [35] H. Chen, W. Jiang, Y. Yang, Y. Yang, X. Man, State of the art on food waste  
 319 research : a bibliometrics study from 1997 to 2014, 140 (2017) 840–846.

- 320 <https://doi.org/10.1016/j.jclepro.2015.11.085>.
- 321 [36] W. Gao, Y. Chen, Y. Liu, H. cheng Guo, Scientometric analysis of phosphorus  
322 research in eutrophic lakes, *Scientometrics*. (2015).  
323 <https://doi.org/10.1007/s11192-014-1500-7>.
- 324 [37] J.M. Merigó, J. Miranda, N.M. Modak, G. Boustras, Forty years of Safety  
325 Science : A bibliometric overview, *Saf. Sci.* 115 (2019) 66–88.  
326 <https://doi.org/10.1016/j.ssci.2019.01.029>.
- 327 [38] O. Persson, R. Danell, J.W. Schneider, How to use Bibexcel for various types of  
328 bibliometric analysis, *Celebr. Sch. Commun. Stud. A Festschrift Olle Persson His*  
329 *60th Birthd.* (2009).
- 330 [39] S. Zhong, Y. Geng, W. Liu, C. Gao, W. Chen, A bibliometric review on natural  
331 resource accounting during 1995 e 2014, *J. Clean. Prod.* 139 (2016) 122–132.  
332 <https://doi.org/10.1016/j.jclepro.2016.08.039>.
- 333 [40] A. Yataganbaba, B. Ozkahraman, I. Kurtbas, Worldwide trends on encapsulation  
334 of phase change materials: A bibliometric analysis (1990–2015), *Appl. Energy*.  
335 185 (2017) 720–731. <https://doi.org/10.1016/j.apenergy.2016.10.107>.
- 336 [41] J.E. Hirsch, An index to quantify an individual’s scientific research output, *Proc.*  
337 *Natl. Acad. Sci. U. S. A.* (2005). <https://doi.org/10.1073/pnas.0507655102>.
- 338 [42] R. Salvador, M.V. Barros, L.M. da Luz, C.M. Piekarski, A.C. de Francisco,  
339 Circular business models: Current aspects that influence implementation and  
340 unaddressed subjects, *J. Clean. Prod.* 250 (2020) 119555.  
341 <https://doi.org/10.1016/j.jclepro.2019.119555>.
- 342 [43] Z. Li, Y.S. Ho, Use of citation per publication as an indicator to evaluate  
343 contingent valuation research, *Scientometrics*. (2008).  
344 <https://doi.org/10.1007/s11192-007-1838-1>.
- 345 [44] N.J. Van Eck, L. Waltman, Software survey: VOSviewer, a computer program  
346 for bibliometric mapping, *Scientometrics*. 84 (2010) 523–538.  
347 <https://doi.org/10.1007/s11192-009-0146-3>.
- 348 [45] N.J. Van Eck, L. Waltman, Visualizing Bibliometric Networks, in: *Meas. Sch.*  
349 *Impact Methods Pract.*, 2014: pp. 285–320. [https://doi.org/10.1007/978-3-319-](https://doi.org/10.1007/978-3-319-10377-8_13)  
350 [10377-8\\_13](https://doi.org/10.1007/978-3-319-10377-8_13).
- 351 [46] Y. Qi, X. Chen, Z. Hu, C. Song, Y. Cui, Bibliometric Analysis of Algal-Bacterial  
352 Symbiosis in Wastewater Treatment, *Int. J. Environ. Res. Public Health*. (2019).  
353 <https://doi.org/10.3390/ijerph16061077>.
- 354 [47] Y. Su, A. Mennerich, B. Urban, Synergistic cooperation between wastewater-  
355 born algae and activated sludge for wastewater treatment: Influence of algae and  
356 sludge inoculation ratios, *Bioresour. Technol.* 105 (2012) 67–73.  
357 <https://doi.org/10.1016/j.biortech.2011.11.113>.
- 358 [48] A. Sepehri, M.-H. Sarrafzadeh, M. Avateffazeli, Interaction between *Chlorella*  
359 *Vulgaris* and nitrifying-enriched activated sludge in the treatment of wastewater  
360 with low C/N ratio, *J. Clean. Prod.* 247 (2020).  
361 <https://doi.org/10.1016/j.jclepro.2019.119164>.
- 362 [49] S.F. Mohsenpour, S. Hennige, N. Willoughby, A. Adeloje, T. Gutierrez,  
363 Integrating micro-algae into wastewater treatment: A review, *Sci. Total Environ.*

- 364 752 (2021) 142168. <https://doi.org/10.1016/j.scitotenv.2020.142168>.
- 365 [50] N. Renuka, A. Guldhe, R. Prasanna, P. Singh, F. Bux, Microalgae as multi-  
366 functional options in modern agriculture: current trends, prospects and  
367 challenges, *Biotechnol. Adv.* 36 (2018) 1255–1273.  
368 <https://doi.org/10.1016/j.biotechadv.2018.04.004>.
- 369 [51] X. Ji, M. Jiang, J. Zhang, X. Jiang, Z. Zheng, The interactions of algae-bacteria  
370 symbiotic system and its effects on nutrients removal from synthetic wastewater,  
371 *Bioresour. Technol.* 247 (2018) 44–50.  
372 <https://doi.org/10.1016/j.biortech.2017.09.074>.
- 373 [52] B. Zhang, P.N.L. Lens, W. Shi, R. Zhang, Z. Zhang, Y. Guo, X. Bao, F. Cui,  
374 Enhancement of aerobic granulation and nutrient removal by an algal–bacterial  
375 consortium in a lab-scale photobioreactor, *Chem. Eng. J.* 334 (2018) 2373–2382.  
376 <https://doi.org/10.1016/j.cej.2017.11.151>.
- 377 [53] Y. Wang, S.-H. Ho, C.-L. Cheng, W.-Q. Guo, D. Nagarajan, N.-Q. Ren, D.-J.  
378 Lee, J.-S. Chang, Perspectives on the feasibility of using microalgae for industrial  
379 wastewater treatment, *Bioresour. Technol.* 222 (2016) 485–497.  
380 <https://doi.org/10.1016/j.biortech.2016.09.106>.
- 381 [54] J. Liu, Y. Wu, C. Wu, K. Muylaert, W. Vyverman, H.-Q. Yu, R. Muñoz, B.  
382 Rittmann, Advanced nutrient removal from surface water by a consortium of  
383 attached microalgae and bacteria: A review, *Bioresour. Technol.* 241 (2017)  
384 1127–1137. <https://doi.org/10.1016/j.biortech.2017.06.054>.
- 385 [55] L. Liu, H. Fan, Y. Liu, C. Liu, X. Huang, Development of algae-bacteria granular  
386 consortia in photo-sequencing batch reactor, *Bioresour. Technol.* 232 (2017) 64–  
387 71. <https://doi.org/10.1016/j.biortech.2017.02.025>.
- 388 [56] F. Meng, L. Xi, D. Liu, W. Huang, Z. Lei, Z. Zhang, W. Huang, Effects of light  
389 intensity on oxygen distribution, lipid production and biological community of  
390 algal-bacterial granules in photo-sequencing batch reactors, *Bioresour. Technol.*  
391 (2019). <https://doi.org/10.1016/j.biortech.2018.10.059>.
- 392 [57] L. Liu, Y. Hong, X. Ye, L. Wei, J. Liao, X. Huang, C. Liu, Biodiesel production  
393 from microbial granules in sequencing batch reactor, *Bioresour. Technol.* (2018).  
394 <https://doi.org/10.1016/j.biortech.2017.10.105>.
- 395 [58] Z. Zhao, X. Yang, W. Cai, Z. Lei, K. Shimizu, Z. Zhang, M. Utsumi, D.J. Lee,  
396 Response of algal-bacterial granular system to low carbon wastewater: Focus  
397 Response of algal-bacterial granular system to low carbon wastewater: Focus on  
398 granular, *Bioresour. Technol.* (2018).  
399 <https://doi.org/10.1016/j.biortech.2018.07.114>.
- 400 [59] Y. Gou, J. Yang, F. Fang, J. Guo, H. Ma, Feasibility of using a novel algal-  
401 bacterial biofilm reactor for efficient domestic wastewater treatment, *Environ.*  
402 *Technol. (United Kingdom)*. 41 (2020) 400–410.  
403 <https://doi.org/10.1080/09593330.2018.1499812>.
- 404 [60] C.C. Tang, Y. Tian, Z.W. He, W. Zuo, J. Zhang, Performance and mechanism of  
405 a novel algal-bacterial symbiosis system based on sequencing batch suspended  
406 biofilm reactor treating domestic wastewater, *Bioresour. Technol.* 265 (2018)  
407 422–431. <https://doi.org/10.1016/j.biortech.2018.06.033>.
- 408 [61] L. Sun, Y. Tian, J. Zhang, L. Li, J. Zhang, J. Li, A novel membrane bioreactor

