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# Produtos biotecnológicos de microalgas: uma análise de tendências

# Biotechnological products from microalgae: a trend analysis

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**Resumo.** As microalgas são microrganismos heterogêneos, versáteis e disponíveis em todo o mundo. Seu uso tem sido descrito em várias áreas, com vários objetivos, especialmente na remediação de resíduos de variadas origens. Neste artigo, é apresentado um levantamento bibliográfico de trabalhos publicados em periódicos de alto impacto, utilizando como critério de pesquisa as palavras chave “chlorococcum” e “bioproducts”. Posteriormente, esses trabalhos foram filtrados, sendo considerados apenas aqueles publicados em revistas com fator de impacto igual ou superior a 5. Por último, foi realizada uma triagem dos resultados para separar artigos de pesquisa de artigos de revisão. Foram obtidos, após a pesquisa em três bases de dados e triagem, 238 trabalhos, entre revisões e artigos de pesquisa. Ao fim dos filtros, o número final de artigos utilizados no relatório foi de 128 trabalhos. Após análise, pôde-se perceber o crescimento recente do interesse do uso de microalgas para remediação de águas residuárias e outros resíduos, bem como para a produção de moléculas de interesse, principalmente carotenoides, e também do uso dessa biomassa para produção de combustíveis, em especial o biodiesel.
**Palavras-chaves** Biomassa, Biocombustíveis, *Chlorococcum*

**Abstract.** Microalgae are heterogeneous, versatile worldwide available microorganisms. Its use has been described in several areas, with several objectives, especially in the remediation of residues of different origins. In this article, a bibliographic survey of papers published in high impact journals is presented, using the keywords “chlorococcum” and “bioproducts” as search criteria. Subsequently, these works were filtered, considering only those published in journals with an impact factor equal to or greater than 5. Finally, the results were screened to separate research articles from review articles. After researching three databases and screening articles, 238 works were obtained, including reviews and research articles. At the end of the filters, the final number of articles used in the report was 128 papers. After analysis, it was possible to perceive the recent growth of interest in the use of microalgae for the remediation of wastewater and other residues, as well as for the production of molecules of interest, mainly carotenoids, and also the use of this biomass for the production of fuels, in especially biodiesel.
**Keywords:** Biomass, Biofuels, *Chlorococcum*

## Introdução

O termo "algas" descreve um grupo vasto e incrivelmente diverso de organismos eucarióticos e fotossintéticos, incluindo microalgas unicelulares e algas marinhas. As algas existem em todos os ambientes, desde lagoas, rios, lagos, oceanos, águas salobras e neve (Pradhan *et al*., 2022).

As algas contêm na sua composição vários compostos químicos bioativos e metabólitos secundários, como fibras alimentares, antioxidantes, aminoácidos vitais, vitaminas, ácidos graxos poli-insaturados e minerais (Pradhan *et al*., 2022). Além disso, sua biomassa pode ser utilizada como matéria-prima para a produção de biocombustíveis e como fonte de produtos químicos de alto valor agregado, como carotenoides, ficobilinas e polissacarídeos (Lakshmi *et al*., 2020).

Organismos deste grupo variam em tamanho, de micrômetros a várias dezenas de metros para algumas algas. As maiores, as macroalgas, são geralmente visíveis a olho nu e são muitas vezes conhecidas como “algas marinhas”. As menores, microalgas, são algas microscópicas que podem ocorrer separadamente ou em colônias (Hachicha *et al*., 2022).

As microalgas são microrganismos aquáticos unicelulares com mais de 50.000 espécies classificadas (Ampofo *et al*., 2022). Atualmente, a biomassa de microalgas está sendo usada como alimento humano, ração animal ou produtos agrícolas, como bioestimulantes e biofertilizantes. Produtos de alta qualidade derivados de microalgas, como astaxantina ou ficocianina, também estão no mercado para uso nas indústrias de alimentos funcionais, cosméticos e nutracêuticos (Chen *et al*., 2022).

A biomassa de microalgas consiste em proteínas, lipídios e carboidratos, que podem ser usados como matéria-prima para a geração de biocombustíveis (por exemplo, biodiesel, bioetanol, biogás e biohidrogênio) e produtos de valor agregado, como ácidos graxos poliinsaturados, pigmentos, vitaminas, e inúmeras outras substâncias nutritivas (You *et al*., 2022).

Dentro do grupo das microalgas, os microrganismos fotossintéticos podem ser divididos em células eucarióticas, incluindo os filos Chlorophyta, Rhodophyta, Glaucophyta, Cryptophyta, Euglenozoa, Cercozoa, Heterokontophyta, Haptophyta e Miozoa; os procarióticos também são chamados de microalgas verdes azuis ou cianobactérias (Hachicha *et al*., 2022).

As microalgas são um tipo de organismo com a maior eficiência fotossintética da natureza. A eficiência fotossintética das microalgas é de 10 a 20%, ou seja, superior a maioria das plantas terrestres, que apresentam cerca de 1% a 2% (Chen *et al.*, 2022).

A atenção dada às microalgas está principalmente relacionada à sua eficiência de bioacumulação, assimilação de nutrientes e produtividade de biomassa. Na produção de biomassa para energia e outros bioprodutos (pigmentos, bioplásticos, ácidos graxos, entre outros), as microalgas apresentam uma gama de características que as tornam vantajosas em relação às matérias-primas convencionais, como a não competição por terras agrícolas e água limpa, favorecendo a produção de alimentos e outros produtos agrícolas (Calijuri *et al*., 2022). Não apenas produtos, mas também processos baseados em microalgas foram implementados industrialmente nas últimas décadas.

