Microalgae cultivation in wastewater from agricultural industries to benefit next generation of bioremediation: a bibliometric analysis

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Abstract
The aim of this study was to provide a bibliometric analysis and mapping of existing scientific papers, focusing on microalgae cultivation coupled with biomass production and bioremediation of wastewater from agricultural industries, including cassava, dairy, and coffee. Using the Web of Science (WoS) database for the period 1996–2021, a search was performed using a keyword strategy, aiming at segregating the papers in groups. For the first search step, the keywords “wastewater treatment”, AND “microalgae”, AND “cassava” OR “dairy” OR “coffee” were used, resulting in 59 papers. For the second step, the keywords “wastewater treatment” AND “biomass productivity” AND “microalgae” AND “economic viability” OR “environmental impacts” were used, which resulted in 34 articles. In these papers, keywords such as “carbon dioxide biofixation” and “removal of nutrients by the production of biomass by microalgae” followed by “environmental and economic impacts” were highlighted. Some of these papers presented an analysis of the economic feasibility of the process, which reveal the state-of-the-art setup required to make the cultivation of microalgae economically viable. Researches focusing on the efficiency of microalgae biomass harvesting are needed to improve the integration of microalgae production in industrial eco-parks using wastewater to achieve the global goal of bioremediation and clean alternatives for renewable energy generation.

Keywords Algae · Effluent · Environmental impact · Coffee industry · Cassava industry · Dairy industry

Abbreviations
WoS Web of Sciences
COD Chemical oxygen demand
LCA Life cycle assessment
GGE Greenhouse gas emissions

Introduction
Microalgae are photosynthetic microorganisms capable of growing in industrial effluents, producing a biomass rich in oils and carbohydrates, which are the raw materials for generating clean energy and biofertilizers; they contribute to the bioremediation process simultaneously (Andrade et al. 2021; Woertz et al. 2009). Wastewater can be used to grow microalgae in the chain production process as a sustainable water source and as a medium rich in nutrients, containing organic carbon source for the heterotrophic and mixotrophic groups (Andrade et al. 2020; Lowrey et al. 2015). For instance, the *Scenedesmus obliquus* cultivated in municipal wastewater achieved higher lipid and carbohydrate than those grown in synthetic medium (Ansari et al. 2019). For palm oil mill wastewater treatment, Emparan et al. (2020) indicated *Nannochloropsis* sp. as an option to produce microalgal biomass simultaneously.
Our study analyzed articles that focused on the cultivation of microalgae in wastewater from three types of agro-industrial companies that processed soluble coffee, cassava, and dairy products. Coffee is one of the most consumed beverages in the world (Mussatto et al. 2011); the industrial processing of coffee beans generates enormous amounts of wastewater having high contents of organic matter, known to induce severe environmental risks (Panchangam and Janakiraman 2015). Wastewater from cassava (Manihot esculenta Crantz) contains a higher concentration of organic and inorganic chemicals, such as carbohydrates, ammonia, calcium, chloride, inorganic phosphate, magnesium, nitrate, organic carbon, organic phosphorus, potassium, sodium, and sulfate (Selvan et al. 2019). Wastewater from the dairy industry has been described as an excellent source of nutrients for microalgae growth (Gonçalves et al. 2017). The cultivation of microalgae in dairy effluents (which is rich in C:N:P) replaces the culture medium containing mineral nutrients and fresh water generally used for microalgae cultivation, thereby reducing the cost of production (Kumar et al. 2020). According to Valizadeh and Davaran (2020), biological purification of dairy effluents is an efficient and essential approach that leads to a healthy and clean environmental ecosystem.

According to the search terms, textual mining scanning is important in identifying scientific publications and still allows mapping of scientific development, in addition to showing the growing interest in the topic addressed. In our study, bibliometric mapping was applied to verify the main topics discussed in the existing literature and investigate the associations among the most cited words, such as the association of “bioremediation of agro-industrial effluents” with “microalgae cultivation” along with understanding the economic and environmental viability of these projects. Bibliometric studies have re-explored the research in microalgae on a global scale (Garrido-Cardenas et al. 2018), with a focus on microalgae bioproducts (de Souza et al. 2019), highlighting the microalgae biomass market and their products (Rumin et al. 2020), microalgae-derived biodiesel (Ma et al. 2018), microalgae wastewater bioremediation (Pacheco et al. 2020) and algal species, products, and pretreatment techniques used for extraction (de Carvalho et al. 2020).