- 409 inoculated with symbiotic sludge bacteria and algae: Performance and microbial  
410 community analysis, *Bioresour. Technol.* 251 (2018) 311–319.  
411 <https://doi.org/10.1016/j.biortech.2017.12.048>.
- 412 [62] J. Yang, Y. Gou, F. Fang, J. Guo, L. Lu, Y. Zhou, H. Ma, Potential of wastewater  
413 treatment using a concentrated and suspended algal-bacterial consortium in a  
414 photo membrane bioreactor, *Chem. Eng. J.* 335 (2018) 154–160.  
415 <https://doi.org/10.1016/j.cej.2017.10.149>.
- 416 [63] L. Sun, Y. Tian, J. Zhang, H. Cui, W. Zuo, J. Li, A novel symbiotic system  
417 combining algae and sludge membrane bioreactor technology for wastewater  
418 treatment and membrane fouling mitigation: performance and mechanisms,  
419 *Bioresour. Technol.* 251 (2018) 311–319.
- 420 [64] L. Sun, J. Ma, L. Li, Y. Tian, Z. Zhang, H. Liao, J. Li, W. Tang, D. He,  
421 Exploring the essential factors of performance improvement in sludge membrane  
422 bioreactor technology coupled with symbiotic algae, *Water Res.* (2020).  
423 <https://doi.org/10.1016/j.watres.2020.115843>.
- 424 [65] M.B. Paddock, J.D. Fernández-Bayo, J.S. VanderGheynst, The effect of the  
425 microalgae-bacteria microbiome on wastewater treatment and biomass  
426 production, *Appl. Microbiol. Biotechnol.* (2020). [https://doi.org/10.1007/s00253-](https://doi.org/10.1007/s00253-019-10246-x)  
427 [019-10246-x](https://doi.org/10.1007/s00253-019-10246-x).
- 428 [66] J. Fan, Y. Chen, T.C. Zhang, B. Ji, L. Cao, Performance of *Chlorella*  
429 *sorokiniana*-activated sludge consortium treating wastewater under light-limited  
430 heterotrophic condition, *Chem. Eng. J.* (2020).  
431 <https://doi.org/10.1016/j.cej.2019.122799>.
- 432 [67] S. Rossi, F. Casagli, M. Mantovani, V. Mezzanotte, E. Ficara, Selection of  
433 photosynthesis and respiration models to assess the effect of environmental  
434 conditions on mixed microalgae consortia grown on wastewater, *Bioresour.*  
435 *Technol.* 305 (2020). <https://doi.org/10.1016/j.biortech.2020.122995>.
- 436 [68] S. Petrini, P. Foladori, L. Donati, G. Andreottola, Comprehensive respirometric  
437 approach to assess photosynthetic, heterotrophic and nitrifying activity in  
438 microalgal-bacterial consortia treating real municipal wastewater, *Biochem. Eng.*  
439 *J.* 161 (2020) 107697. <https://doi.org/10.1016/j.bej.2020.107697>.
- 440 [69] S. Rossi, E. Sforza, M. Pastore, M. Bellucci, F. Casagli, F. Marazzi, E. Ficara,  
441 Photo-respirometry to shed light on microalgae-bacteria consortia—a review,  
442 *Rev. Environ. Sci. Biotechnol.* 19 (2020) 43–72. [https://doi.org/10.1007/s11157-](https://doi.org/10.1007/s11157-020-09524-2)  
443 [020-09524-2](https://doi.org/10.1007/s11157-020-09524-2).
- 444 [70] S. Rossi, M. Bellucci, F. Marazzi, V. Mezzanotte, E. Ficara, Activity assessment  
445 of microalgal-bacterial consortia based on respirometric tests, *Water Sci.*  
446 *Technol.* 78 (2018) 207–215. <https://doi.org/10.2166/wst.2018.078>.
- 447 [71] E. Sforza, M. Pastore, A. Spagni, A. Bertucco, Microalgae-bacteria gas exchange  
448 in wastewater: how mixotrophy may reduce the oxygen supply for bacteria,  
449 *Environ. Sci. Pollut. Res.* 25 (2018) 28004–28014.  
450 <https://doi.org/10.1007/s11356-018-2834-0>.
- 451 [72] P. Foladori, S. Petrini, G. Andreottola, Evolution of real municipal wastewater  
452 treatment in photobioreactors and microalgae-bacteria consortia using real-time  
453 parameters, *Chem. Eng. J.* 345 (2018) 507–516.

- 454 <https://doi.org/10.1016/j.cej.2018.03.178>.
- 455 [73] M. Mantovani, F. Marazzi, R. Fornaroli, M. Bellucci, E. Ficara, V. Mezzanotte,  
456 Outdoor pilot-scale raceway as a microalgae-bacteria sidestream treatment in a  
457 WWTP, *Sci. Total Environ.* 710 (2020).  
458 <https://doi.org/10.1016/j.scitotenv.2019.135583>.
- 459 [74] A.W.J. Oswald, H.B. Gotaas, C.G. Golueke, W.R. Kellen, E.F. Gloyna, S.  
460 Sewage, *I. Wastes, N. Apr, J. Oswald, R. Kellen, Algae in Waste Treatment,*  
461 *Sewage Ind. Waste.* 29 (1957) 437–457.
- 462 [75] Y. Nurdogan, W.J. Oswald, Enhanced nutrient removal in high-rate ponds, *Water*  
463 *Sci. Technol.* 31 (1995) 33–43. [https://doi.org/10.1016/0273-1223\(95\)00490-E](https://doi.org/10.1016/0273-1223(95)00490-E).
- 464 [76] P.S. Lau, N.F.Y. Tam, Y.S. Wong, Effect of algal density on nutrient removal  
465 from primary settled wastewater, *Environ. Pollut.* 89 (1995) 59–66.  
466 [https://doi.org/10.1016/0269-7491\(94\)00044-E](https://doi.org/10.1016/0269-7491(94)00044-E).
- 467 [77] M.A. Khan, S.I. Ahmad, Performance evaluation of pilot waste stabilization  
468 ponds in subtropical region, *Water Sci. Technol.* 26 (1992) 1717–1728.  
469 <https://doi.org/10.2166/wst.1992.0615>.
- 470 [78] M.A. Khan, M.A. Khan, The potential of waste stabilization ponds effluent as a  
471 liquid fertilizer, *Pakistan J. Bot.* 39 (2007) 817–829.
- 472 [79] Y. Su, A. Mennerich, B. Urban, Municipal wastewater treatment and biomass  
473 accumulation with a wastewater-born and settleable algal-bacterial culture, *Water*  
474 *Res.* 45 (2011) 3351–3358. <https://doi.org/10.1016/j.watres.2011.03.046>.
- 475 [80] W.J. Oswald, A.M. ASCE, H.B. Gotaas, M. ASCE, Photosynthesis in sewage  
476 treatment, *Am. Soc. Civ. Eng.* 2849 (1985) 33.
- 477 [81] H.F. Ludwig, W.J. Oswald, H.B. Gotaas, V. Lynch, J. Oswald, F. Ludwig, Algae  
478 Symbiosis in Oxidation Ponds: I. Growth Characteristics of “*Euglena Gracilis*”  
479 Cultured in Sewage, *Sewage Ind. Waste.* 23 (1951) 1337–1355.
- 480 [82] I. de Godos, V.A. Vargas, S. Blanco, M.C.G. González, R. Soto, P.A. García-  
481 Encina, E. Becares, R. Muñoz, A comparative evaluation of microalgae for the  
482 degradation of piggery wastewater under photosynthetic oxygenation, *Bioresour.*  
483 *Technol.* 101 (2010) 5150–5158. <https://doi.org/10.1016/j.biortech.2010.02.010>.
- 484 [83] E. Tamer, M.A. Amin, E.T. Ossama, M. Bo, G. Benoit, Biological treatment of  
485 industrial wastes in a photobioreactor, *Water Sci. Technol.* 53 (2006) 117–125.  
486 <https://doi.org/10.2166/wst.2006.344>.
- 487 [84] E. Safonova, K. V. Kvitko, M.I. Iankevitch, L.F. Surgko, I.A. Afti, W. Reisser,  
488 Biotreatment of industrial wastewater by selected algal-bacterial consortia, *Eng.*  
489 *Life Sci.* 4 (2004) 347–353. <https://doi.org/10.1002/elsc.200420039>.
- 490 [85] J.P. Hoffmann, Wastewater treatment with suspended and nonsuspended algae, *J.*  
491 *Phycol.* 34 (1998) 757–763. <https://doi.org/10.1046/j.1529-8817.1998.340757.x>.
- 492 [86] N.C. Boelee, H. Temmink, M. Janssen, C. Buisman, R. Wijffels, Scenario  
493 analysis of nutrient removal from municipal wastewater by microalgal biofilms,  
494 *Water (Switzerland).* (2012). <https://doi.org/10.3390/w4020460>.
- 495 [87] I. de Godos, C. González, E. Becares, P.A. García-Encina, R. Muñoz,  
496 Simultaneous nutrients and carbon removal during pretreated swine slurry  
497 degradation in a tubular biofilm photobioreactor, *Appl. Microbiol. Biotechnol.* 82