O potencial de produção de microalgas usando diferentes tipos de água (água doce, água do mar, esgoto urbano etc.) e diferentes fontes de nutrientes (fertilizantes, gases de combustão, resíduos agrícolas, resíduos industriais etc.) são consideradas as chaves para aumentar a sustentabilidade da produção industrial (Villaró *et al*., 2022).

Diante do exposto, o objetivo do presente trabalho foi realizar o levantamento bibliográfico acerca de produtos biotecnológicos obtidos a partir de microalgas, considerando o período de 01 de janeiro de 2021 a 04 de maio de 2022. Foram considerados trabalhos publicados em periódicos com fatores de impacto maiores ou iguais a 5, com objetivo de identificar as tendências na área.

## Material e Métodos

Foi realizada uma pesquisa no dia 3 de maio de 2022 nas três principais bases de dados de artigos científicos: Google Acadêmico, Science Direct e Web of Science. Foi definido inicialmente um fator de impacto ≥3, considerando apenas números inteiros, para a pesquisa e utilizando as palavras-chave “chlorococcum” e “bioproducts”. Posteriormente, o critério de busca do fator de impacto foi alterado para periódicos com fator de impacto ≥5.

A partir disso, foram excluídos da pesquisa trabalhos que não passaram por revisão em pares (capítulos de livro, teses, dissertações, monografias, resumos em congressos). Depois, os artigos obtidos foram separados entre artigos científicos e revisões de literatura, que foram analisados separadamente. Os artigos foram discriminados em tabelas para melhor visualização, sendo descritos seus produtos, métodos de extração, periódicos, etc.

## Resultados e Discussão

Dentre as três plataformas, apenas a plataforma Web of Science oferece a possibilidade de filtrar os periódicos por fator de impacto já nos parâmetros da pesquisa. Nesta plataforma, a pesquisa inicial retornou apenas 3 trabalhos. Quando o filtro fator de impacto foi aplicado, nenhum dos trabalhos atingiu o fator de impacto a ser considerado.

Durante o levantamento, percebeu-se que a plataforma Google Acadêmico também indexava as publicações da editora Elsevier, que publica os artigos apresentados nos resultados da plataforma

Science Direct. Portanto, devido à falta de trabalhos nesse tema disponíveis na plataforma Web of Science e a redundância dos resultados entre Google Acadêmico e o Science Direct, a plataforma da Google foi utilizada como a fonte primária de resultados desse trabalho.

A primeira pesquisa (apenas com as palavras-chave) retornou 480 resultados. Após a aplicação do primeiro filtro (fator de impacto maior ou igual a 3) e da exclusão de trabalhos que não passaram por revisão em pares, esse número diminuiu para 238 resultados, com fatores de impacto chegando até 15.

Após uma breve análise, se concluiu que esse número ainda era bastante alto para que a análise pretendida fosse realizada. Portanto, o critério fator de impacto foi alterado de ≥3 para ≥5, reduzindo assim para o número de 128 trabalhos que foram usados nas análises aqui apresentadas.

*Produtos biotecnológicos e métodos de cultivo*

O objetivo geral do trabalho é fornecer uma perspectiva recente das tendências de pesquisa em produtos derivados de microalgas. Antes do produto, os métodos de cultivo são a principal preocupação dos grupos de pesquisa em qualquer área. Esses métodos de produção também foram analisados na pesquisa, abordando a integração dos métodos de cultivo, de coleta e extração dos produtos de interesse. A pesquisa que foi realizada juntamente com os critérios que filtravam os resultados, foram sumarizados na Tabela 1.

**Tabela 1**. Bioprodutos produzidos por microalgas e seus métodos de extração

| Fator de Impacto | Título do Trabalho | Produto | Periódico | Autores |
|---|---|---|---|---|
| 14 | Augmented $CO_2$ tolerance by expressing a single H+ pump enables microalgal valorization of industrial flue gas | Otimização de uma cepa modelo para produção de bioprodutos a base de $CO_2$ | Nature Communications | Choi *et al*., 2021 |
| 13 | Enhanced microalgal biofilm formation and facilitated microalgae harvesting using a novel pH-responsive, crosslinked patterned and vibrating membrane | Coleta de biomassa utilizando biofilmes | Chemical Engineering Journal | Zhao *et al*., 2021 |
| 13 | Experiments and modeling of *Komvophoron* sp. Growth in hydraulic fracturing wastewater | Sistema de tratamento de efluentes por cultivo de microalgas | Chemical Engineering Journal | Concas *et al*., 2021 |
| 10 | Transcriptomic analysis unravels the modulating mechanisms of the biomass and value-added bioproducts accumulation by light spectrum in *Eustigmatos* cf. *Polyphem* (Eustigmatop hyceae) | Ácido palmitoleico; beta-caroteno | Bioresource Technology | Zhang *et al*., 2021 |
| 10 | Biomass production and phycoremediation of microalgae cultivated in polluted river water | Ácidos graxos metil-esterificados; biomassa | Bioresource Technology | Ummalyma; Singh, 2022 |
| 10 | Evaluation of microalgal strains and microalgal consortium for higher lipid productivity and rich fatty acid profile towards sustainable biodiesel production | Biomassa; Lipídeos | Bioresource Technology | Arutselvan *et al*., 2021 |
| 9 | Synergistic effect of ultrasound and switchable hydrophilicity solvent promotes microalgal cell disruption and lipid extraction for biodiesel production | Lipídeos | Bioresource Technology | Guo *et al*., 2022 |
| 8 | Exploring the critical factors of algal biomass and lipid production for renewable fuel production by machine learning | Otimização da produção de biomassa e lipídeos | Renewable Energy | Coşgun *et al*., 2021 |
| 8 | Improving hydrogen recovery from anaerobic co-digestion of algae and food waste by high-pressure homogenisation pre-treatment | Otimização da produção de hidrogênio | Environmental Chemistry Letters | Zhao *et al*., 2021 |
| 7 | Isolation and identification of microalgal strains with potential as carotenoids producers from a municipal solid waste landfill | Bioprospecção de espécies produtoras de carotenoides | Science of The Total Environment | Suarez-Montes *et al*., 2022 |