In this framework, our study aimed to perform a temporal analysis of articles focused on the cultivation of microalgae coupled with the bioremediation of wastewater from cassava, dairy, and coffee industries to identify specific and relevant publications in the literature using specific terms and examining their connections with different countries and the most cited articles.

Methodology

For bibliometric analysis, it was applied the procedures described by Cobo et al. (2011) as follows: (i) detect the topics treated by research fields, (ii) search by keywords in the literature/data collection, (iii) quality/preprocessing evaluation, (iv) visualize themes and thematic links, (v) visualize the different map elements (clusters) and network, (vi) synthesis and data analysis, and (vii) interpretation of the results. Bibliometric analysis was performed in the main collection of WoS of the Thomson Reuters Institute of Scientific Information (ISI), from January 1996 to September, 2021, using two steps. For the first step, the keywords “wastewater treatment” AND “microalgae” AND “cassava” OR “dairy” OR “coffee” were used (Fig. 1). For the second step, we consider the following keywords: “wastewater treatment”, AND “microalgae”, AND “economic viability” OR “environmental impacts”, in addition to the same set of research included for the term “biomass productivity”, being, therefore, “wastewater treatment”, AND “biomass productivity”, AND “microalgae”, AND “economic viability” OR “environmental impacts” (Fig. 2).

Based on the keywords, after applying the exclusion criteria for duplication and review papers, 59 and 34 papers were selected from the first and second steps (Tables 1 and 2), respectively, and used for cluster analyses. Based on the text data from the previously exported from WoS database, the VOSviewer 1.6.13 software was used for cluster analyses. Two word-clouds were generated by the keyword-terms (previous described) and by “complete record” and “cited references,” and the binary count used was based on the term minimum occurrence (Figs. 1 and 2).

Results and discussion

Microalgae biomass using wastewater

The clusters obtained in the first step showed significant clustering matching to microalgae bioremediation of dairy, cassava, and coffee wastewater themes. The main link among the clusters is due to the term “microalgae” and “growth.” The keywords of the articles were as follows: (i) dairy wastewater related to the removal of nutrients and associated with C. vulgaris, biomass production (red and blue cluster); and (ii) wastewater associated with nutrient removal and biodiesel production (green and yellow clusters) (Fig. 1). Understanding the connections among the groups is important because they refer to the use of microalgae for the bioremediation of agro-industrial effluents.
A large part of the studies on bioremediation of wastewater from agroindustry associated with the cultivation of microalgae shows that dairy is the most researched using microalgae species of the genus *Chlorella* and followed by species of *Scenedesmus* (Table 3). It is noteworthy that the main results of these studies are to produce microalgae biomass, aiming at removing nutrients from effluents, highlighting the production of bioenergy and carbon dioxide fixation. Cyanobacteria are also used for growth in agro-industrial wastewater, highlighting the species of *Arthrospira platensis, pseudoanabaena*, among others, which have been used to produce co-products of biomass and enzymes (Table 3).

Studies that used microalgae for dairy wastewater treatment aimed to develop a technology to produce raw materials for low-cost biodiesel production. For instance, Woertz...
et al. (2009) investigated the lipid productivity and the removal of nutrients by green microalgae cultivated in dairy wastewater, which was supplemented by CO₂ due to carbon limitation that accelerated microalgae growth. In addition, Johnson and Wen (2010) cultivated *Chlorella* sp. in dairy wastewater using foam to perform cell fixation, which resulted in better biomass and fatty acid yield. Additionally, Kothari et al. (2012) used *C. pyrenoidosa* in two stages: in the first stage, the wastewater quality parameters were evaluated, and nutrient removal was assessed for nitrogen and phosphorus; in the second stage, high oil and fat production was verified. Labbé et al. (2017) reported that *Chlorella* sp. and *Scenedesmus* sp. were capable of growing in different dairy farm effluents, showing that there is potential in using microalgae growth for treating these effluents and improving the finances of small and medium dairy farms.