- 498 (2009) 187–194. <https://doi.org/10.1007/s00253-008-1825-3>.
- 499 [88] B. Ji, M. Zhang, J. Gu, Y. Ma, Y. Liu, A self-sustaining synergetic microalgal-  
500 bacterial granular sludge process towards energy-efficient and environmentally  
501 sustainable municipal wastewater treatment, *Water Res.* 179 (2020) 115884.  
502 <https://doi.org/10.1016/j.watres.2020.115884>.
- 503 [89] L.E. de-Bashan, M. Moreno, J.P. Hernandez, Y. Bashan, Removal of ammonium  
504 and phosphorus ions from synthetic wastewater by the microalgae *Chlorella*  
505 *Vulgaris* coimmobilized in alginate beads with the microalgae growth-promoting  
506 bacterium *Azospirillum Brasilense*, *Water Res.* 36 (2001) 2941–2948.  
507 [https://doi.org/10.1016/S0043-1354\(01\)00522-X](https://doi.org/10.1016/S0043-1354(01)00522-X).
- 508 [90] L.E. de-Bashan, J.P. Hernandez, T. Morey, Y. Bashan, Microalgae growth-  
509 promoting bacteria as “helpers” for microalgae: A novel approach for removing  
510 ammonium and phosphorus from municipal wastewater, *Water Res.* 38 (2003)  
511 466–474. <https://doi.org/10.1016/j.watres.2003.09.022>.
- 512 [91] A. Sánchez-Zurano, J.A. Garrido-Cárdenas, C. Gómez-Serrano, M. Morales-  
513 Amaral, F.G. Acién-Fernández, J.M. Fernández-Sevilla, E. Molina-Grima, Year-  
514 long assessment of a pilot-scale thin-layer reactor for microalgae wastewater  
515 treatment. Variation in the microalgae-bacteria consortium and the impact of  
516 environmental conditions, *Algal Res.* 50 (2020) 101983.  
517 <https://doi.org/10.1016/j.algal.2020.101983>.
- 518 [92] L.M. Trebuch, B.O. Oyserman, M. Janssen, R.H. Wijffels, L.E.M. Vet, T. V.  
519 Fernandes, Impact of hydraulic retention time on community assembly and  
520 function of photogranules for wastewater treatment, *Water Res.* 173 (2020)  
521 115506. <https://doi.org/10.1016/j.watres.2020.115506>.
- 522 [93] F. Casagli, G. Zuccaro, O. Bernard, J.P. Steyer, E. Ficara, ALBA: A  
523 comprehensive growth model to optimize algae-bacteria wastewater treatment in  
524 raceway ponds, *Water Res.* 190 (2021) 1–60.  
525 <https://doi.org/10.1016/j.watres.2020.116734>.
- 526 [94] A. Solimeno, C. Gomez-Serrano, F.G. Acién, BIO \_ ALGAE 2 : improved model  
527 of microalgae and bacteria consortia for wastewater treatment, *Environ. Sci.*  
528 *Pollut. Res.* 26(25) (2019) 25855–25868.
- 529 [95] S. Arun, N.A. Manikandan, K. Pakshirajan, G. Pugazhenthii, Novel shortcut  
530 biological nitrogen removal method using an algae-bacterial consortium in a  
531 photo-sequencing batch reactor: Process optimization and kinetic modelling, *J.*  
532 *Environ. Manage.* 250 (2019) 109401.  
533 <https://doi.org/10.1016/j.jenvman.2019.109401>.
- 534 [96] A. Sánchez-Zurano, E. Rodríguez-Miranda, J.L. Guzmán, F.G. Acién-Fernández,  
535 J.M. Fernández-Sevilla, E.M. Grima, Abaco: A new model of microalgae-  
536 bacteria consortia for biological treatment of wastewaters, *Appl. Sci.* 11 (2021)  
537 1–24. <https://doi.org/10.3390/app11030998>.
- 538 [97] Á. Robles, G. Capson-Tojo, A. Gales, A. Viruela, B. Sialve, A. Seco, J.P. Steyer,  
539 J. Ferrer, Performance of a membrane-coupled high-rate algal pond for urban  
540 wastewater treatment at demonstration scale, *Bioresour. Technol.* 301 (2020)  
541 122672. <https://doi.org/10.1016/j.biortech.2019.122672>.
- 542 [98] L. Sun, Y. Tian, J. Zhang, H. Li, C. Tang, J. Li, Wastewater treatment and

- 543 membrane fouling with algal-activated sludge culture in a novel membrane  
544 bioreactor : Influence of inoculation ratios, *Chem. Eng. J.* 343 (2018) 455–459.  
545 <https://doi.org/10.1016/j.cej.2018.03.022>.
- 546 [99] A.M. Rada-Ariza, D. Fredy, C.M. Lopez-Vazquez, N.P. Van der Steen, P.N.L.  
547 Lens, Ammonium removal mechanisms in a microalgal-bacterial sequencing-  
548 batch photobioreactor at different solids retention times, *Algal Res.* 39 (2019)  
549 101468. <https://doi.org/10.1016/j.algal.2019.101468>.
- 550 [100] M. Wang, H. Yang, S.J. Ergas, P. van der Steen, A novel shortcut nitrogen  
551 removal process using an algal-bacterial consortium in a photo-sequencing batch  
552 reactor (PSBR), *Water Res.* 87 (2015) 38–48.  
553 <https://doi.org/10.1016/j.watres.2015.09.016>.
- 554 [101] D. Marín, E. Posadas, D. García, D. Puyol, R. Lebrero, R. Muñoz, Assessing the  
555 potential of purple phototrophic bacteria for the simultaneous treatment of  
556 piggery wastewater and upgrading of biogas, *Bioresour. Technol.* 281 (2019) 10–  
557 17. <https://doi.org/10.1016/j.biortech.2019.02.073>.
- 558 [102] G. Guo, J. Guan, S. Sun, J. Liu, Y. Zhao, Nutrient and heavy metal removal from  
559 piggery wastewater and CH<sub>4</sub> enrichment in biogas based on microalgae  
560 cultivation technology under different initial inoculum concentration, *WATER*  
561 *Environ. Res.* 92 (2020) 922–933. <https://doi.org/10.1002/wer.1287>.
- 562 [103] S. Arun, A. Sinharoy, K. Pakshirajan, P.N.L. Lens, Algae based microbial fuel  
563 cells for wastewater treatment and recovery of value-added products, *Renew.*  
564 *Sustain. Energy Rev.* 132 (2020) 110041.  
565 <https://doi.org/10.1016/j.rser.2020.110041>.
- 566 [104] B. Zhang, W. Li, Y. Guo, Z. Zhang, W. Shi, F. Cui, P.N.L. Lens, J.H. Tay,  
567 Microalgal-bacterial consortia: From interspecies interactions to biotechnological  
568 applications, *Renew. Sustain. Energy Rev.* 118 (2020) 109563.  
569 <https://doi.org/10.1016/j.rser.2019.109563>.
- 570 [105] J. Lee, J. Lee, S.K. Shukla, J. Park, T.K. Lee, Effect of algal inoculation on COD  
571 and nitrogen removal, and indigenous bacterial dynamics in municipal  
572 wastewater, *J. Microbiol. Biotechnol.* 26 (2016) 900–908.  
573 <https://doi.org/10.4014/jmb.1512.12067>.
- 574 [106] B. Holmes, M.B. Paddock, J.S. VanderGheynst, B.T. Higgins, Algal  
575 photosynthetic aeration increases the capacity of bacteria to degrade organics in  
576 wastewater, *Biotechnol. Bioeng.* 117 (2020) 62–72.  
577 <https://doi.org/10.1002/bit.27172>.
- 578 [107] M.M.M. Kuypers, H.K. Marchant, B. Kartal, The microbial nitrogen-cycling  
579 network, *Nat. Publ. Gr.* (2018). <https://doi.org/10.1038/nrmicro.2018.9>.
- 580 [108] Y. Wang, S. Wang, L. Sun, Z. Sun, D. Li, Screening of a *Chlorella*-bacteria  
581 consortium and research on piggery wastewater purification, *Algal Res.* 47  
582 (2020). <https://doi.org/10.1016/j.algal.2020.101840>.
- 583 [109] T. Cai, S.Y. Park, Y. Li, Nutrient recovery from wastewater streams by  
584 microalgae: Status and prospects, *Renew. Sustain. Energy Rev.* 19 (2013) 360–  
585 369. <https://doi.org/10.1016/j.rser.2012.11.030>.
- 586 [110] P. Foladori, S. Petrini, M. Nessenzia, G. Andreottola, Enhanced nitrogen removal  
587 and energy saving in a microalgal-bacterial consortium treating real municipal



