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Review

# The Role of Microalgae in Enhancing Anaerobic Digestion: A Bibliometric Review

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## ABSTRACT

Anaerobic digestion (AD) is a well-established and extensively explored technology for waste management. However, the literature review related to the effect of microalgae on biogas production in the anaerobic co-digestion with different substrates is limited. Using scientometric tools can offer valuable insights into research gaps and emerging trends, facilitate the updating of scientific datasets, and expand knowledge in this field. Therefore, this bibliometric review will focus on the investigation of the advancements, trends, and recent updates in the co-digestion of microalgae with different substrates. The Web of Science database was used for document selection, and the bibliometric analysis was conducted using the VOSviewer version 1.6.19 software. The findings of this study reveal that, up until 2024, the major focus areas in the field are environmental studies related to biogas production, emphasizing microbiological and engineering aspects. Key opportunities and trends identified include the integration of feedstock pretreatment before AD to enhance biogas yield and quality. Adding microalgae as a co-substrate in anaerobic reactors has emerged as a promising strategy to boost AD process efficiency. Microalgae contribute additional organic matter and nutrients for AD and provide environmental benefits such as carbon sequestration and wastewater treatment, aligning with Sustainable Development Goals (SDGs). Gaining a deeper understanding of the role of microalgae in the systems is essential to establishing AD as a profitable and sustainable waste management solution, offering substantial economic and environmental advantages.

**Keywords:** Anaerobic, Microalgae, Co-digestion, Bibliometric, Sustainable Development Goals

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## INTRODUCTION

The increasing energy demand and interest in sustainable solutions emphasize the importance of renewable energy sources (Muhammad Nasir et al., 2012). The production of biogas through anaerobic digestion (AD) should be particularly encouraged in both low- and middle-income countries because of its ability to reduce dependence on fossil fuels and positive contribution to waste management (Rahman et al., 2015). The biogas systems, which produce renewable energy, decrease greenhouse gases, improve waste management, provide nutrient-rich fertilizer, enhance sustainable agriculture, support local economies, create jobs, reduce pollution pressure of the wastes on land and surface waters. The systems also serve most of the United Nations (UN) Sustainable Development Goals (SDGs). Increasing regulatory pressures (Collivignarelli et al., 2015), and the cost of conventional wastewater treatment systems necessitate investigation of the alternative processes such as microalgae. The produced microalgae can be used as a co-substrate in anaerobic processes.

The inclusion of microalgae in AD is frequently emphasized in the literature for its potential to increase methane production. Microalgae, which can adapt to different environments (freshwater, saltwater, and wastewater) with autotrophic, heterotrophic, and mixotrophic feeding modes, stand out with their biomass production capacities and environmental adaptation characteristics (Bingül et al., 2021; Xue et al., 2020). Microalgal biomass increases the biodegradability of waste in addition to being an ideal substrate for bacteria in anaerobic reactors, thereby enhancing methane yield (Costa et al., 2022). It has been shown that protein-rich species, in particular, can accelerate the hydrolysis and methanogenesis stages (Magdalena et al., 2018).

Microalgae like *Chlorella vulgaris* and *Scenedesmus* have been reported to be used for optimizing methane production by increasing the biological degradability of organic waste. For example, the use of *Chlorella vulgaris* together with wastewater treatment sludge, increases methane production while reducing ammonia toxicity, thereby improving process efficiency (Solé-Bundó et al., 2019a). Additionally, the mixture of *Chlorella vulgaris* biomass with cattle manure provides high methane yield (Mahdy et al., 2017). Under mesophilic conditions, *Scenedesmus* biomass has shown promising results with 70% chemical oxygen demand removal and high biogas production (Greses et al., 2017). These findings indicate that both species can be effectively used in anaerobic reactors.

The use of microalgae for bioenergy and alternative material production has been a subject of intense research for decades. However, the practical applications of microalgae for bioenergy purposes have mostly remained at the laboratory scale (Zhu et al., 2020). Despite limited full-scale applications, microalgae have the potential to increase biogas in anaerobic reactors, and they can be used as a valuable substrate. Nevertheless, to increase methane yield, microalgae may need to be pretreated or co-digested with different substrates (Vargas-Estrada et al., 2022). Studies in the literature also include the use of microalgae with sewage sludge, fertilizers, food waste, and industrial waste (Solé-Bundó et al., 2019b).

