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ALGAL BIOMASS AS A SOURCE OF RESOURCES FOR NUTRIENT RECOVERY IN WASTEWATER: A SYSTEMATIC REVIEW

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Abstract: This study presents an analysis of the scientific literature through a systematic review, regarding the application of microalgae to recover resources present in domestic wastewater, such as nitrogen and phosphorus. A bibliometric analysis and qualitative meta-synthesis of the data obtained in the systematic review were carried out, for which articles constructed with experimental data and published in the period from 2018 to 2023 provided in the Scopus^{TM} database were considered. To define co-occurrence trends, VoSviewer software was used, which showed the main terms addressed in the mapped scientific articles, which were: algae, biofilm, microalgae, nutrient recovery, nutrient removal, wastewater and wastewater treatment. Through the qualitative meta-synthesis, a final portfolio was carried out that provides a current overview of the subject matter of the study, allowing to identify gaps and point out areas in development for future research and challenges were identified regarding the recovery of nutrients in polishing ponds from algal biomass and economic viability for this type of treatment.

Keywords: Algal biomass, nutriente recovery, polishing ponds, wastewater.

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INTRODUCTION

The reuse of treated domestic sewage has become an effective measure for the problem of water scarcity (Sun et al., 2022). However, effluents from Effluent Treatment Stations (ETEs) may contain dissolved and recalcitrant organic matter, trace amounts of synthetic organic compounds and transformation products (Hu et al., 2016; Michael-Kordatou et al., 2015).

The presence of organic and inorganic compounds in wastewater, specifically in domestic sewage, adds large amounts of nutrients, such as nitrogen (N) and phosphorus (P), to water bodies, causing the phenomenon of eutrophication, disturbing aquatic ecosystems. Therefore, the application of microalgae to treat wastewater becomes an emerging approach (Singh et al., 2020).

Algae have high growth rates and productivity even under unfavorable conditions and accumulation of large amounts of fatty acids. In addition, they have the flexibility to survive in extreme environmental conditions, absorb N and P, and sustain the amount of dissolved oxygen to facilitate the removal of pathogens (Liu et al., 2020a; Das et al., 2019). Among the advantages of algae-based technologies are: high fixation of carbon dioxide (CO_2) and ecological and sustainable production of biomass (Shanmugam et al., 2020; Leng et al., 2020).

The post-treatment of wastewater in polishing ponds (LP) or algae ponds (LA) has gained prominence (Nagarajan et al., 2020), due to the activity carried out by microalgae that use CO2 and release oxygen, in addition to simultaneously absorbing nitrogen and phosphorus present in the effluent (Kesaano and Sims, 2014), converting them into bioresources (Zhuang et al., 2020), enabling sustainable development based on the concept of circular economy (Cheng et al., 2020; Su, 2021). In order to understand and explore technological advances in the area of wastewater treatment using polishing ponds and algae activity, the present study sought to compile information on the removal and recovery of nutrients from algal biomass, based on bibliometric analysis and metasynthesis considering articles who worked with experimental data published and indexed in the Scopus™ database, during the period from 2018 to 2023.

METHODOLOGY

The work is characterized as a qualitative research, as bibliometrics and metasynthesis were carried out for data analysis based on the theme "Recovery of nutrients from algal biomass". The research was carried out in May 2023, initially the keywords were defined: "algal biomass", "nutrient recovery", "polishing ponds" and then carried out a search in the literature of scientific articles with experimental data published in journals indexed and made available in the Scopus™ database from 2018 to 2023. For that, the countries that focus on this area of study were highlighted, the publication trends, the challenges in the area and the interpretative synthesis of the final portfolio that will serve as a contribution for future studies.

The bibliometric analysis was carried out with the aid of the VoSviewer software, which establishes interactions and co-occurrences from the main terms present in keywords extracted from articles published in the scientific literature. To explore the themes of greater importance in the investigated subject, the options "co-occurrence" and "keywords of the author" were selected in the VOSviewer software, identifying the keywords cited at least four times among the publications for better detailing of the results.