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| 7 | A photobioreactor using *Nannochloropsis 88culate* marine microalgae for removal of polycyclic aromatic hydrocarbons and sorption of metals in produced water | Modelo de tratamento de água a partir de um sistema de fotobiorreator | Chemosphere | Marques *et al*., 2021 |
| 7 | Formation of silver nanoparticles in aquatic environments facilitated by algal extracellular polymeric substances: Importance of chloride ions and light | Nanopartículas de prata | Science of The Total Environment | Xiong *et al*., 2021 |
| 7 | Assessment of the performance of an anoxic-aerobic microalgal-bacterial system treating digestate | Consórcio de bactérias e microalgas para tratamento de resíduos alimentares digeridos | Chemosphere | Torres-Franco *et al*., 2021 |
| 7 | Single-cell sorting of microalgae and identification of optimal conditions by using response surface methodology coupled with life-cycle approaches | Desenvolvimento de estratégias para otimizar processos biológicos | Science of The Total Environment | Zhao *et al*., 2022 |
| 6 | Synthesis, characterization, and application of intracellular Ag/AgCl nanohybrids biosynthesized in *Scenedesmus* sp. As neutral lipid inducer and antibacterial agent | Nanopartículas | Environmental Research | Kashyap *et al*., 2021 |
| 6 | Central composite design for the optimization of CaO and $Fe_2(SO4)_3$ facilitated transesterification of *Scenedesmus* sp. Oil for fatty acid methyl ester production | Ácidos graxos | Fuel | Brindhadevi *et al*., 2022 |
| 6 | Bio-ethanol production: A route to sustainability of fuels using bio-based heterogeneous catalyst derived from waste | Bioetanol | Process Safety and Environmental Protection | Gohain *et al*., 2021 |
| 6 | Small scale photobioreactor, outdoor open pond cultivation of *Chlorella* sp. And harvesting at log and stationary growth phase towards lipids and methyl ester production | Comparação de tipos de cultivo visando a produção de lipídeos e metil-ésteres | Fuel | Chi *et al*., 2022 |
| 6 | Spectral changes by dye sensitized solar modules influence the pigment composition and productivity of *Arthrospira maxima* and increase the overall energy efficiency | Biomassa; ficocianina | Advanced Sustainable Systems | Borella *et al*., 2022 |
| 6 | Microalgae growth and diversity in anaerobic digestate compared to synthetic media | Comparação do crescimento de microalgas quando cultivadas em ALD ou em meios sintéticos | Biofuel Research Journal | Ermis *et al*., 2022 |
| 6 | A biorefinery approach for high value-added bioproduct (astaxanthin) from alga *Haematococcus* sp. And residue pyrolysis for biochar synthesis and metallic iron production from hematite (Fe2O3) | Uso de fotobiorreatores para produção de biomassa, ferro metálico e astaxantina | Fuel | Ashokkumar *et al*., 2021 |
| 5 | Statistical optimization of levulinic acid and formic acid production from lipid-extracted residue of *Chlorella vulgaris* | Ácido levulínico; ácido fórmico | Journal of Environmental Chemical Engineering | Jeong; Kim, 2021 |
| 5 | Microalgae and cyanobacteria strains as producers of lipids with antibacterial and antibiofilm activity | Lipídeos | Marine Drugs | Cepas *et al*., 2021 |
| 5 | Assessment of the in vitro anticancer activities of cyanobacteria mediated silver oxide and gold nanoparticles in human colon CaCo-2 and cervical HeLa cells | Nanopartículas de prata e de ouro | Environmental Nanotechnology, Monitoring & Management | El-Sheekh *et al*., 2021 |

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| 5 | Hydrothermal conversion of microalgae *Chlorella* sp. Into 5-hydroxymethylfurfural and levulinic acid by metal sulfate catalyst | 5-HMF e ácido levulínico | Biomass and Bioenergy | Jeong; Kim, 2021 |
| 5 | Integration of bioelectricity generation from algal biophotovoltaic (BPV) devices with remediation of palm oil mill effluent (POME) as substrate for algal growth | Dispositivos biofotovoltaicos | Environmental Technology & Innovation | Ng *et al*., 2021 |
| 5 | Separation of microalgae cultivated in anaerobically digested black water using *Moringa oleifera* Lam seeds as coagulant | Biomassa | Journal of Water Process Engineering | Silva *et al*., 2021 |
| 5 | An integrated approach for phycoremediation of municipal wastewater and production of sustainable transportation fuel using oleaginous *Chlorella* sp. | Ficorremediação de águas residuais e aproveitamento da biomassa para produção de biodiesel | Journal of Water Process Engineering | Katiyar *et al*., 2021 |
| 5 | Effective lipid extraction from undewatered microalgae liquid using subcritical dimethyl ether | Lipídeos | Biotechnology for Biofuels | Wang *et al*., 2021 |
| 5 | Trophic Transition Enhanced Biomass and Lipid Production of the Unicellular Green Alga *Scenedesmus acuminatus* | Cultivo mixotrófico para otimização da produção de biomassa e lipídeos | Frontiers in Bioengineering and Biotechnology | Zhang *et al*., 2021 |

Fonte: o autor.