Microalgae stand out as a valuable resource not only in biogas systems but also in the production of various biofuels (biohydrogen, syngas, biobutanol, and bioethanol) and bio-products (Nagarajan et al., 2021; Dolganyuk et al., 2020). The presence of high amounts of biologically active compounds in their structures, such as proteins, polysaccharides, lipids, vitamins, pigments, and enzymes, makes them an ideal candidate for many sustainable applications (Dolganyuk et al., 2020). Furthermore, it has been shown that microalgae have higher $CO_2$ capture capacities compared to terrestrial plants (Cea-Barcia et al., 2018). The contribution of microalgae cultivation to processes such as wastewater treatment, nutrient recovery, and $CO_2$ capture, offers a synergistic approach for environmental sustainability.

This study aims to systematically evaluate research focused on the role of microalgae in AD processes through bibliometric analysis. The bibliometric technique can provide a comprehensive mapping of the existing literature and identify unrecognized gaps in the research field. Despite the significant interest in the potential of microalgae to enhance methane production for biogas production, there has been a lack of comprehensive research on this topic in the literature. This study aims to contribute to the literature by carefully evaluating the effect of microalgae on AD, analyzing microalgae potential in the system and identifying research gaps.

## MATERIALS AND METHODS

This study used the Web of Science (WoS) database to obtain the scientific output data. The WoS database search was accessed from 2009 up to 1 January 2024. The search keywords used were 'microalgae' and 'biogas' and 'co-digestion,' excluding 'Document Types: Review Article,' 'Publication Years: 2024,' and 'Document Types: Book Chapters.' Our keyword-based search yielded a total of 228 publications in the form of articles. Using VOSviewer version 1.6.19 software, the data was examined for the most productive countries, the most cited documents, co-occurrence networks, keyword clusters of authors, publication years, and major countries involved in research. These components provide a comprehensive perspective on the state of research, highlighting the significance of bibliometric studies. The VOS viewer software used in the study is an open-source and user-friendly program widely used for network creation and visualization of bibliometric data (Van & Waltman, 2010).

In the WoS database, the search results can be refined by the UN SDGs. In our study, the search results are exported to an Excel program, and the percentage of each SDG to the total number of papers was calculated.

All data (n=288) were searched for the specific microalgae species used. This search was carried out through paper abstracts. The data obtained were recorded separately for each microalgae species. A separate classification was made according to the habitats of these microalgae. In addition to this classification for microalgae species, pretreatment methods preferred in the literature were examined over all data (n=228) through the abstracts. The collected data were categorized separately for each pretreatment.

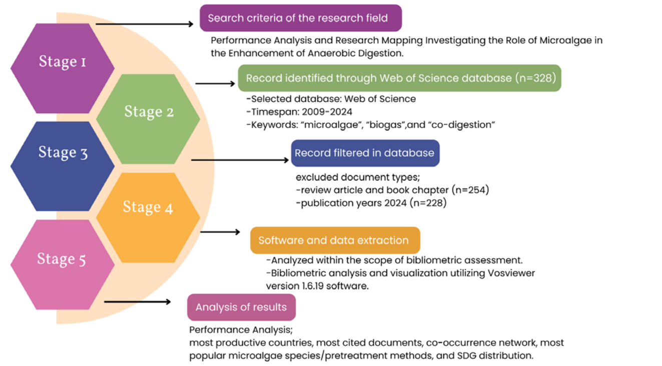


**Figure 1.** Research methodology.

## RESULT AND DISCUSSION

In this study, the bibliometric analysis related to the use of microalgae in AD are presented, focusing on prominent countries, publication numbers by year, most cited articles, and journals. Additionally, the analyses were carried out for determining the relationship between keywords, the most commonly used microalgae species, frequently applied pretreatment methods, and the SDG distributions of the publications. Each section of the results was discussed to provide detailed data on the research progress and trends in the AD technology of microalgae.

**Leading countries for studies on the use of microalgae in AD**

The distribution by country of scientific studies examining the contribution of microalgae to AD is an important tool to understand the research intensity and international trends in the field. In Figure 2, the number of papers published by specific countries is shown on a colour-coded world map. This analysis is derived from bibliometric data and reveals regional differences in scientific productivity in the field.

The map shows that Spain is in the leading position with 64 papers. Spain is followed by China with 28 papers. The USA, which ranks third, makes a significant contribution with 25 articles thanks to diversified academic studies and funding sources in this field. The USA was followed by India (21 papers), Brazil's (18 papers), Poland (12 papers). The countries have more interest in anaerobic co-digestion systems with microalgae. Australia (7 papers), and Egypt (7 papers) contribute to the field with a more limited number of publications. The low number of publications in these countries can be attributed to the interest for other research priorities.

This analysis provides a basis for understanding the geographical differences in scientific research on the contribution of microalgae to AD. The map reveals a significant geographical disparity in scientific publications on microalgae and AD, particularly in Africa and the Middle East. It has been determined that scientific publications are high in some countries and quite low in others. The reason for this is that, despite extensive laboratory-scale studies in this identified field of research, full-scale studies are lacking. Therefore, the studies conducted in this area cannot be applied to real systems, which limits interest for research. This geographical analysis provides a broader perspective on studies conducted on the contribution of microalgae to AD. In future studies, including the missing regions in the research network will contribute to a more balanced increase in knowledge in the field.