Then, filters were used to obtain the final portfolio. The first filter used was the exclusion of gray literature, characterized by printed or multi-copied documents, such as works published in congresses, book chapters, books, course conclusion works, dissertations and theses. Posteriorly, readings of the abstracts, objectives, methodology and conclusion were carried out, in order to verify which articles addressed the subject matter of this work, resulting in 16 articles for the final portfolio, according to data presented in Table 1.

RESULTS

The systematic review resulted in 52 scientific documents published in the time frame studied in different countries. The 10 countries that most published were China, United States of America, India, Brazil, Spain, Australia, Greece, Italy, South Korea and Iran (Figure 1). The biggest publication trend with these keywords occurred in the year 2020 with 14 articles published. It was noted that the three main subject areas published were Environmental Science, Chemical Engineering and Energy, highlighting the need for sustainable technologies in the recovery of resources such as nutrientes (nitrogen and phosphorus) and bioenergy from algal biomass, as well as understanding the mechanisms involved in the treatment through microalgae.

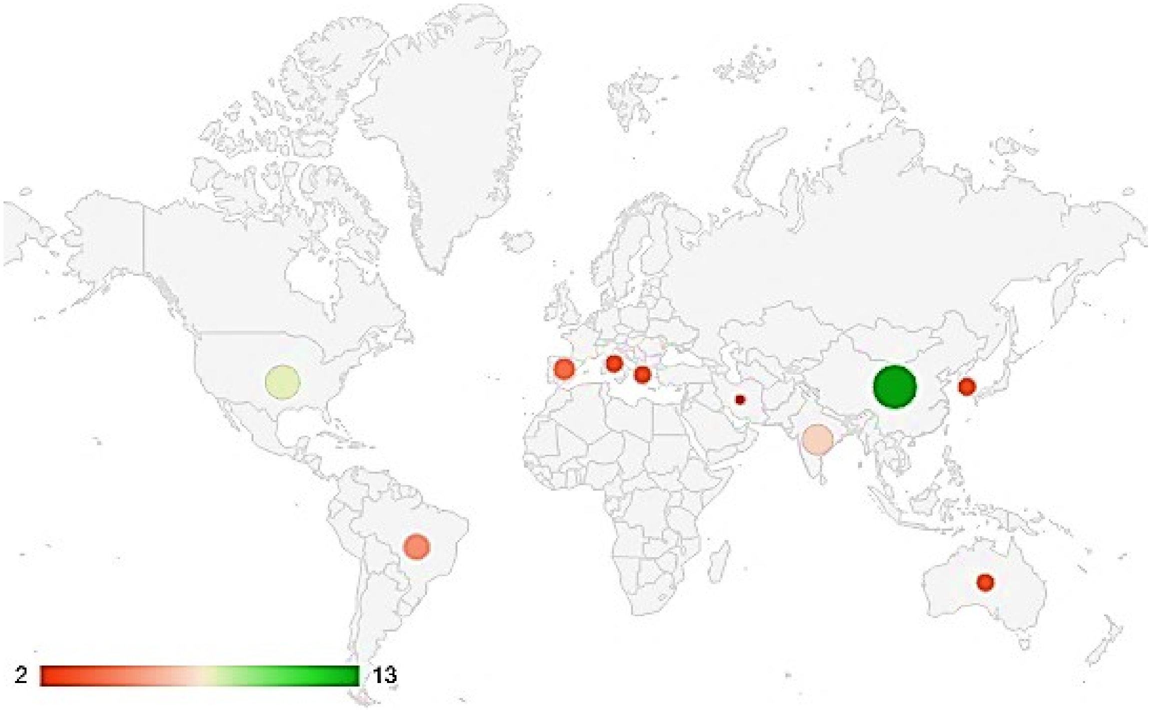

Figure 1. Distribution of publications in countries.