There are few publications on the cultivation of microalgae in cassava wastewater (“manipueira”), aiming at the treatment of this effluent through algal biomass production. Yang et al. (2008) used cassava powder as a raw material for *C. pyrenoidosa* cultivation in undiluted wastewater from ethanol fermentation to generate biomass, regulate the pH, and reduce the chemical oxygen demand (COD). However, the focus of some related studies on cassava is on organic carbon supplementation in the microalgae culture medium to increase biomass production. The use of this organic carbon source is justified by the reduction in costs, in addition to increasing biomass production and lipid accumulation (Wei et al. 2009).

Publications address the use of microalgae in the industrial process of manufacturing cassava, aiming at the improvement, simplification, and optimization of production

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**Table 1** Summary of the geographical distribution of country affiliations of publications and the number of citations related to the following terms of the research 1: “wastewater treatment”, AND “microalgae”, AND “cassava”, OR “dairy” OR “coffee” in the WoS database, from January 1, 1996, to September, 2021

| N°  | Reference               | Citation | Country   | N°  | Reference               | Citation | Country   |
|-----|------------------------|----------|-----------|-----|------------------------|----------|-----------|
| 1   | Audu et al. (2021)     | 00       | USA       | 31  | Ferreira et al. (2018) | 33       | Portugal  |
| 2   | Bolognesi et al. (2021)| 03       | Italy     | 32  | Hena et al. (2018)     | 37       | Australia |
| 3   | Gumbi et al. (2021)    | 01       | South Africa | 33 | Hülsen et al. (2018)  | 60       | Australia |
| 4   | Khalaji et al. (2021)  | 01       | Iran      | 34  | Tsolcha et al. (2018)  | 13       | Greece    |
| 5   | Pishbin et al. (2021)  | 00       | Iran      | 35  | Dębowksi et al. (2017) | 18       | Poland    |
| 6   | Samiotis et al. (2021) | 00       | Greece    | 36  | Labbé et al. (2017)    | 16       | Spain     |
| 7   | Tsolcha et al. (2021)  | 01       | Greece    | 37  | Zamanpour et al. (2017)| 34       | Iran      |
| 8   | Zapata et al. (2021)   | 00       | Colombia  | 38  | Chang et al. (2016)    | 31       | China     |
| 9   | Zkeri et al. (2021)    | 03       | Greece    | 39  | Choi (2016)            | 24       | South Korea |
| 10  | Ahmad et al. (2020)    | 07       | India     | 40  | Qin et al. (2016)      | 53       | China     |
| 11  | Asadi et al. (2020)    | 05       | Iran      | 41  | Calicioglu and Demirer (2015) | 06 | USA       |
| 12  | Barsanti et al. (2021) | 01       | Italy     | 42  | Hena et al. (2015)     | 22       | Malaysia  |
| 13  | Chawla et al. (2020)   | 11       | India     | 43  | Gentili (2014)         | 75       | Sweden    |
| 14  | Feng et al. (2020)     | 02       | China     | 44  | Posadas et al. (2014)  | 48       | Spain     |
| 15  | Handayani et al. (2020)| 00       | Indonesia | 45  | Tricolicci et al. (2014a) | 09 | Romania |
| 16  | Katam and Bhattacharryya (2020) | 00 | India | 46  | Tricolicci et al. (2014b) | 24 | Romania |
| 17  | Lorentz et al. (2020)  | 02       | Brazil    | 47  | Uggetti et al. (2014)  | 160      | France    |
| 18  | Oubssassi et al. (2020)| 01       | Morocco   | 48  | Jermigan et al. (2013) | 17       | USA       |
| 19  | Pang et al. (2020)     | 01       | China     | 49  | Zhu et al. (2013)      | 92       | China     |
| 20  | Valizadeh and Davarpanah (2020) | 20 | Iran | 50  | Christenson and Sims (2012) | 197 | USA       |
| 21  | Asadi et al. (2019)    | 16       | Iran      | 51  | Kothari et al. (2012)  | 111      | India     |
| 22  | Beigbeder et al. (2019)| 06       | Canada    | 52  | Zhang et al (2012)     | 113      | China     |
| 23  | Daneshvar et al. (2019)| 55       | Finland   | 53  | Cho et al. (2011)      | 207      | South Korea |
| 24  | Hadiyanto et al. (2019)| 06       | Indonesia | 54  | Levine et al. (2011)  | 114      | USA       |
| 25  | Hemalatha et al. (2019)| 32       | India     | 55  | Johnson and Wen (2010) | 231      | USA       |
| 26  | Ling et al. (2019)     | 20       | China     | 56  | Woertz et al., (2009)  | 385      | USA       |
| 27  | Makut et al. (2019)    | 23       | India     | 57  | Bernal et al. (2008)   | 26       | Mexico    |
| 28  | Zhu et al. (2019)      | 16       | China     | 58  | González et al. (1997) | 267      | Mexico    |
| 29  | Ahmad et al. (2018)    | 18       | India     | 59  | Lincoln et al. (1996)  | 64       | USA       |
| 30  | Daneshvar et al. (2018)| 51       | Finland   |     |                        |          |           |
steps; for example, a study implements the simultaneous saccharification of cassava starch (using enzymes) and fermentation (using *C. protothecoides*) to avoid hydrolysis in several stages of the process (Lu et al. 2010). Another study reported that when *C. vulgaris* was grown mixotrophically in hydrolyzed cassava waste powder, the protein content and protein productivity of the biomass increased (Abreu et al. 2012). A study by Romaidi et al. (2018) using *Scenedesmus* sp., which was cultured to enhance the lipid production and nutrient removal from tapioca wastewater, showed the high potential of using microalgae to produce raw material for bioenergy and wastewater bioremediation.