- 588 wastewater, *Water Sci. Technol.* 78 (2018) 174–182.  
589 <https://doi.org/10.2166/wst.2018.094>.
- 590 [111] A.S. Guerra-Renteria, M.A. García-Ramírez, C. Gómez-Hermosillo, A. Gómez-  
591 Guzmán, Y. González-García, O. González-Reynoso, Metabolic pathway  
592 analysis of nitrogen and phosphorus uptake by the consortium between *C.*  
593 *Vulgaris* and *P. Aeruginosa*, *Int. J. Mol. Sci.* 20 (2019).  
594 <https://doi.org/10.3390/ijms20081978>.
- 595 [112] C.C. Tang, Y. Tian, H. Liang, W. Zuo, Z.W. Wang, J. Zhang, Z.W. He,  
596 Enhanced nitrogen and phosphorus removal from domestic wastewater via algae-  
597 assisted sequencing batch biofilm reactor, *Bioresour. Technol.* (2018).  
598 <https://doi.org/10.1016/j.biortech.2017.11.028>.
- 599 [113] J. Zhou, Y. Lyu, M.L. Richlen, D.M. Anderson, Z. Cai, Quorum Sensing Is a  
600 Language of Chemical Signals and Plays an Ecological Role in Algal-Bacterial  
601 Interactions, *CRC. Crit. Rev. Plant Sci.* 35 (2016) 81–105.  
602 <https://doi.org/10.1080/07352689.2016.1172461>.
- 603 [114] A. Mitsutani, I. Yamasaki, H. Kitaguchi, J. Kato, S. Ueno, Y. Ishida, Analysis of  
604 algicidal proteins of a diatom-lytic marine bacterium *Pseudoalteromonas* sp.  
605 strain A25 by two-dimensional electrophoresis, *Phycologia.* 40 (2001) 286–291.  
606 <https://doi.org/10.2216/i0031-8884-40-3-286.1>.
- 607 [115] W.C. Fuqua, S.C. Winans, E.P. Greenberg, Quorum sensing in bacteria: The  
608 LuxR-LuxI family of cell density- responsive transcriptional regulators, *J.*  
609 *Bacteriol.* 176 (1994) 269–275. <https://doi.org/10.1128/jb.176.2.269-275.1994>.
- 610 [116] S.A. Amin, L.R. Hmelo, H.M. Van Tol, B.P. Durham, L.T. Carlson, K.R. Heal,  
611 R.L. Morales, C.T. Berthiaume, M.S. Parker, B. Djunaedi, A.E. Ingalls, M.R.  
612 Parsek, M.A. Moran, E. V. Armbrust, Interaction and signalling between a  
613 cosmopolitan phytoplankton and associated bacteria, *Nature.* 522 (2015) 98–101.  
614 <https://doi.org/10.1038/nature14488>.
- 615 [117] L.A. Pagnussat, G. Maroniche, L. Curatti, C. Creus, Auxin-dependent alleviation  
616 of oxidative stress and growth promotion of *Scenedesmus obliquus* C1S by  
617 *Azospirillum brasilense*, *Algal Res.* 47 (2020).  
618 <https://doi.org/10.1016/j.algal.2020.101839>.
- 619 [118] L.E. de-Bashan, Y. Bashan, Increased growth of the microalga *Chlorella Vulgaris*  
620 when coimmobilized and cocultured in alginate beads with the plant-growth-  
621 promoting bacterium *Azospirillum Brasilense*, *Appl. Environ. Microbiol.* 66  
622 (2000) 1527–1531. <https://doi.org/10.1128/AEM.66.4.1527-1531.2000>.
- 623 [119] H.M. Najdenski, L.G. Gigova, I.I. Iliev, P.S. Pilarski, J. Lukavský, I. V.  
624 Tsvetkova, M.S. Ninova, V.K. Kussovski, Antibacterial and antifungal activities  
625 of selected microalgae and cyanobacteria, *Int. J. Food Sci. Technol.* 48 (2013)  
626 1533–1540. <https://doi.org/10.1111/ijfs.12122>.
- 627 [120] B. Zhang, Y. Guo, P.N.L. Lens, Z. Zhang, W. Shi, F. Cui, J.H. Tay, Effect of  
628 light intensity on the characteristics of algal-bacterial granular sludge and the role  
629 of N-acyl-homoserine lactone in the granulation, *Sci. Total Environ.* 659 (2019)  
630 372–383. <https://doi.org/10.1016/j.scitotenv.2018.12.250>.
- 631 [121] D. Zhou, C. Zhang, L. Fu, L. Xu, X. Cui, Q. Li, J.C. Crittenden, Responses of the  
632 Microalga *Chlorophyta* sp. to Bacterial Quorum Sensing Molecules (N-