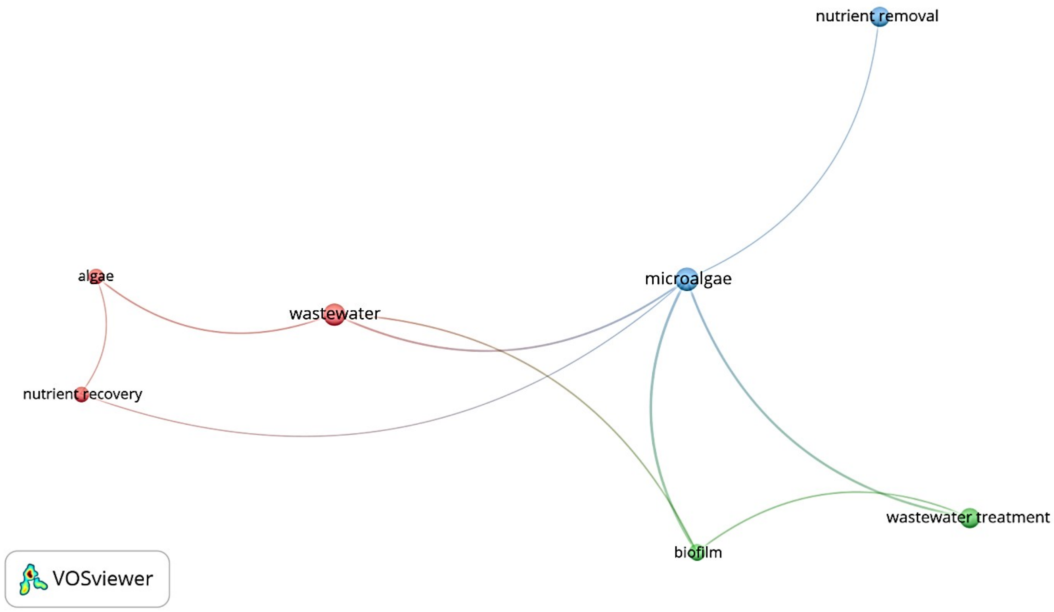

Figure 2. Network diagram of interaction and co-occurrence of terms.

Analyzing the keywords of the publications allows a perception of important information regarding the evolution of the subject studied, demonstrating the main lines of study in recent years or the analyzed period, allowing the verification of trends in lines of research and themes (Calazans et al ., 2015).

To create the interaction network shown in Figure 2, words that occurred at least four times were considered, so that eight keywords participated in the interaction network.

The association between the main terms occurs through the formation of clusters. The first blue-colored cluster has “microalgae” as its main theme and showed greater interaction with the themes “wastewater treatment”, “biofilm” and “nutrient removal”, indicating that algae are used more frequently in the treatment of wastewater to generate biomass and nutrient removal, however the term “nutrient removal” distanced itself from the others, evidencing the trends of publications on nutrient recovery, taking into account that the materials converted during wastewater treatment become bioresources.

In the second red cluster, there was a correlation between recovery of nutrients from algae in the treatment of wastewater, this theme, according to the timeline, received greater prominence than the other keywords, proving that the term recovery has gained emphasis on sanitation. The third cluster in green color presents the term “wastewater treatment” associated with “biofilm”, an expected reaction since publications tend to generate algal biomass that will be converted into a bioresource.

Thus, it can be seen in Figure 2 that the application of microalgae in wastewater treatment has gained prominence, as these microorganisms have the potential to reduce pollutants while producing valuable biomass that can be converted into bioenergy (Silveira et al. ., 2021). Microalgae use nutrients as growth promoters and provide other secondary advantages such as CO_2 capture for photosynthesis, energy savings, biofertilization and source of renewable raw materials (Du et al., 2018; Eze et al., 2018).

Some challenges still need to be overcome in wastewater treatment through the cultivation of microalgae, among which the following stand out: (1) creating an adequate relationship between microalgae and bacteria; (2) promote the removal of COD, as the occurrence of microalgae can increase the concentration of organic carbon through the excretion of extracellular polymeric substances (EPS) (Gouveia et al., 2016); (3) increase the C/N ratio to promote nutrient removal and recovery (Zhuang et al., 2016; Makut et al., 2019).