Observando a tabela, percebe-se uma tendência na busca por biocombustíveis (Gohain *et al*., 2021; Zhao *et al*., 2021; Katiyar *et al*., 2021) e precursores industriais de importância (Jeong; Kim, 2021; Zhang *et al*., 2021;), em especial lipídeos (Ummalyma; Singh, 2022; Arutselvan *et al*., 2021; Guo *et al*., 2022; Coşgun *et al*., 2021; Brindhadevi *et al*., 2022; Chi *et al*., 2022; Cepas *et al*., 2021; Wang *et al*., 2021; Zhang *et al*., 2021), além dos carotenoides (Suarez-Montes *et al*., 2022; Borella *et al*., 2022; Ashokkumar *et al*., 2021; Zhang *et al*., 2021). É importante destacar o potencial das microalgas na produção de combustíveis, já que são apontadas como uma das mais promissoras fontes de matéria-prima para biocombustíveis da história recente dentro do contexto ambiental (Peter *et al*., 2021).

A produção de energia é de claro interesse dos grupos de pesquisa e isso não se resume a combustíveis. O uso de microalgas tem sido apontado na construção de células de combustíveis microbianas (Borella *et al*., 2022) e até em dispositivos bio-fotovoltaicos (Ng *et al.,* 2021).

Dentre os combustíveis, o bioetanol se destaca como o mais proeminente (Gohain *et al*., 2021) porém os grupos também têm se focado na produção de biohidrogênio (Zhao *et al*., 2021) e de biodiesel (Katiyar *et al*., 2021). Para a produção desses produtos, águas residuais de diferentes origens chamam atenção como o principal sistema de cultivo, e a integração dessa produção com a biorremediação dessas águas aparece como uma impactante aplicação ambiental desse processo (Marques *et al*., 2021).

Os objetivos dos cultivos em biorreatores variam entre produção de biomassa (Silva *et al*., 2021) e produção de carotenoides (Ashokkumar *et al*., 2021). Técnicas como *machine learning* aparecem para o ajuste de parâmetros de cultivo (Coşgun *et al*., 2021), apontando caminhos para o escalonamento dos processos utilizando aspectos de inteligência artificial.

Algumas estratégias de cultivo são bastante inovadoras, como o cultivo mixotrófico para produção de biomassa e lipídeos (Zhang *et al*., 2021). Esse tipo de cultivo pode estabelecer um modelo para produção futura da biomassa com objetivos específicos, a depender das espécies utilizadas.

Dentre os processos de extração, o uso de pressão e tratamentos ácidos desempenham papel importante, principalmente na extração de lipídeos (Coşgun *et al*., 2021). Na produção de hidrogênio, mais uma vez os tratamentos a alta pressão aparecem nos resultados (Zhao *et al*., 2021).

Todas as publicações são de periódicos de alto fator de impacto, o que reforça o entendimento de que as tendências de fato existem e que o interesse nesses conhecimentos é crescente.

*Revisões de literatura*

Dentre os resultados obtidos ao realizar a busca, o maior número de trabalhos encontrados se trata de revisões de literatura. Como apresentado na Tabela 2, dos 81 trabalhos, pelo menos 12 deles mencionam biocombustíveis diretamente e estes ainda são mencionados indiretamente algumas outras vezes, quando se toca no tópico economia circular ou remediação de águas residuais.

**Tabela 2:** Revisões de literatura sobre bioprodutos de microalgas

| Fator de Impacto | Título do Trabalho | Temática | Periódico | Referência |
|---|---|---|---|---|
| 15 | An overview of carotenoid extractions using green solvents assisted by Z-isomerization | O uso de solventes verdes e novas técnicas de extração | Trends in Food, Science & Tecnology | Yu *et al*., 2022 |
| 15 | Supercritical fluid extraction of seed oils - a short review of current trends | Extração de óleos por técnica de fluido supercrítico | Trends in Food, Science & Tecnology | Ahangari *et al*., 2021 |
| 14 | Current advances in microalgae harvesting and lipid extraction processes for improved biodiesel production: a review | Avaliação das abordagens de colheita, extração de lipídeos e métodos mecânicos para lise celular | Renewable and Sustainable Energy Reviews | Vasistha *et al*., 2021 |
| 14 | Harnessing solar energy using phototrophic microorganisms: A sustainable pathway to bioenergy, biomaterials, and environmental solutions | Uso de microrganismos fototróficos e o papel deles na produção de soluções e produtos | Renewable and Sustainable Energy Reviews | Tanvir *et al*., 2021 |
| 14 | Bio-based flocculants for sustainable harvesting of microalgae for biofuel production: A review | Uso de biofloculantes para recuperação de biomassa algal | Renewable and Sustainable Energy Reviews | Ogbonna *et al*., 2021 |
| 14 | Transgenicism in algae: Challenges in compatibility, global scenario and future prospects for next generation biofuel production | Técnicas de engenharia genética e o impacto no cultivo de microalgas e cianobactérias | Renewable and Sustainable Energy Reviews | Bharathiraja *et al*., 2022 |
| 14 | Algae biostimulants: A critical look at microalgal biostimulants for sustainable agricultural practices | Bioestimulantes de microalgas e perspectivas de comercialização | Biotechnology Advances | Kapoore *et al*., 2021 |
| 14 | Bioethanol and biodiesel: Bibliometric mapping, policies and future needs | Estado da arte da produção de bioetanol e biodiesel | Renewable and Sustainable Energy Reviews | Osman *et al*., 2021 |
| 14 | Renewable and Sustainable Energy Reviews | Papel das microalgas como matéria prima para biocombustíveis de terceira geração | Renewable and Sustainable Energy Reviews | Debnath *et al*., 2021 |
| 14 | Biological characteristics of energy conversion in carbon fixation by microalgae | Elucidação do mecanismo de fixação de carbono e novos métodos para fixação de carbono por microalgas | Renewable and Sustainable Energy Reviews | Zeng *et al*., 2021 |
| 11 | Reuniting the Biogeochemistry of Algae for a Low-Carbon Circular Bioeconomy | Sistemas de cultivo focados na produção de biocombustíveis | Trends in Plant Science | Leong *et al*., 2021 |
| 11 | A comprehensive review on the application of novel disruption techniques for proteins release from microalgae | Métodos de ruptura mecânicos e não mecânicos e potencial para a extração de proteínas | Critical Reviews in Food Science and Nutrition | Timira *et al*., 2022 |
| 11 | Microalgae as source of functional ingredients in new-generation foods: challenges, technological effects, biological activity, and regulatory issues | Uso de biomassa de microalgas para suplementação alimentar | Critical Reviews in Food Science and Nutrition | Medeiros *et al*., 2022 |