When using different sources of organic carbon in microalgae heterotrophic growth, the C/N ratio of wastewater should be carefully examined to gather valuable information on how to optimize and control the performance of cultivation systems. The C/N ratio of cassava starch appears to be a significant factor affecting the metabolism performance of cyanobacterium *Aphanthece microscopica Nägeli* (Santos et al. 2017). The feasibility of increasing bioenergy production by fermentation of non-detoxified cassava bagasse hydrolysate as an alternative carbon source for microalgae biomass production was highlighted by Lu et al. (2010) using *C. protothecoides* and by Liu et al. (2018) with a consortium of *C. pyrenoidosa* and red yeast *Rhodotorula glutinis*.

Using different residues, Sun et al. (2019) showed that the addition of *C. pyrenoidosa* biomass to rice residue and in thermo-chemical hydrolysis and biological acidification processes enhanced gaseous biofuel production during the anaerobic digestion of the raw material mixture in a short time.

Among the publications that address microalgae growing in coffee wastewater, a study by Posadas et al. (2014) was identified that evaluated a consortium of microalgae (*Phormidium*, *Oocystis*, and *Microspora*) and bacteria from activated sludge in five distinct fresh effluents from different agro-industries, one of them being from a lyophilized-coffee manufacturing factory. The authors detected low biodegradability, but found interesting results for nutrient recovery and microbial biomass generation.

**Economic and environmental analyses associated with microalgae cultivation**

The clusters obtained in the second search show the different approaches identified by the keywords related to terms such as “economic viability” and “environmental impacts.” Three groups were identified: (i) red cluster: microalgae cultivation for biomass and oil productivity, and techno-economic analysis, (ii) green cluster: microalgae for energy production, and clean and renewable energy sources; (iii) blue cluster: biodiesel production from biomass generated through microalgae cultivation (Fig. 2).

The integration of microalgae cultivation using the treatment of agro-industrial wastewater in the production of biofuels is a promising solution. The main link among the clusters is due to the term’s “growth” and “biodiesel production”. In addition to microalgae cultivation, the growth term