Guiding parameters were defined to detail in a deep and structured way the content of the articles in the final portfolio, provoking comparisons between them. Therefore, the parameter to be investigated in the metasynthesis refers to verifying whether the publications belonging to the final portfolio presented removals or recoveries of nutrients related to algal biomass. Table 1 shows data from the final bibliographic portfolio.

Table 1. Final bibliographic portfolio.

Type of Reactor	Objective of Work	Reference
Revolving Algal Biofilm (RAB)	Evaluate RAB system nutrient removal (N and P) and algal biomass production in a variety of wastewater streams.	Zhao *et al.* (2018)
Polishing Ponds (LP)	Analyze the removal of nutrients from wastewater in polishing lagoons, as well as the fixation of algal biomass on different support surfaces, the lagoons contained vertically oriented geotextiles, cotton fabrics and polyethylene sheets to facilitate the development of algal biofilm.	Orfanos and Manariotis (2019)
High-rate algal ponds and Photobioreactors	Evaluate the specific effect of solid retention time (SRT) on mixed community phototrophic structures and nutrient recovery in suspended growth systems.	Bradley *et al.* (2019)
Forward Osmosis	Concentrate and recover municipal wastewater resources with a direct osmosis system.	Rood *et al.* (2020)
Anaerobic Lagoon	Isolate and characterize a new strain of extremophile microalgae with high ammonia tolerance. Also tested in this study was the mixotrophic cultivation method with wastewater treatment to reuse nutrients from dairy effluent for the production of algal biomass and bioproducts.	Pang *et al.* (2020)
Sedimentator followed by algae membrane photobioreactor	Design sedimenter followed by membrane photobioreactor system and operate under low SRT for high yield biomass production and in situ biomass harvesting.	Parakh et al. (2020)
Photobioreactors (PBR)	Test a biofilm system for microalgae production with anaerobic effluent diluted in seawater, explore the effect of phytohormones on microalgae during cultivation and understand the mechanisms involved.	Yu *et al.* (2020)
Photobioreactors (PBR)	Investigate the influence of CO_2 supplementation on the removal and recovery of nutrients by microalgae, specifically *Tetradesmus obliquus.*	Ma *et al.* (2020)
Photobioreactors (PBR)	To evaluate the ability of *Chlorella sorokiniana* in the treatment with microalgae to remove phosphorus and nitrogen from anaerobically digested effluent without the addition of CO_2.	Slompo *et al.* (2020)

Algal-activated sludge	Understand the role of SRT in the performance of algae-activated sludge reactors in carbon and nutrient removal and study the production and composition of lipids and FAME (fatty acid methyl esters) obtained from algal biomass during treatment.	Katam and Bhattacharyya (2020)
Aerated lagoon	Evaluate the performance and maintenance of five ponds operated at different hydraulic retention time (HRT), using swine effluent and microalgae as a culture medium. Possible routes for valuing the by-products generated in the swine production chain and in the circular economy were also pointed out.	Silveira *et al.* (2021)
Polishing pond followed by wetlands (LP-CW)	Operate an LP-CW system, use part of the biomass harvested from the LP as an additional source of carbon for CWs, analyze its influence on material flow and nutrient recovery, determine the ideal location and amount of microalgae to be added to the CWS.	Li *et al.* (2022)
Membrane photobioreactor (MPBRs)	Investigate the potential and stability of antibiotic and nutrient removal in the membrane photobioreactor, understand the mechanisms of antibiotic removal, and explore the kinetics of antibiotic removal in a continuous flow system and then simulate the data using the computational fluid dynamic (CFD) method.	Kiki *et al.* (2022)
Glass fiber filters	Use a strain of *Chlorella vulgaris* for low-resistance microalgae-based effluent polishing and biomass production.	Wang *et al.* (2022)
High-rate algal ponds (HRAPs)	Identify the effects of the presence of Cu in the cultivation of microalgae considering the interferences in the removal of nutrients, identify the mechanisms that act in the removal of Cu, and evaluate changes in the biomass composition and production according to Cu concentrations.	de Sousa Oliveira *et al.* (2023)
Photobioreactors (PBR)	Investigate microalgae-bacteria development in a PBR under various operating conditions for municipal wastewater treatment.	Zhang *et al.* (2023)