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| 11 | The colorful world of carotenoids: a profound insight on therapeutics and recent trends in nano delivery systems | Técnicas novas e tradicionais de nanoencapsulamento de carotenóides e possíveis usos | Critical Reviews in Food Science and Nutrition | Maghsoudi *et al*., 2022 |
| 10 | Algal biomass valorization to high-value chemicals and bioproducts: Recent advances, opportunities and challenges | Ácidos graxos poliinsaturados, açúcares, lipídeos, oleoquímicos e proteínas | Bioresource Technology | Zhou *et al*., 2022 |
| 10 | Neoteric solvent-based blue biorefinery: for chemicals, functional materials and fuels from oceanic biomass | Biorrefinarias azuis, recursos marinhos e comoddities desenvolvidas com as biomassas de origem marinha | The Royal Society of Chemistry - Green Chemistry | Sequeira *et al*., 2021 |
| 10 | Microalgal-based removal of contaminants of emerging concern | Sistemas de biorremediação baseados em microalgas para tratamento de contaminantes | Journal of Hazardous Materials | Sousa *et al*., 2022 |
| 9 | Integrated microalgal biorefinery – Routes, energy, economic and environmental perspectives | Biodiesel | Journal of Cleaner Production | Wang et al., 2022 |
| 9 | Recent progress in flocculation, dewatering and drying technologies for microalgae utilization: Scalable and low-cost harvesting process development | Progressos do setor de produção de microalgas | Bioresource Technology | Min *et al*., 2022 |
| 9 | Resource recovery from industrial effluents through the cultivation of microalgae: A review | Avaliação da recuperação de recursos através do cultivo de microalgas em efluentes industriais | Bioresource Technology | Ali *et al*., 2021 |
| 9 | Microalgal and bacterial auxin biosynthesis: implications for algal biotechnology | Uso de fitormônios para aumento da biomassa de microalgas em associação com bactérias | Current Opinion in Biotechnology | Lin *et al*., 2022 |
| 9 | Carotenoids from fungi and microalgae: A review on their recent production, extraction, and developments | Carotenóides de origem fúngica e algal e as relações entre os métodos de extração verdes | Bioresource Technology | Liu *et al*., 2021 |
| 9 | Assessment of Microalgal-Bacterial Granular Sludge Process for Environmentally Sustainable Municipal Wastewater Treatment | Estado da arte do uso de lodo granular microalgal-bacteriano para tratamento de esgoto municipal | ACS ES&T Water | Liu *et al*., 2021 |
| 9 | Overview on stress-induced strategies for enhanced microalgae lipid production: Application, mechanisms and challenges | Estratégias de acumulação de lipídeos por estresse | Resources, Conservation and Recycling | Song *et al*., 2022 |
| 9 | Recent advances in mixotrophic bioprocessing for production of high value microalgal products | Processo mixotrófico de produção de produtos de alto valor agregado por microalgas | Bioresource Technology | Patel *et al*., 2021 |
| 9 | Insights into the genetic and metabolic engineering approaches to enhance the competence of microalgae as biofuel resource: A review | Engenharia genética e metabólica para o aprimoramento da microalga como matéria-prima para biocombustíveis | Bioresource Technology | Brar *et al*., 2021 |