| N° | Reference | Citation | Country  | N° | Reference | Citation | Country |
|----|-----------|----------|----------|----|-----------|----------|----------|
| 1  | Marangon et al. (2021) | 03 Brazil  | 18    | Ge et al. (Ge et al. 2018) | 62 Canada  |
| 2  | Rebello et al. (2021) | 01 Brazil  | 19    | Khiewwijit et al. (2018) | 09 Netherlands  |
| 3  | Silveira et al. (2021) | 01 Brazil  | 20    | Juneja and Murthy (2017) | 22 USA  |
| 4  | Singh and Patidar (2021) | 02 India  | 21    | Roostaei and Zhang (2017) | 36 USA  |
| 5  | Thielemann et al. (2021) | 02 Germany  | 22    | Silveira et al. (2017) | 18 Brazil  |
| 6  | Tua et al. (2021) | 03 Italy  | 23    | Colloita et al (2016) | 11 Italy  |
| 7  | Ummalyma et al. (2021) | 04 India  | 24    | Lee et al (2015) | 03 Canada  |
| 8  | Couto et al. (2020) | 11 Brazil  | 25    | Miranda et al. (2015) | 22 Australia  |
| 9  | Ruiz-Marin et al. (2020) | 03 Mexico  | 26    | Muradov et al. (2015) | 104 Australia  |
| 10 | Tavakoli and Barkdell (2020) | 04 USA  | 27    | Roberts et al. (2015) | 20 USA  |
| 11 | Yadav et al. (2020) | 02 India  | 28    | Fortier et al. (2014) | 121 USA  |
| 12 | Al Ketife et al. (2019) | 19 Qatar  | 29    | Mu et al. (2014) | 66 USA  |
| 13 | Chan (2019) | 01 China  | 30    | Steele et al. (2014) | 13 USA  |
| 14 | Cruce and Quinn (2019) | 27 USA  | 31    | Udom et al. (2013) | 111 USA  |
| 15 | Hess et al. (2019) | 03 USA  | 32    | Demirbas (2011) | 67 Turkey  |
| 16 | Pacheco et al. (2019) | 02 Brazil  | 33    | Levine et al. (2011) | 124 USA  |
| 17 | Arashiro et al. (2018) | 77 Spain  | 34    | Clarens et al. (2010) | 760 USA  |
### Table 3  Summary of some published studies using wastewater, microalgae species, and main products and results

| Wastewaters                  | Microalgae                                                                 | Outcome                                                                 | Ref                                                                 |
|------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------|
| Dairy                        | Chlorella protothecoides, *Tetraselmus obliquus*, *Rhizoclonium sp.*,      | Biomass, bio-oil, lipid, plant biostimulants, β-galactosidase, chemical | Viegas et al. (2021); Audu et al. (2021); Khalaji et al. (2021);     |
|                              | *Stigemonium sp.*, *Cladophora sp.*, *Gomphonema sp.*, *Oscillatoria sp.*, | oxigen demand, nutrient removal, biofuel, phytohormones               | Pishbin et al. (2021); Samiotis et al. (2021); Zapata et al. (2021); |
|                              | *C. vulgaris*, *Synechococcus elongatus*, *Spirulina (Arthrospira) plat-  |                                                                         | Zkeri et al. (2021); Barsanti et al. (2021); Santos et al. (2021);   |
|                              | ensis*; Euglena gracilis WZSL mutant; *C. sorokiniana* (2); *C. pyrenoidosa*;|                                                                         | Ahmad et al. (2020); Asadi et al. (2020); Feng et al. (2020);        |
|                              | *Scenedesmus*, *Pseudanabaena galeata*, *Scenedesmus dimorphus*, *C. polypynoideum*, *C. sorokiniana*, *C. protothecoides*; *S. obliquus* |                                                                         | Handayani et al. (2020); Lorentz et al. (2020); Ouhassi et al. (2020); |
| Dairy and fish               | *Chroococcus* sp., *Haematococcus pluvialis*, *Dunaliella sp.*, *Coelastrae saipanensis*, *Chlorella* sp. | Carbohydrates, protein, lipid, Carotenoids | Vidya et al. (2021) |
| Dairy and poultry            | Chlorella sp.                                                               | Lipid, protein and carbohydrates                                       | Gumbi et al. (2021) |
| Dairy and winery             | Leptolyngbya sp.                                                            | Biomass, bioethanol                                                     | Tsolcha et al. (2021) |
| Slaughterhouse, municipal and dairy | *C. vulgaris*, *C. minutissima*, *C. pyrenoidosa*, *Chroococcus sp.*, *Spirulina* sp. | Biomass and nutrient removal                                           | Chawla et al. (2020) |
| Tapioca and cassava ethanol  | *S. platensis*, *C. pyrenoidosa*                                            | Bioelectricity and biomass                                             | Hadiyanto et al. (2019); Yang et al. (2008) |
| Poultry, swine, cattle, brewery, urban and dairy | *S. obliquus*                  | Biomass biohydrogen (BioH2), nutrient removal                           | Ferreira et al. (2018) |
| Potato, fish animal feed, yeast and coffee | *Phormidium*, *Oocystis*, *Mirospora*                                      | Nutrient removal                                                        | Posadas et al. (2014) |
| Municipal and dairy          | *Arthrospira jenneri*, *Coccomonas sp.*, *Polytomella sp.*, *P. tetralatre*, *Chlamydomonas caeca*, *Geitlerinema*, *Synecho-| Lipid, biomass, nutrient removal                                      | Woertz et al. (2009); Bernal et al. (2008) |
is associated with the selection of strains that best adapt to the medium and thus, obtain higher biomass productivity; therefore, the other prominent term is “biodiesel produc-
tion,” which is directly linked to the microalgal biomass acquisi-
tion process. This is because, with the decrease in fossil fuel reserves and environmental deterioration, stud-
ies involving microalgae and renewable energy sources are gaining prominence because they offer more economic and sustainable technologies.