Microalgae can be harnessed in a wide variety of processes and reactor configurations, such as continuous high flow rate ponds (HRAPs) (Park et al., 2011) and photobioreactors PBRs (Viruela et al., 2016). Analyzing the data in Table 1, a greater application of the photobioreactor in the treatment of effluents with microalgae cultivation is identified, and this is mainly due to the ease of controlling factors such as intensity and quality of light, which is essential for the photosynthesis process. In addition to these parameters, other factors influence the growth and cultivation of microalgae, such as gas diffusion, temperature, nutrients, substrate, extracellular polymeric substances (EPS) and interactions between species (Schnurr and Allen 2015; Voloshin et al., 2016).

The region's climate directly influences the type of reactor to be used due to the need for solar radiation or artificial lighting, therefore, aerated or high-rate polishing ponds are usually applied in regions with a hot or tropical climate, due to their settings (open system). Ponds generally operate without distinction between hydraulic retention time (HRT) and solid retention time (SRT). It should be noted that HRT is an essential operational parameter, as it controls nutrient load, sludge age, biomass productivity and its biochemical composition (De Sousa Oliveira et al., 2023).

It was observed that the main objective of the articles in the final portfolio was nutrient removal and algal biomass production. However, Ma et al. (2020), carried out the N and P balance obtaining recovery efficiencies of 84% and 90%, respectively, in a photobioreactor with Tetradesmus obliquus cultivation, the authors concluded that with CO_2 supplementation to microalgae they could promote nitrogen assimilation and reduce its loss in the form of ammonia gas (N-NH_3). However, for settings such as polishing ponds or algae ponds, the effect of CO_2 supplementation will not be relevant due to the large light path.

Kiki et al.(2022) monitored a membrane photobioreactor with the cultivation of *Scenedesmus quadricauda* treating synthetic effluent and achieved efficiencies of up to 100% phosphorus removal with 12 hours HRT, in addition to showing greater algal biomass growth compared to other species analyzed, such as *Haematococcus pluvialis*, *Selenastrum capricornutum* and *Chlorella vulgaris*. The species *Scenedesmus quadricauda* is characterized by the rapid capacity for mixotrophic/heterotrophic growth under moderate input of light nutrients (Leite et al., 2016). The other articles that used photobioreactors showed N and P removal efficiencies ranging between 60 and 90%.

Orfanos and Manariotis (2019), used polishing ponds with *Chlorococcum sp.* for nutrient removal and biofilm production, achieving removal efficiencies of 99% of nitrate (N-NO_3^-) and 97% of P, artificial lighting was provided using 36 W fluorescent lamps. De Sousa Oliveira et al. (2023), achieved efficiencies of up to 100% of removal of ammoniacal nitrogen (N-NH4+)

and 72% of P, operating high rate ponds with swine effluent and cultivation of *Chlorella sp.* with solar radiation as a light source. It was also observed that the addition of copper (Cu) affects the removal of $N\text{-}NH_4^+$, but increases the assimilation of P by the microalgae.

Similar $N\text{-}NH_4^+$ removal efficiencies were found by Silveira et al. (2021) using aerated ponds with natural lighting, however the research did not reach significant P removal values, with percentages close to 20%, which may be related to the HRT used, since with low indices, the tendency is that the P load applied nutrients increase resulting in system overload, compromising P assimilation (Sutherland et al., 2020).

One of the difficulties encountered in this systematic review and qualitative meta-synthesis was finding articles with specific results of removal or recovery of $N\text{-}NH_4^+$, as the studies presented different forms of nitrogenous species, making, for example, a meta-analysis of the results of the final portfolio unfeasible. , moreover, even specifying in the keywords "polishing ponds" the final result shows the need for research carried out in this type of reactor, in addition to improving the balance of nitrogenous species for nutrient recovery, since in biological systems it is essential to removal of N by assimilation of algal biomass, avoiding the loss of $N\text{-}NH_3$ to the atmosphere (De Sousa Oliveira et al., 2023), for which it is necessary to control the pH in the medium.