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| 9 | Food waste valorization: Energy production using novel integrated systems | Análise das tecnologias disponíveis para alcançar a sustentabilidade da administração dos resíduos alimentares | The Royal Society of Chemistry - Green Chemistry | Sequeira *et al*., 2021 |
| 9 | Advances in microalgal research for valorization of industrial wastewater | Utilização de águas residuais como meio de cultura para microalgas | Bioresource Technology | Maurya *et al*., 2022 |
| 9 | Insights into upstream processing of microalgae: A review | Processos upstream de microalgas | Bioresource Technology | Daneshvar *et al*., 2021 |
| 9 | Algae as an emerging source of bioactive pigments | Produção de pigmentos de algas e seu potencial frente aos pigmentos sintéticos | Bioresource Technology | Patel *et al*., 2022 |
| 9 | Novel application of microalgae platform for biodesalination process: A review | Problemática dos métodos físico-químicos de dessalinização e destaque de métodos baseados em microalgas | Bioresource Technology | Patel *et al*., 2021 |
| 9 | Microalgae-based carbohydrates: A green innovative source of bioenergy | Uso de biomassa de microalgas como matéria-prima para biocombustíveis de terceira geração | Bioresource Technology | Silvello *et al*., 2022 |
| 9 | Light modulates transcriptomic dynamics upregulating astaxanthin accumulation in *Haematococcus*: A review | Uso de luz como indutor de estresse para a acumulação de bioastaxantina | Bioresource Technology | Ahirwar *et al*., 2021 |
| 9 | Regimes of hydrochar yield from hydrothermal degradation of various lignocellulosic biomass: A review | Biomassa de microalgas como matéria-prima promissora para hidrocarvão | Journal of Cleaner Production | Khan *et al*., 2021 |
| 9 | A review on anaerobic digestion of energy and cost-effective microalgae pretreatment for biogas production | Elucidação da relação entre os métodos de enfraquecimento de parede celular e sua produtividade | Bioresource Technology | Kannah *et al*., 2021 |
| 8 | Biomass utilization and production of biofuels from carbon neutral materials | Natureza dos resíduos disponíveis, diferentes estratégias para quebra ou hidrólise e sistemas microbianos eficientes | Environmental Pollution | Srivastava *et al*., 2021 |
| 8 | Lignocellulose, algal biomass, biofuels and biohydrogen: a review | Comparação entre matérias-primas para a produção de biocombustíveis e biohidrogênio | Environmental Chemistry Letters | Kaloudas *et al*., 2021 |
| 7 | Recent biotechnological developments in reshaping the microalgal genome: a signal for green recovery in biorefinery practices | Crescimento de microalgas a partir da combinação de técnicas de manipulação genética | Chemosphere | Singh *et al*., 2022 |
| 7 | A comprehensive review on carbon source effect of microalgae lipid accumulation for biofuel production | Efeitos do carbono no acúmulo de lipídeos na produção de biomassa de microalgas e produção de biodiesel | Science of the Total Environment | Ma *et al*., 2022 |

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| 7 | Advancement of green technologies: a comprehensive review on the potential application of microalgae biomass | Desenvolvimento de tecnologias verdes e aplicações para biomassa de microalgas | Chemosphere | Yap *et al*., 2021 |
| 7 | Emerging microalgae-based technologies in biorefinery and risk assessment issues: bioeconomy for sustainable development | Biorrefinaria de microalgas | Science of the Total Environment | Sharma *et al*., 2022 |
| 7 | Algae as an attractive source for cosmetics to counter environmental stress | Cosméticos a partir de algas como solução para problemas de pele | Science of the Total Environment | Aslam *et al*., 2021 |
| 7 | Review on integrated biofuel production from microalgal biomass through the outset of transesterification route: a cascade approach for sustainable bioenergy | Produção de biocombustível | Science of the Total Environment | Karpagam *et al*., 2021 |
| 7 | A critical review on different harvesting techniques for algal based biodiesel production | Análise técnico-econômica dos processos de cultivo de microalga em larga escala | Science of the Total Environment | Ananthi *et al*., 2021 |
| 7 | Microalgae as sustainable food and feed sources for animals and humans - Biotechnological and environmental aspects | Aplicações de microalgas no setor de rações animais e setor de alimentos | Chemosphere | Kusmayadi *et al*., 2021 |
| 7 | Biofertilizers and nanofertilizers for sustainable agriculture: phycoprospects and challenges | Biofertilizantes de algas | Science of the Total Environment | Mahapatra *et al*., 2022 |
| 7 | Microalgae harvesting techniques: updates and recent technological interventions | Desafios e avanços do cultivo de microalgas | Critical Reviews in Biotechnology | Kumar *et al*., 2022 |
| 7 | High-value biochemical products & applications of freshwater eukaryotic microalgae | Produtos de valor agregado produzidos a partir de microalgas de água doce | Science of the Total Environment | Russell *et al*., 2022 |
| 7 | Technical insights into the production of green fuel from $CO_2$ sequestered algal biomass: a conceptual review on green energy | Impacto da bioenergia à base de algas na energia verde e no meio ambiente | Science of the Total Environment | Arun *et al*., 2021 |
| 7 | Microalgae as a solution of third world energy crisis for biofuels production from wastewater toward carbon neutrality: an updated review. | Desenvolvimento de química verde e sustentabilidade ambiental a partir de microalgas | Chemosphere | Li *et al*., 2022 |
| 7 | Algae utilization and its role in the development of green cities | Desafios e perspectivas econômicas na utilização de microalgas para a criação de tecnologias verdes | Chemosphere | Chew *et al*., 2021 |
| 7 | Wastewater based microalgal biorefinery for bioenergy production: progress and challenges | Tratamento de águas residuais, cultivo e tecnologias de conversão de biomassa em bioenergia | Science of the Total Environment | Bhatia *et al*., 2021 |