Algae biodiesel has been the target of numerous studies because of the reduction of greenhouse gases compared to fossil fuels (Benemann et al. 2012). In addition, microalgae can be used to generate other derived chemicals, such as bioethanol, biokerosene, bioplastics, hydrogen biofuels, and biogas (Chisti and Yan 2011).

Biofuels derived from microalgae are still not commerci-
ally viable because their costs are higher than gasoline (Cruce and Quinn 2019). Thus, the sustainability of pro-
jects that aim to cultivate microalgae for the production of biofuels and other bioproducts is generally evaluated using technoeconomic analysis and/or life cycle assessment (LCA) (Grierson et al. 2013). One of the main “bottlenecks” high-
lighted by several authors with respect to the implementation of microalgae cultivation systems are the high costs arising from these processes. These can be defined as the sum of used energy, installation, pond downtime, capital costs (investment), operational, maintenance, and environmental issues, among others (Dusan et al. 2019; Strazza et al. 2015), and determinants for the implementation of algal biomass production systems (because they can result in negative eco-

Most recent publications on the economic feasibility and environmental impacts using agro-industrial wastewater for microalgae cultivation and bioremediation are related to life cycle analysis (Table 2). In part of these studies, the eco-

Aiming increase the production of biofuels from microal-
gae, future studies should focus on the areas of biotechnol-
yogy and synthetic biology related to the efficient production of several bioproducts of economic interest, overcoming the previously mentioned bottleneck (Chen et al. 2019). Besides the economic aspects, microalgae projects are garnering interest due to the reduction in their environmental impacts. Agro-industrial residues are abundant and easily available. When not treated, wastewater contains nitrogen and phosphorus, which can lead to eutrophication and environmental problems, affecting bio-system recycling (Umamaheswari and Shanthakumar 2016). The irregular disposal of waste-
water compromises the environment because the soil, when

receiving constant loads above the necessary, can change its characteristics and consequently the water bodies that its holds. The changes in water quality are mainly due to the polluting agents in the water; changing the water quality from the presence of nutrients leads to the eutrophication process (disordered growth of algae and macrophytes) that interferes with water use and ecosystem balance.

Microalgae are photosynthetic microorganisms and reduce greenhouse by CO₂ fixation, even when they are growing mixotrophically using organic carbon from waste-
water (De Bhowmick et al. 2014); for instance, the produc-
tion of 1.0 kg of microalgal biomass can fix up to 1.83 kg of CO₂ (Jiang et al. 2013).

The integration of microalgae cultivation with wastewater treatment significantly reduces the environmental impacts because it is an emerging technology, and the use of agricultural and industrial waste for microalgae cultivation ensures sustainability and reduces the high costs of cultivation (Fig. 3). Agroindustry integration through microalgal cultivation is an economically feasible and ecologically sus-
tainable approach for wastewater treatment, bioenergy pro-
duction chain, and the food industry (Andrade et al. 2020; de Carvalho et al. 2020).