- 633 Acylhomoserine Lactones): Aromatic Protein-Induced Self-Aggregation,  
 634 Environ. Sci. Technol. 51 (2017) 3490–3498.  
 635 <https://doi.org/10.1021/acs.est.7b00355>.
- 636 [122] B. Zhang, P.N.L. Lens, W. Shi, R. Zhang, Z. Zhang, Y. Guo, X. Bao, F. Cui, The  
 637 attachment potential and N-acyl-homoserine lactone-based quorum sensing in  
 638 aerobic granular sludge and algal-bacterial granular sludge, Appl. Microbiol.  
 639 Biotechnol. 102 (2018) 5343–5353. <https://doi.org/10.1007/s00253-018-9002-9>.
- 640 [123] X. Ji, X. Luo, J. Zhang, D. Huang, Effects of exogenous vitamin B12 on nutrient  
 641 removal and protein expression of algal-bacterial consortium, Environ. Sci.  
 642 Pollut. Res. 28 (2021) 15954–15965. <https://doi.org/10.1007/s11356-020-11720-0>.
- 644 [124] L.E. de-Bashan, V.K. Lebsky, J.P. Hernandez, J.J. Bustillos, Y. Bashan, Changes  
 645 in the metabolism of the microalga *Chlorella vulgaris* when coimmobilized in  
 646 alginate with the nitrogen-fixing *Phyllobacterium myrsinacearum*, Can. J.  
 647 Microbiol. 46 (2000) 653–659. <https://doi.org/10.1139/w00-041>.
- 648 [125] C. Zhang, Q. Li, L. Fu, D. Zhou, J.C. Crittenden, Quorum sensing molecules in  
 649 activated sludge could trigger microalgae lipid synthesis, Bioresour. Technol.  
 650 263 (2018) 576–582. <https://doi.org/10.1016/j.biortech.2018.05.045>.
- 651 [126] C. Zhang, S.H. Ho, A. Li, L. Fu, D. Zhou, Co-culture of *Chlorella* and  
 652 *Scenedesmus* could enhance total lipid production under bacteria quorum sensing  
 653 molecule stress, J. Water Process Eng. 39 (2021) 101739.  
 654 <https://doi.org/10.1016/j.jwpe.2020.101739>.
- 655 [127] K. Fukami, T. Nishijima, Y. Ishida, Stimulative and inhibitory effects of bacteria  
 656 on the growth of microalgae, Hydrobiologia. 358 (1997) 185–191.  
 657 [https://doi.org/10.1007/978-94-017-2097-7\\_29](https://doi.org/10.1007/978-94-017-2097-7_29).
- 658 [128] N. Rashid, W.-K. Park, T. Selvaratnam, Binary culture of microalgae as an  
 659 integrated approach for enhanced biomass and metabolites productivity,  
 660 wastewater treatment, and bioflocculation, Chemosphere. 194 (2018) 67–75.  
 661 <https://doi.org/10.1016/j.chemosphere.2017.11.108>.
- 662 [129] L.P. Acurio, D.M. Salazar, A.F. Valencia, D.R. Robalino, A.C. Barona, F.C.  
 663 Alvarez, C.A. Rodriguez, Antimicrobial potential of *Chlorella* algae isolated  
 664 from stacked waters of the Andean Region of Ecuador, IOP Conf. Ser. Earth  
 665 Environ. Sci. 151 (2018). <https://doi.org/10.1088/1755-1315/151/1/012040>.
- 666 [130] X. Chen, Z. Hu, Y. Qi, C. Song, G. Chen, The interactions of algae-activated  
 667 sludge symbiotic system and its effects on wastewater treatment and lipid  
 668 accumulation, Bioresour. Technol. (2019).  
 669 <https://doi.org/10.1016/j.biortech.2019.122017>.
- 670 [131] L.M. González-González, L.E. De-Bashan, Toward the enhancement of  
 671 microalgal metabolite production through microalgae–bacteria consortia, Biology  
 672 (Basel). 10 (2021) 1–20. <https://doi.org/10.3390/biology10040282>.
- 673 [132] B.T. Higgins, I. Gennity, S. Samra, T. Kind, O. Fiehn, J.S. VanderGheynst,  
 674 Cofactor symbiosis for enhanced algal growth, biofuel production, and  
 675 wastewater treatment, Algal Res. 17 (2016) 308–315.  
 676 <https://doi.org/10.1016/j.algal.2016.05.024>.
- 677 [133] S.N. Li, C. Zhang, F. Li, N.Q. Ren, S.H. Ho, Recent advances of algae-bacteria

- 678 consortia in aquatic remediation, *Crit. Rev. Environ. Sci. Technol.* 0 (2022) 1–25.  
679 <https://doi.org/10.1080/10643389.2022.2052704>.
- 680 [134] M.B. Cooper, A.G. Smith, Exploring mutualistic interactions between microalgae  
681 and bacteria in the omics age, *Curr. Opin. Plant Biol.* 26 (2015) 147–153.  
682 <https://doi.org/10.1016/j.pbi.2015.07.003>.
- 683 [135] M.T. Nazari, J.F. Freitag, V.A.F. Cavanhi, L.M. Colla, Microalgae harvesting by  
684 fungal-assisted bioflocculation, *Rev. Environ. Sci. Biotechnol.* 19 (2020) 369–  
685 388. <https://doi.org/10.1007/s11157-020-09528-y>.
- 686 [136] Z. Ding, I. Bourven, G. Guibaud, E.D. van Hullebusch, A. Panico, F. Pirozzi, G.  
687 Esposito, Role of extracellular polymeric substances (EPS) production in  
688 bioaggregation: application to wastewater treatment, *Appl. Microbiol.*  
689 *Biotechnol.* 99 (2015) 9883–9905. <https://doi.org/10.1007/s00253-015-6964-8>.
- 690 [137] B. Zhang, W. Li, Y. Guo, Z. Zhang, W. Shi, F. Cui, P.N.L. Lens, J.H. Tay,  
691 Microalgal-bacterial consortia: From interspecies interactions to biotechnological  
692 applications, *Renew. Sustain. Energy Rev.* 118 (2020).  
693 <https://doi.org/10.1016/j.rser.2019.109563>.
- 694 [138] L. Ferro, M. Colombo, E. Posadas, C. Funk, R. Muñoz, Elucidating the symbiotic  
695 interactions between a locally isolated microalga *Chlorella Vulgaris* and its co-  
696 occurring bacterium *Rhizobium* sp. in synthetic municipal wastewater, *J. Appl.*  
697 *Phycol.* 31 (2019) 2299–2310. <https://doi.org/10.1007/s10811-019-1741-1>.
- 698 [139] Q. Wang, W. Jin, X. Zhou, S. Guo, S.H. Gao, C. Chen, R. Tu, S.F. Han, J. Jiang,  
699 X. Feng, Growth enhancement of biodiesel-promising microalga *Chlorella*  
700 *pyrenoidosa* in municipal wastewater by polyphosphate-accumulating organisms,  
701 *J. Clean. Prod.* 240 (2019) 118148.  
702 <https://doi.org/10.1016/j.jclepro.2019.118148>.
- 703 [140] T. Kuba, A. Wachtmeister, M.C.M. Van Loosdrecht, J.J. Heijnen, Effect of  
704 nitrate on phosphorus release in biological phosphorus removal systems, in:  
705 *Water Sci. Technol.*, 1994. <https://doi.org/10.2166/wst.1994.0277>.
- 706 [141] Y. Hu, X. Hao, M. van Loosdrecht, H. Chen, Enrichment of highly settleable  
707 microalgal consortia in mixed cultures for effluent polishing and low-cost  
708 biomass production, *Water Res.* 125 (2017) 11–22.  
709 <https://doi.org/10.1016/j.watres.2017.08.034>.
- 710 [142] N.C. Boelee, H. Temmink, M. Janssen, C.J.N. Buisman, R.H. Wijffels,  
711 Balancing the organic load and light supply in symbiotic microalgal – bacterial  
712 biofilm reactors treating synthetic municipal wastewater, *Ecol. Eng.* 64 (2014)  
713 213–221. <https://doi.org/10.1016/j.ecoleng.2013.12.035>.
- 714 [143] N.C. Boelee, H. Temmink, M. Janssen, C.J.N. Buisman, R.H. Wijffels, Nitrogen  
715 and phosphorus removal from municipal wastewater effluent using microalgal  
716 biofilms, *Water Res.* 45 (2011) 5925–5933.  
717 <https://doi.org/10.1016/j.watres.2011.08.044>.
- 718 [144] V. Ashok, A. Shriwastav, P. Bose, Nutrient Removal Using Algal-Bacterial  
719 Mixed Culture, *Appl. Biochem. Biotechnol.* (2014).  
720 <https://doi.org/10.1007/s12010-014-1229-z>.
- 721 [145] Y. Luo, P. Le-Clech, R.K. Henderson, Simultaneous microalgae cultivation and  
722 wastewater treatment in submerged membrane photobioreactors: A review, *Algal*