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| 7 | Advanced microalgae-based renewable biohydrogen production systems: a review | Produção de $H_2$ a partir de microalgas | Bioresource Technology | Goswami *et al*., 2021 |
| 7 | Biohydrogen production from microalgae for environmental sustainability | Avanços na produção de biohidrogênio a partir de microalgas | Chemosphere | Li *et al*., 2022 |
| 7 | Constructed microalgal-bacterial symbiotic (MBS) system: classification, performance, partnership and perspectives | Efeitos da relação microalga-bactéria na formação da biofloculação | Science of the Total Environment | Wang *et al*., 2022 |
| 7 | Supercritical fluid extraction (SCFE) as green extraction technology for high-value metabolites of algae, its potential trends in food and human health | Tecnologias de extração de metabólitos de algas de alto valor | Food Research International | Singh *et al*., 2021 |
| 6 | Algal biofuels: technological perspective on cultivation, fuel extraction and engineering genetic pathway for enhancing productivity | Biocombustíveis | Fuel | Yaashikaa *et al*., 2022 |
| 6 | Phyco-remediation of swine wastewater as a sustainable model based on circular economy | Modelo de ficorremediação de efluentes | Journal of Environmental Management | López-Pacheco *et al*., 2022 |
| 6 | Microalgae biomass as a sustainable source for biofuel, biochemical and biobased value-added products: an integrated biorefinery concept | Cultivo, lise celular, extração de biocombustíveis e compostos de valor agregado | Fuel | Siddiki *et al*., 2022 |
| 6 | Prospects and environmental sustainability of phyconanotechnology: a review on algae-mediated metal nanoparticles synthesis and mechanism | Síntese de diferentes tipos de nanopartículas de metal a partir de diferentes espécies de microalgas | Environmental Research | Chan *et al*., 2022 |
| 6 | Advancement and role of abiotic stresses in microalgae biorefinery with a focus on lipid production | Avanços no cultivo de microalgas e estratégias de indução da produção de lipídeos | Fuel | Bibi *et al*., 2022 |
| 6 | Bioprocesses for the recovery of bioenergy and value-added products from wastewater: a review | Biorrefinaria microbiana | Journal of Environmental Management | Vasistha *et al*., 2021 |
| 6 | Microalgae-based livestock wastewater treatment (MbWT) as circular bioeconomy approach: enhancement of biomass productivity, pollutant removal and high-value compound production | Microalgas cultivadas em águas residuais da pecuária como ferramenta de remediação e abordagem de economia circular | Journal of Environmental Management | López-Sánchez *et al*., 2022 |
| 6 | Microalgae as a multipotential role in commercial applications: current scenario and future perspectives | Biocombustíveis, bioenergia e outros produtos de valor agregado | Fuel | Kandasamy *et al*., 2022 |
| 6 | Pollution prevention and waste phycoremediation by algal-based wastewater treatment technologies: the applications of high-rate algal ponds (HRAPs) and algal turf scrubber (ATS) | Tecnologias de tratamento de águas residuais | Journal of Environmental Management | Leong *et al*., 2021 |

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| 6 | Attempts to alleviate inhibitory factors of anaerobic digestate for enhanced microalgae cultivation and nutrients removal: a review | Cultivo de microalgas a partir de produtos da digestão anaeróbica de resíduos orgânicos | Journal of Environmental Management | Al-Mallahi *et al*., 2022 |
| 5 | Microalgal Biorefinery Concepts' Developments for Biofuel and Bioproducts: Current Perspective and Bioproducts: Current Perspectives and Bottlenecks | Tendências em produção de produtos via microalgas em escala industrial | International Journal of Molecular Sciences | Sivaramakrishan *et al*., 2022 |
| 5 | Latest developments in wastewater treatment and biopolymer production by microalgae | Avanços, resultados e perspectivas no uso e cultivo de microalgas em águas residuais | Journal of Environmental Chemical Engineering | Lutzu *et al*., 2021 |
| 5 | The role of microalgae in the bioeconomy | Análise econômica da indústria de microalgas | New Biotechnology | Fernández *et al*., 2021 |
| 5 | Recent advances and future prospects of electrochemical processes for microalgae harvesting | Métodos eletroquímicos de coleta de microalga | Journal of Environmental Chemical Engineering | Krishnamoorty *et al*., 2021 |
| 5 | Current analytical techniques for the characterization of lipophilic bioactive compounds from microalgae extracts | Avanços e limitações de técnicas analíticas para a caracterização de ácidos graxos poliinsaturados, fitoesteróis e carotenóides a partir dos extratos de microalgas | Biomass and Bioenergy | Pérez *et al*., 2021 |
| 5 | Sustainable production of food grade omega-3 oil using aquatic protists: Reliability and future horizons | Avanços no desenvolvimento da economia circular | New Biotechnology | Russo *et al*., 2021 |
| 5 | Recent insights into microalgae-assisted microbial fuel cells for generating sustainable bioelectricity | Células de combustível microbianas assistidas por microalgas | International Journal of Hydrogen Energy | Elshobary *et al*., 2021 |
| 5 | Microalgae-based biorefineries for sustainable resource recovery from wastewater | Biorrefinarias de microalgas cultivadas em águas residuais | Journal of Water Process Engineering | Goswami *et al*., 2021 |
| 5 | Biochemical and Immunological implications of Lutein and Zeaxanthin | Luteína e zeaxantina | International Journal of Molecular Sciences | Zafar *et al*., 2021 |
| 5 | Reuse of sea water reverse osmosis brine to produce *Dunaliella salina* based β-carotene as a valuable bioproduct: A circular bioeconomy perspective | Produção de β-caroteno a partir do tratamento de águas residuais | Journal of Environmental Management | Yildirim *et al*., 2022 |
| 5 | Genetic Engineering of Microalgae for Secondary Metabolite Production: Recent Developments, Challenges, and Future Prospects | Estratégias de engenharia metabólica para otimização da produção de metabólitos secundários em microalgas | Frontiers in Bioengineering and Biotechnology | Sreenikethanam *et al*., 2022 |
| 5 | Recent Advancements and Future Perspectives of Microalgae-Derived Pharmaceuticals | Avanços recentes em biotecnologia de microalgas e as perspectivas futuras para o uso na indústria farmacêutica | Marine Drugs | Xia *et al*., 2021 |