A trend was observed in the final portfolio, between the years 2020 to 2023, of studies using synthetic effluent, this is due to the ease of controlling the chemical species present, however studies are needed that use real effluent to facilitate its application in the market. Pig farming effluent also appears in the final portfolio between these years, due to the need to treat different types of effluents, especially from slaughterhouses and pig farming, which cannot be released directly into water bodies. The swine effluent has a high content of nutrients, organic matter and metals such as Cu (Cheng et al., 2019) and the treatment of this type of effluent is crucial.

Among the microalgae species studied by the authors of the final portfolio are *Chlorococcum sp., Chlorella sp., Pseudanabaena sp., Chlamydomonas sp., Acutodesmus sp., Ankistrodesmus falcatus, Graesiella emersonii, Scenedesmus obliquus, Tetradesmus obliquus, Haematococcus pluvialis, Selenastrum capricornutum, Scenedesmus quadricauda, Chlorella sorokiniana* and *Chlorella vulgaris*. *Chlorella sp.* appears more frequently in the works, being associated with other species such as *Scenedesmus sp.* the cultivation of both microalgae results in the removal of nitrogen and phosphorus, with percentages greater than 70% (Cheng et al., 2019; Li et al., 2020a, 2020b). Species of the genera *Chlorella* and *Scenedesmus* are often used in effluent treatment due to their high tolerance to changes and high potential for accumulation of biomass and lipids (Wang et al., 2016).

The presence of bacteria in wastewater can favor the growth of microalgae and the production of valuable compounds through complex mechanisms and nutrient exchange (Fuentes et al., 2016; Toyama et al., 2018). Xue et al. (2018) observed an increase in algal biomass and quality of biodiesel produced from biomass, in an associated cultivation system between microalgae-bacteria. The reason may be associated with what bacteria can provide, such as inorganic nutrients and metabolic compounds, which promote microalgae growth (Jia and Yuan, 2016).

However, it was observed in the final portfolio that the authors did not adequately specify the mechanisms involved in microalgae activity, only identifying the genus or species used, highlighting the need for in-depth studies on this topic, as well as analysis of the economic viability of the application of microalgae in wastewater treatment for biomass production and resource recovery, such as nutrients and bioenergy in the form of biogas and biodiesel.

De Sousa Oliveira et al. (2023) carried out economic considerations related to the recovery of nutrients from algal biomass and concluded that P removals have positive impacts related to the reduction of the polluting potential in the environment, however, the recovered concentrations are insignificant in economic terms. Phosphorus recovery can show greater economic viability when associated with other materials such as struvite and coal (Sánchez, 2020; Maroušek and Gavurová, 2022).

Maroušek et al. (2022) highlighted that obtaining bioenergy from algal biomass presents considerable economic challenges. Emphasizing that the large-scale production of microalgae-based products must be an industrial process in which product quality and economic viability are guaranteed (Vazquez-Romero et al., 2022).

CONCLUSIONS

The recovery of resources from algal biomass proves to be a promising topic in the technical-scientific field, but it needs to overcome limitations and improve the mechanisms for recovering these resources, such as nutrients, and carefully analyze the economic viability. Bibliometric analysis and metasynthesis provided relevant data on the types of reactors with microalgae cultivation most used in the world for the treatment of wastewater aiming recovery and removal of nutrients. Thus, showing that polishing ponds need to be better studied and discussed as an alternative to recover these resources in a sustainable way and achieve viable economic prospects, providing resources with added value to the market.

Among the challenges to be overcome for the application of polishing ponds in the recovery of nutrients is the loss of N-NH_3 to the atmosphere, it is known that microalgae raise the pH of the effluent through the photosynthesis process that favors the precipitation of P, in the However, other P removal mechanisms must be addressed so that the conversion of the ammonium ion to ammonia gas does not occur due to the increase in pH, so that assimilation by microalgae occurs.

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