- 723 Res. 24 (2017) 425–437. <https://doi.org/10.1016/j.algal.2016.10.026>.
- 724 [146] J.S. Arcila, D. Céspedes, G. Buitrón, Influence of wavelength photoperiods and  
725 N/P ratio on wastewater treatment with microalgae–bacteria, *Water Sci. Technol.*  
726 00 (2021) 1–13. <https://doi.org/10.2166/wst.2021.257>.
- 727 [147] H.J. Choi, S.M. Lee, Effect of the N/P ratio on biomass productivity and nutrient  
728 removal from municipal wastewater, *Bioprocess Biosyst. Eng.* 38 (2015) 761–  
729 766. <https://doi.org/10.1007/s00449-014-1317-z>.
- 730 [148] S. Eixler, U. Karsten, U. Selig, Phosphorus storage in *Chlorella Vulgaris*  
731 (*Trebouxiophyceae*, *Chlorophyta*) cells and its dependence on phosphate supply,  
732 *Phycologia*. 45 (2006) 53–60. <https://doi.org/10.2216/04-79.1>.
- 733 [149] A. Crimp, N. Brown, A. Shilton, Microalgal luxury uptake of phosphorus in  
734 waste stabilization ponds - frequency of occurrence and high performing genera,  
735 *Water Sci. Technol.* 78 (2018) 165–173. <https://doi.org/10.2166/wst.2017.632>.
- 736 [150] N. Powell, A. Shilton, S. Pratt, Y. Chisti, Luxury uptake of phosphorus by  
737 microalgae in full-scale waste stabilisation ponds, *Water Sci. Technol.* (2011).  
738 <https://doi.org/10.2166/wst.2011.116>.
- 739 [151] Y. Yang, X. Shi, W. Ballent, B.K. Mayer, Biological Phosphorus Recovery:  
740 Review of Current Progress and Future Needs, *Water Environ. Res.* 89 (2017)  
741 2122–2135. <https://doi.org/10.2175/106143017x15054988926424>.
- 742 [152] T. Mino, M.C.M. Van Loosdrecht, J.J. Heijnen, Microbiology and biochemistry  
743 of the enhanced biological phosphate removal process, *Water Res.* 32 (1998)  
744 3193–3207. [https://doi.org/10.1016/S0043-1354\(98\)00129-8](https://doi.org/10.1016/S0043-1354(98)00129-8).
- 745 [153] E.R. Coats, C.K. Brinkman, S. Lee, Characterizing and contrasting the microbial  
746 ecology of laboratory and full-scale EBPR systems cultured on synthetic and real  
747 wastewaters, *Water Res.* 108 (2017) 124–136.  
748 <https://doi.org/10.1016/j.watres.2016.10.069>.
- 749 [154] L. Xing, L. Ren, B. Tang, G. Wu, Y. Guan, Dynamics of intracellular polymers  
750 in enhanced biological phosphorus removal processes under different organic  
751 carbon concentrations, *Biomed Res. Int.* 2013 (2013).  
752 <https://doi.org/10.1155/2013/761082>.
- 753 [155] W. Huang, B. Li, C. Zhang, Z. Zhang, Z. Lei, B. Lu, B. Zhou, Effect of algae  
754 growth on aerobic granulation and nutrients removal from synthetic wastewater  
755 by using sequencing batch reactors, *Bioresour. Technol.* 179 (2015) 187–192.  
756 <https://doi.org/10.1016/j.biortech.2014.12.024>.
- 757 [156] T.J. Belli, J. Karla, B. Bernardelli, R. Emanuely, J.P. Bassin, M. Cristina, S.  
758 Amaral, F.R. Lapolli, Effect of solids retention time on nitrogen and phosphorus  
759 removal from municipal wastewater in a sequencing batch membrane bioreactor,  
760 *Environ. Technol.* 38 (2017) 806–815.  
761 <https://doi.org/10.1080/09593330.2016.1212934>.
- 762 [157] S. Zhu, L. Qin, P. Feng, C. Shang, Z. Wang, Z. Yuan, Treatment of low C/N ratio  
763 wastewater and biomass production using co-culture of *Chlorella Vulgaris* and  
764 activated sludge in a batch photobioreactor, *Bioresour. Technol.* 274 (2019) 313–  
765 320. <https://doi.org/10.1016/j.biortech.2018.10.034>.
- 766 [158] N. Artan, R. Tasli, N. Özgür, D. Orhon, The fate of phosphate under anoxic  
767 conditions in biological nutrient removal activated sludge systems, *Biotechnol.*

- 768 Lett. 20 (1998) 1085–1090. <https://doi.org/10.1023/A:1005419408097>.
- 769 [159] F. Lananan, S.H. Abdul Hamid, W.N.S. Din, N. Ali, H. Khatoon, A. Jusoh, A.  
770 Endut, Symbiotic bioremediation of aquaculture wastewater in reducing  
771 ammonia and phosphorus utilizing Effective Microorganism (EM-1) and  
772 microalgae (*Chlorella* sp.), *Int. Biodeterior. Biodegrad.* 95 (2014) 127–134.  
773 <https://doi.org/10.1016/j.ibiod.2014.06.013>.
- 774 [160] J. García, R. Mujeriego, M. Hernández-Mariné, High rate algal pond operating  
775 strategies for urban wastewater nitrogen removal, *J. Appl. Phycol.* 12 (2000)  
776 331–339. <https://doi.org/10.1023/A:1008146421368>.
- 777 [161] N. Nirmalakhandan, T. Selvaratnam, D. Tchinda, I.S.A. Abeywardana-  
778 Arachchige, H.M.K. Delanka-Pedige, S.P. Munasinghe-Arachchige, Algal  
779 wastewater treatment : Photoautotrophic vs . mixotrophic processes, *Algal Res.*  
780 41 (2019) 101569. <https://doi.org/10.1016/j.algal.2019.101569>.
- 781 [162] B. Picot, H. El Halouani, C. Casellas, S. Moersidik, J. Bontoux, Nutrient removal  
782 by high rate pond system in a Mediterranean climate (France), *Water Sci.*  
783 *Technol.* 23 (1991) 1535–1541. <https://doi.org/10.2166/wst.1991.0607>.
- 784 [163] E. Posadas, M. del M. Morales, C. Gomez, F.G. Acién, R. Muñoz, Influence of  
785 pH and CO<sub>2</sub> source on the performance of microalgae-based secondary domestic  
786 wastewater treatment in outdoors pilot raceways, *Chem. Eng. J.* 265 (2015) 239–  
787 248. <https://doi.org/10.1016/j.cej.2014.12.059>.
- 788 [164] R. Craggs, D. Sutherland, H. Campbell, Hectare-scale demonstration of high rate  
789 algal ponds for enhanced wastewater treatment and biofuel production, *J. Appl.*  
790 *Phycol.* 24 (2012) 329–337. <https://doi.org/10.1007/s10811-012-9810-8>.
- 791 [165] J.B.K. Park, R.J. Craggs, Wastewater treatment and algal production in high rate  
792 algal ponds with carbon dioxide addition, *Water Sci. Technol.* 61 (2010) 633–  
793 639. <https://doi.org/10.2166/wst.2010.951>.
- 794 [166] J.B.K. Park, R.J. Craggs, Nutrient removal in wastewater treatment high rate  
795 algal ponds with carbon dioxide addition, *Water Sci. Technol.* (2011).  
796 <https://doi.org/10.2166/wst.2011.114>.
- 797 [167] S. Van Den Hende, H. Vervaeren, S. Desmet, N. Boon, Bioflocculation of  
798 microalgae and bacteria combined with flue gas to improve sewage treatment, *N.*  
799 *Biotechnol.* 29 (2011) 23–31. <https://doi.org/10.1016/j.nbt.2011.04.009>.
- 800 [168] V.M. Vadivelu, J. Keller, Z. Yuan, Free ammonia and free nitrous acid inhibition  
801 on the anabolic and catabolic processes of *Nitrosomonas* and *Nitrobacter*, *Water*  
802 *Science and Technology*, 2007. <https://doi.org/10.2166/wst.2007.612>.
- 803 [169] A. Abeliovich, Y. Azov, Toxicity of ammonia to algae in sewage oxidation  
804 ponds, *Appl. Environ. Microbiol.* (1976). [https://doi.org/10.1128/aem.31.6.801-](https://doi.org/10.1128/aem.31.6.801-806.1976)  
805 [806.1976](https://doi.org/10.1128/aem.31.6.801-806.1976).
- 806 [170] S. Rossi, R. Díez-Montero, E. Rueda, F. Castillo Cascino, K. Parati, J. García, E.  
807 Ficara, Free ammonia inhibition in microalgae and cyanobacteria grown in  
808 wastewaters: Photo-respirometric evaluation and modelling, *Bioresour. Technol.*  
809 305 (2020). <https://doi.org/10.1016/j.biortech.2020.123046>.
- 810 [171] F. Casagli, S. Rossi, J.P. Steyer, O. Bernard, E. Ficara, Balancing Microalgae and  
811 Nitrifiers for Wastewater Treatment: Can Inorganic Carbon Limitation Cause an  
812 Environmental Threat?, *Environ. Sci. Technol.* 55 (2021) 3940–3955.