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| 5 | Anti-Inflammatory and Anticancer Effects of Microalgal Carotenoids | Carotenóides e suas atividades promissoras para a saúde humana | Marine Drugs | Ávila-Román *et al*., 2021 |
| 5 | Marine Algae-Derived Bioactive Compounds: A New Wave of Nanodrugs? | Principais produtos nutracêuticos algáceos | Marine Drugs | Menaa *et al*., 2021 |
| 5 | Advancements in the application of surfactants in microalgal production, harvesting and processing: A review | Avanços do uso de surfactantes em cultivo, colheita e processamento de microalgas | Journal of Environmental Chemical Engineering | Qin *et al*., 2022 |
| 5 | Phycoremediation of effluents containing dyes and its prospects for value-added products: A review of opportunities | Problemas ecológicos relativos ao uso de corantes sintéticos e os variados métodos de ficorremediação | Journal of Water Process Engineering | Bhardwaj *et al*., 2021 |
| 5 | Value added cassava waste management and environmental sustainability in Nigeria: A review | Geração de resíduos de macaxeira na Nigéria que podem ocasionar a obtenção de produtos de alto valor agregado | Environmental Challenges | Oghenejoboh *et al*., 2021 |
| 5 | Microalgae in aquatic environs: A sustainable approach for remediation of heavy metals and emerging contaminants | Cultivo de microalgas em ambientes poluídos como estratégia de remediação de contaminantes | Environmental Technology & Innovation | Singh *et al*., 2021 |

Fonte: o autor.

É válido destacar o papel que as microalgas desempenham quando se trata em bioeconomia circular. Esse conceito se baseia em permitir que as sociedades façam a transição para uma economia de base biológica, uma vez que o aumento populacional e o aquecimento global têm criado uma urgente necessidade pela minimização do dano ambiental e pela preservação dos recursos naturais (Kostas *et al*., 2021). Dentro dessa problemática, vale pontuar a importância das microalgas para o desenvolvimento de energias e processos industriais mais limpos. Em alguns trabalhos encontrados, as microalgas são vistas como pontos chave de indústrias que são grandes geradoras de resíduos e das grandes cidades, geradoras de altos volumes de esgoto residencial e industrial (Ali *et al*., 2021; Maurya *et al*., 2022; Bhatia *et al*., 2021; Liu *et al*., 2021).

Grande parte dos trabalhos reforçam o que já é consenso: as aplicações biotecnológicas das microalgas são inúmeras, indo principalmente da remediação de resíduos (Leong *et al*., 2021; Lutzu *et al*., 2021; Singh *et al*., 2021), passando pela bioenergia (Arun *et al*., 2021; Kandasamy *et al*., 2022) e incluindo a produção de moléculas com potencial farmacêutico (Aslam *et al*., 2021; Xia *et al*., 2021; Menaa *et al*., 2021) e para aplicação em saúde humana no geral (Ávila-Román *et al*., 2021).

Também foi encontrada uma revisão bastante interessante do uso de microalgas como bioestimulantes em práticas agrícolas (Kapoore *et al*., 2021). Os autores destacam a necessidade de uma transição de uma economia baseada no petróleo para uma economia de base biológica por meio do desenvolvimento de uma economia circular sustentável e de abordagens de biorrefinaria. Dentro deste contexto, os autores pontuam aspectos-chave como efeitos bioestimulantes específicos causados por extratos de microalgas, viabilidade e potencial de co-culturas e posterior co-aplicação com outros bioestimulantes/biofertilizantes. Por fim, são expostos os gargalos e as perspectivas envolvidas na comercialização bem-sucedida de bioestimulantes de microalgas para práticas agrícolas sustentáveis.

As revisões focadas em bioenergia apareceram com grande frequência, passando por bioetanol (Osman *et al*., 2021), biodiesel (Wang *et al*., 2022; Ma *et al*., 2022), hidrocarvão (Khan *et al*., 2021) e biohidrogênio (Kaloudas *et al*., 2021; Li *et al*., 2022; Goswami *et al*., 2021). Alguns trabalhos focados no processamento da biomassa apareceram com certa frequência (Medeiros *et al*., 2022; Sequeira *et al*., 2021; Yap *et al*., 2021), o que mais uma vez confirma o interesse crescente da indústria e dos pesquisadores nessa biomassa e em seus produtos metabólicos.

## Conclusão

As microalgas possuem um imenso potencial biotecnológico e podem ser a base para uma nova geração de bioprodutos renováveis e sustentáveis, conforme evidenciado pela literatura. Essas biofábricas microscópicas já demonstraram viabilidade técnica para a biossíntese de uma ampla variedade de moléculas de interesse comercial, incluindo biocombustíveis e intermediários da indústria química. Com o amadurecimento das tecnologias de cultivo e processamento, é provável que as microalgas assumam um papel central em biorrefinarias integradas no futuro. Em longo prazo, o aproveitamento biotecnológico das microalgas pode viabilizar a transição para uma bioeconomia regenerativa baseada em recursos renováveis, reduzindo a dependência de matérias-primas fósseis não sustentáveis. Além disso, as microalgas permitem a captura de $CO_2$, contribuindo para estratégias de descarbonização. Contudo, para a plena concretização desse potencial, são necessários avanços científicos multidisciplinares

ainda não alcançados. As áreas de biologia sintética, engenharia metabólica e bioprocessos trazem perspectivas promissoras para tornar viável e economicamente competitivo o uso biotecnológico em larga escala das microalgas, mas é inegável que um longo caminho já foi trilhado revelando perspectivas animadoras.

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