Geographical distribution of publications

From the first step in the WoS database from January 1, 1996, to September, 2021, on the use of microalgae in the wastewater treatment of instant coffee, dairy, and cassava flour industries, 59 articles were analyzed (Table 1). The geographic distribution of these studies among the 23 coun-
tries to which the authors are affiliated shows that the ones that stand out are the USA and China with 13.5% each, fol-
lowed by India (11.8%), Iran (10.2%), and Greece (6.8%),
which can be explained by the importance of the agro-
industrial sector and research investments in these countries. In step 2, most of the 34 articles were with authors affiliated with institutions in the USA (35.3%), Brazil (17.8%), and India (8.9%) followed by Canada and Italy with 5.9% each. In general, the publications have the participation of researchers from more than one institution and/or country, which highlights the importance of the role of networks in research.

Future research trends on microalgae cultivation

Studies that associate microalgae life cycle evaluation and economic technical analysis are essential to identify the paths to follow and achieve sustainability in bioenergy generation and bioproducts. The particularities and diversity of agro-industrial effluents can provide economic, environmen-
tal, and social resources from the use of microalgae in biore-
mediation and biomass production. The challenge of making
the production of microalgae biofuels more accessible is due to the integration of biorefineries with respect to exploring other bioproducts of higher value, thus compensating the process production costs. For algae biofuels, electricity coproduction and high protein value products are the most studied in the literature, especially the study of algae flour as a food source (Cruce and Quinn 2019).

Brazil is considered a pioneer in the development of technologies to produce renewable biofuels, although the country has fewer investments compared to the USA and European countries (Roth et al. 2020). Fossil energy use is the main contributor to greenhouse gas emissions (GGE), and carbon dioxide emissions are the most common gas released by human activities, representing three-quarters of the global emissions of GGE (Dasan et al. 2019). Therefore, there is a need to develop renewable energy sources to meet the energy demands of the world.

In addition, public policies that benefit the cultivation of microalgae in agro-industrial effluents, through taxes on production (subsidies), financing for the sector, and carbon credits, are important to stimulate research, development, and innovation and integrate universities and public and private research agencies, while adding more and more research efforts to explore the cultivation of microalgae and their bioproducts.

To increase wastewater bioremediation systems with microalgae cultivation, a survey of fractional harvest of algal biomass in each cycle is suggested. In addition to cycle implementation with semi-continuous feeding, the option of using consortia of microalgae and methodologies for previous adaptation of species to be used in wastewater must be studied. Studying methods for harvesting microalgae biomass on a large-scale using wastewater should be a concern to solve one of the bottlenecks in the algae production chain.

Other alternatives to improve microalgae growth include cell suspension aeration and pH adjustment to adequate values for microbial cell multiplication. Concerning pH correction and/or nutrient complementation, the mixture of two or more different effluents should be further investigated in order to benefit the agroindustry involved.

The construction of eco parks for the benefit of one or more agroindustry is a solution for effluent treatment with reuse water, that is, when consortia are used, enabling the achievement of economic and environmental objectives within the sector. Therefore, the feasibility and sustainability of these projects are closely linked to the economic feasibility analysis, allowing a better understanding of the costs incurred by their implementation and the development of technologies that include wastewater treatment to obtain microalgae biomass.

Conclusion

The use of agro-industry wastewater in the microalgae production chain for biomass generation is a promising alternative to reduce costs and decrease environmental impacts. Large-scale research on microalgae production in agro-industrial effluents is essential to enable bioproduct generation projects and achieve sustainable and low-cost production of microalgae biomass.

Economic and environmental analyses should be integrated to allow a large-scale project performance evaluation because the technologies arising from microalgae cultivation systems are essential to improve the viability of projects for bioproduct generation, resulting in environmental, economic, and social gains.
Bibliometric analysis, as based on the Web of Science (WoS) database, which addresses the cultivation of microalgae and the treatment of agro-industrial wastewater, shows scientific gains regarding the development of alternative technologies to produce microalgae biomass, especially in the treatment of dairy wastewater. There is a gap in the publications indexed with the topic of cultivating microalgae to treat wastewater from the industrialization of cassava and coffee.

Further research is needed to optimize the biomass/lipid accumulation in microalgae cultivation and better understand the mechanisms underlying the enhanced wastewater treatment. Studies related to algal biomass harvesting should be part of studies on microalgae cultivation using wastewater in industrial eco-parks to reduce costs.

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Data availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

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