- 813 <https://doi.org/10.1021/acs.est.0c05264>.
- 814 [172] B.L. Mellbye, A. Giguere, F. Chaplen, P.J. Bottomley, L.A. Sayavedra-Soto,  
815 Steady-state growth under inorganic carbon limitation conditions increases  
816 energy consumption for maintenance and enhances nitrous oxide production in  
817 *Nitrosomonas europaea*, *Appl. Environ. Microbiol.* 82 (2016) 3310–3318.  
818 <https://doi.org/10.1128/AEM.00294-16>.
- 819 [173] S. Solomon, I.P. on C. Change., I.P. on C. Change., W.G. I., *Climate change*  
820 *2007 : the physical science basis : contribution of Working Group I to the Fourth*  
821 *Assessment Report of the Intergovernmental Panel on Climate Change,*  
822 Cambridge University Press, Cambridge; New York, 2007.
- 823 [174] B.-G. Ryu, J. Kim, J.I. Han, J.W. Yang, Feasibility of using a microalgal-  
824 bacterial consortium for treatment of toxic coke wastewater with concomitant  
825 production of microbial lipids, *Bioresour. Technol.* 225 (2017) 58–66.  
826 <https://doi.org/10.1016/j.biortech.2016.11.029>.
- 827 [175] D.L. Sutherland, C. Howard-Williams, M.H. Turnbull, P.A. Broady, R.J. Craggs,  
828 The effects of CO<sub>2</sub> addition along a pH gradient on wastewater microalgal  
829 photo-physiology, biomass production and nutrient removal, *Water Res.* 70  
830 (2015) 9–26. <https://doi.org/10.1016/j.watres.2014.10.064>.
- 831 [176] I. de Godos, V.A. Vargas, H.O. Guzmán, R. Soto, B. García, P.A. García-Encina,  
832 R. Muñoz, Assessing carbon and nitrogen removal in a novel anoxic-aerobic  
833 cyanobacterial-bacterial photobioreactor configuration with enhanced biomass  
834 sedimentation, *Water Res.* 61 (2014) 77–85.  
835 <https://doi.org/10.1016/j.watres.2014.04.050>.
- 836 [177] C. Alcántara, J.M. Domínguez, D. García, S. Blanco, R. Pérez, P.A. García-  
837 Encina, R. Muñoz, Evaluation of wastewater treatment in a novel anoxic-aerobic  
838 algal-bacterial photobioreactor with biomass recycling through carbon and  
839 nitrogen mass balances, *Bioresour. Technol.* 191 (2015) 173–186.  
840 <https://doi.org/10.1016/j.biortech.2015.04.125>.
- 841 [178] C. Vergara, R. Muñoz, J.L. Campos, M. Seeger, D. Jeison, Influence of light  
842 intensity on bacterial nitrifying activity in algal-bacterial photobioreactors and its  
843 implications for microalgae-based wastewater treatment, *Int. Biodeterior.*  
844 *Biodegrad.* 114 (2016) 116–121. <https://doi.org/10.1016/j.ibiod.2016.06.006>.
- 845 [179] N.D. Manser, M. Wang, S.J. Ergas, J.R. Mihelcic, A. Mulder, J. Van de  
846 Vossenberg, J.B. Van Lier, P. Van der Steen, Biological Nitrogen Removal in a  
847 Photosequencing Batch Reactor with an Algal-Nitrifying Bacterial Consortium  
848 and Anammox Granules, *Environ. Sci. Technol. Lett.* 3 (2016) 175–179.  
849 <https://doi.org/10.1021/acs.estlett.6b00034>.
- 850 [180] S.S. Shalini, K. Joseph, Start-up of the SHARON and ANAMMOX process in  
851 landfill bioreactors using aerobic and anaerobic ammonium oxidising biomass,  
852 *Bioresour. Technol.* 149 (2013) 474–485.  
853 <https://doi.org/10.1016/j.biortech.2013.09.104>.
- 854 [181] K. Egli, U. Fanger, P.J.J. Alvarez, H. Siegrist, J.R. Van der Meer, A.J.B.  
855 Zehnder, Enrichment and characterization of an anammox bacterium from a  
856 rotating biological contactor treating ammonium-rich leachate, *Arch. Microbiol.*  
857 175 (2001) 198–207. <https://doi.org/10.1007/s002030100255>.

- 858 [182] M. Henze, W. Guher, T. Mino, M.C.M. van Loosdrecht, Activated sludge models  
859 ASM1, ASM2, ASM2D and ASM3, *J. Chem. Inf. Model.* 53 (2008) 287.  
860 <https://doi.org/10.1017/CBO9781107415324.004>.
- 861 [183] D.J. Batstone, J. Keller, I. Angelidaki, S. V Kalyuzhnyi, S.G. Pavlostathis, A.  
862 Rozzi, W.T.M. Sanders, H. Siegrist, V.A. Vavilin, Industrial applications of the  
863 IWA anaerobic digestion model No. 1 (ADM1), *Water Sci. Technol.* 47 (2003)  
864 199–206. <https://doi.org/10.2166/wst.2003.0647>.
- 865 [184] M.C.M. Van Loosdrecht, C.M. Lopez-Vazquez, S.C.F. Meijer, C.M. Hooijmans,  
866 D. Brdjanovic, Twenty-five years of ASM1: Past, present and future of  
867 wastewater treatment modelling, *J. Hydroinformatics.* 17 (2015) 697–718.  
868 <https://doi.org/10.2166/hydro.2015.006>.
- 869 [185] D.J. Batstone, J. Keller, J.P. Steyer, A review of ADM1 extensions, applications,  
870 and analysis: 2002-2005, *Water Sci. Technol.* 54 (2006) 1–10.  
871 <https://doi.org/10.2166/wst.2006.520>.
- 872 [186] B.D. Shoener, S.M. Schramm, F. Béline, O. Bernard, B.G. Plósz, S. Snowling, J.  
873 Steyer, D. Wágner, J.S. Guest, Microalgae and cyanobacteria modeling in water  
874 resource recovery facilities: A critical review, *Water Res.* X. (2018) 100024.  
875 <https://doi.org/10.1016/j.wroa.2018.100024>.
- 876 [187] P.A. Vanrolleghem, C. Rosen, U. Zaher, J. Copp, L. Benedetti, E. Ayesa, U.  
877 Jeppsson, Continuity-based interfacing of models for wastewater systems  
878 described by Petersen matrices, *Water Sci. Technol.* 52 (2005) 493–500.  
879 <https://doi.org/10.2166/wst.2005.0558>.
- 880 [188] A. Solimeno, L. Parker, T. Lundquist, J. García, Integral microalgae-bacteria  
881 model ( BIO \_ ALGAE ): Application to wastewater high rate algal ponds, *Sci.*  
882 *Total Environ.* 601–602 (2017) 646–657.  
883 <https://doi.org/10.1016/j.scitotenv.2017.05.215>.
- 884 [189] P. Reichert, D. Borchardt, M. Henze, W. Rauch, P. Shanahan, L. Somlyódy, P.  
885 Vanrolleghem, River Water Quality Model no. 1 (RWQM1):, *Water Sci.*  
886 *Technol.* 43 (2001) 11–30. <https://doi.org/10.2166/wst.2001.0241>.
- 887 [190] G. Wolf, C. Picioreanu, M.C.M. van Loosdrecht, Kinetic modeling of  
888 phototrophic biofilms: The PHOBIA model, *Biotechnol. Bioeng.* 97(5) (2007)  
889 1064–1079.
- 890 [191] T. Gehring, J.D. Silva, O. Kehl, A.B. Castilhos Jr., R.H.R. Costa, F. Uhlenhut, J.  
891 Alex, H. Horn, M. Wichern, Modelling waste stabilisation ponds with an  
892 extended version of ASM3, *Water Sci. Technol.* 61 (2010) 713–720.  
893 <https://doi.org/10.2166/wst.2010.954>.
- 894 [192] N. Broekhuizen, J.B.K. Park, G.B. McBride, R.J. Craggs, Modification,  
895 calibration and verification of the IWA River Water Quality Model to simulate a  
896 pilot-scale high rate algal pond, *Water Res.* 46 (2012) 2911–2926.  
897 <https://doi.org/10.1016/j.watres.2012.03.011>.
- 898 [193] J.D. Muñoz Sierra, C. Picioreanu, M.C.M. Van Loosdrecht, Modeling  
899 phototrophic biofilms in a plug-flow reactor, *Water Sci. Technol.* 70 (2014)  
900 1261–1270. <https://doi.org/10.2166/wst.2014.368>.
- 901 [194] J. Zambrano, I. Krustok, E. Nehrenheim, B. Carlsson, A simple model for algae-  
902 bacteria interaction in photo-bioreactors, *Algal Res.* 19 (2016) 155–161.

- 903 <https://doi.org/10.1016/j.algal.2016.07.022>.
- 904 [195] L.T. Arashiro, A.M. Rada-Ariza, M. Wang, P. van der Steen, S.J. Ergas,  
905 Modelling shortcut nitrogen removal from wastewater using an algal bacterial  
906 consortium, (2017) 1–12. <https://doi.org/10.2166/wst.2016.561>.
- 907 [196] E.M. Grima, F.G. Camacho, J.A.S. Pérez, J.M.F. Sevilla, F.G.A. Fernández, A.C.  
908 Gómez, A mathematical model of microalgal growth in light-limited chemostat  
909 culture, *J. Chem. Technol. Biotechnol.* 61 (1994) 167–173.  
910 <https://doi.org/https://doi.org/10.1002/jctb.280610212>.
- 911 [197] S. Park, W. Bae, J. Chung, S.-C. Baek, Empirical model of the pH dependence of  
912 the maximum specific nitrification rate, *Process Biochem.* 42 (2007) 1671–1676.  
913 <https://doi.org/https://doi.org/10.1016/j.procbio.2007.09.010>.
- 914 [198] A. Packer, Y. Li, T. Andersen, Q. Hu, Y. Kuang, M. Sommerfeld, Growth and  
915 neutral lipid synthesis in green microalgae: A mathematical model, *Bioresour.*  
916 *Technol.* 102 (2011) 111–117.  
917 <https://doi.org/https://doi.org/10.1016/j.biortech.2010.06.029>.
- 918 [199] B. Palabhanvi, V. Kumar, M. Muthuraj, D. Das, Preferential utilization of  
919 intracellular nutrients supports microalgal growth under nutrient starvation:  
920 multi-nutrient mechanistic model and experimental validation., *Bioresour.*  
921 *Technol.* 173 (2014) 245–255.
- 922 [200] X. Bai, P. Lant, S. Pratt, The contribution of bacteria to algal growth by carbon  
923 cycling, *Biotechnol. Bioeng.* 112 (2015) 688–695.  
924 <https://doi.org/https://doi.org/10.1002/bit.25475>.
- 925 [201] R.L.L. Ribeiro, J.V.C. Vargas, A.B. Mariano, J.C. Ordonez, The experimental  
926 validation of a large-scale compact tubular microalgae photobioreactor model,  
927 *Int. J. Energy Res.* 41 (2017) 2221–2235.  
928 <https://doi.org/https://doi.org/10.1002/er.3784>.
- 929 [202] R. Rodríguez, J.J. Espada, J. Moreno, G. Vicente, L.F. Bautista, V. Morales, A.  
930 Sánchez-Bayo, J. Dufour, Environmental analysis of *Spirulina* cultivation and  
931 biogas production using experimental and simulation approach, *Renew. Energy.*  
932 129 (2017) 724–732. <https://doi.org/https://doi.org/10.1016/j.renene.2017.05.076>.
- 933 [203] V.O. Adesanya, M.P. Davey, S.A. Scott, A.G. Smith, Kinetic modelling of  
934 growth and storage molecule production in microalgae under mixotrophic and  
935 autotrophic conditions, *Bioresour. Technol.* 157 (2014) 293–304.  
936 <https://doi.org/https://doi.org/10.1016/j.biortech.2014.01.032>.
- 937 [204] G.M. Figueroa-Torres, J.K. Pittman, C. Theodoropoulos, Kinetic modelling of  
938 starch and lipid formation during mixotrophic, nutrient-limited microalgal  
939 growth, *Bioresour. Technol.* 241 (2017) 868–878.  
940 <https://doi.org/https://doi.org/10.1016/j.biortech.2017.05.177>.
- 941 [205] W. Gujer, *Systems analysis for water technology*, 2008.
- 942 [206] P. Foladori, S. Petrini, G. Andreottola, How suspended solids concentration  
943 affects nitrification rate in microalgal-bacterial photobioreactors without external  
944 aeration, *Heliyon.* 6 (2020) e03088.  
945 <https://doi.org/10.1016/j.heliyon.2019.e03088>.
- 946 [207] P. van der Steen, K. Rahsilawati, A.M. Rada-Ariza, C.M. Lopez-Vazquez, P.N.L.  
947 Lens, A new photo-activated sludge system for nitrification by an algal-bacterial



- 948 consortium in a photo-bioreactor with biomass recycle, (2015) 443–450.  
949 <https://doi.org/10.2166/wst.2015.205>.
- 950 [208] M. Gross, Z. Wen, Yearlong evaluation of performance and durability of a pilot-  
951 scale Revolving Algal Biofilm (RAB) cultivation system, *Bioresour. Technol.*  
952 171 (2014) 50–58. <https://doi.org/10.1016/j.biortech.2014.08.052>.
- 953 [209] M. Kesaano, R.C. Sims, Algal biofilm based technology for wastewater  
954 treatment, *Algal Res.* 5 (2014) 231–240.  
955 <https://doi.org/10.1016/j.algal.2014.02.003>.
- 956 [210] D. Hoh, S. Watson, E. Kan, Algal biofilm reactors for integrated wastewater  
957 treatment and biofuel production: A review, *Chem. Eng. J.* 287 (2016) 466–473.  
958 <https://doi.org/10.1016/j.cej.2015.11.062>.
- 959 [211] W. Blanken, M. Janssen, M. Cuaresma, Z. Libor, T. Bhaiji, R.H. Wijffels,  
960 Biofilm growth of *Chlorella sorokiniana* in a rotating biological contactor based  
961 photobioreactor, *Biotechnol. Bioeng.* 111 (2014) 2436–2445.  
962 <https://doi.org/10.1002/bit.25301>.
- 963 [212] L.B. Christenson, R.C. Sims, Rotating algal biofilm reactor and spool harvester  
964 for wastewater treatment with biofuels by-products, *Biotechnol. Bioeng.* 109  
965 (2012) 1674–1684. <https://doi.org/10.1002/bit.24451>.
- 966 [213] J. Shi, B. Podola, M. Melkonian, Application of a prototype-scale twin-layer  
967 photobioreactor for effective N and P removal from different process stages of  
968 municipal wastewater by immobilized microalgae, *Bioresour. Technol.* 154  
969 (2014) 260–266. <https://doi.org/10.1016/j.biortech.2013.11.100>.
- 970 [214] M. Morales, H. Bonnefond, O. Bernard, Rotating algal biofilm versus planktonic  
971 cultivation: LCA perspective, *J. Clean. Prod.* 257 (2020) 120547.  
972 <https://doi.org/10.1016/j.jclepro.2020.120547>.
- 973 [215] M. Gross, V. Mascarenhas, Z. Wen, Evaluating algal growth performance and  
974 water use efficiency of pilot-scale revolving algal biofilm (RAB) culture systems,  
975 *Biotechnol. Bioeng.* 112 (2015) 2040–2050. <https://doi.org/10.1002/bit.25618>.
- 976 [216] M. Gross, D. Jarboe, Z. Wen, Biofilm-based algal cultivation systems, *Appl.*  
977 *Microbiol. Biotechnol.* 99 (2015) 5781–5789. [https://doi.org/10.1007/s00253-](https://doi.org/10.1007/s00253-015-6736-5)  
978 [015-6736-5](https://doi.org/10.1007/s00253-015-6736-5).
- 979 [217] L.R. de Assis, M.L. Calijuri, E. de A. Do Couto, P.P. Assemany, Microalgal  
980 biomass production and nutrients removal from domestic sewage in a hybrid  
981 high-rate pond with biofilm reactor, *Ecol. Eng.* 106 (2017) 191–199.  
982 <https://doi.org/10.1016/j.ecoleng.2017.05.040>.
- 983 [218] L. Rodrigues de Assis, M.L. Calijuri, P.P. Assemany, T.A. Silva, J.S. Teixeira,  
984 Innovative hybrid system for wastewater treatment: High-rate algal ponds for  
985 effluent treatment and biofilm reactor for biomass production and harvesting, *J.*  
986 *Environ. Manage.* 274 (2020) 111183.  
987 <https://doi.org/10.1016/j.jenvman.2020.111183>.
- 988 [219] G. Quijano, J.S. Arcila, G. Buitrón, Microalgal-bacterial aggregates: Applications  
989 and perspectives for wastewater treatment, *Biotechnol. Adv.* 35 (2017) 772–781.  
990 <https://doi.org/10.1016/j.biotechadv.2017.07.003>.
- 991 [220] K. Milferstedt, W.C. Kuo-Dahab, C.S. Butler, J. Hamelin, A.S. Abouhend, K.  
992 Stauch-White, A. McNair, C. Watt, B.I. Carbajal-González, S. Dolan, C. Park,

993 The importance of filamentous cyanobacteria in the development of oxygenic  
994 photogranules, *Sci. Rep.* 7 (2017) 1–16. <https://doi.org/10.1038/s41598-017->  
995 16614-9.  
996  
997  
998  
999  
1000  
1001