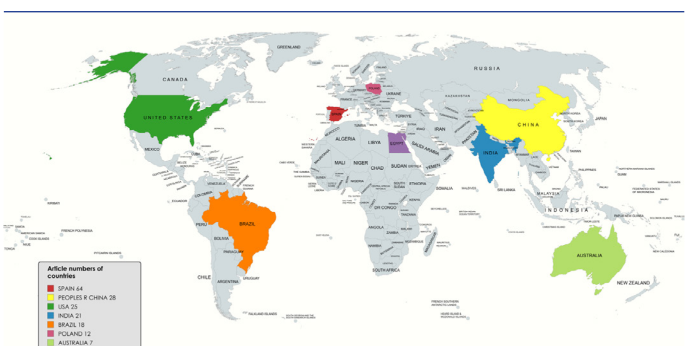


**Figure 2.** The world map displays the major countries involved in research on the use of microalgae in anaerobic studies.

**The most cited publications on the use of microalgae in AD**

Table 1 presents a summary of the top 10 most efficient sources in publishing literature focused on AD with microalgae. This summary includes the total citation count, sources, type of microalgae and co-digestion, and finally, the highest methane yield.

Publications on AD with microalgae have concentrated in the high-impact scientific journal "Bioresource Technology." This journal has 9 publications and a total of 551 citations. The closely following journals are "Science of the Total Environment," "Waste Management," "Biomass Conversion and Biorefinery," and "Water Science and Technology," which have 4, 2, 2, and 2 publications, respectively, and 190, 96, 40, and 27 total citations respectively. These journals have played an important role in publishing academic studies on AD by microalgae. Overall, these top references have contributed to the dissemination of knowledge obtained by researchers and to the advancement of studies on the use of microalgae in anaerobic systems, and represent important platforms for them to promote innovation in this field.

**Preferred microalgae species in bibliometric analysis**

Table 1, which presents the top 10 most cited articles, also highlights the microalgae species preferred in the studies. In order to examine the effective role of microalgae in AD in more detail, the most preferred microalgae species among all bibliometric data (n=228) are given in Figure 3. Publications on AD by microalgae generally focused on *Chlorella* microalgae. 48 articles preferred this microalgae species. *Scenedesmus, Nannochloropsis, Tetraselmis, Spirulina platensis* and *Chlamydomonas* microalgae, which closely follow this microalgae species, were included in 23, 13, 4, 3 and 3 publications, respectively. *Isochrysis galbana, Dunaliella salina, Selenastrum capricornutum, Pinnularia sp., Synechococcus sp.* and *Desertifilum tharense* microalgae are reported in less than 3 publications.

In the light of the data obtained for WoS search, the co-digestion studies focused mainly on *Chlorella* and *Scenedesmus* species, with a smaller number of studies testing *Nannochloropsis* and *Tetraselmis* microalgae. However, considering that microalgae are very diverse with different characteristics, it is important to test the

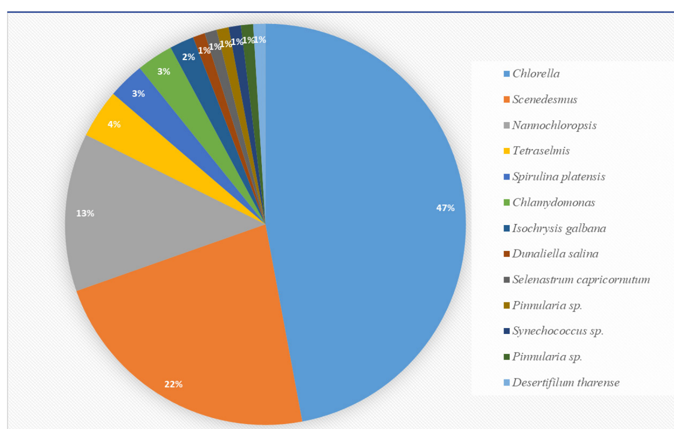


**Figure 3.** Distribution of microalgae used in studies on the role of microalgae in AD.

**Table 1.** The top 10 most cited articles on the role of microalgae in AD.

| Ranking | Citation | Source | Type of microalgae | Waste type use in the co-digestion | Highest Methane yield | References |
|---|---|---|---|---|---|---|
| 1st | 130 | Bioresource technology | *Chlorella* | Waste sludge | 468 mL/g VS | Wang et al., 2013 |
| 2nd | 92 | Science of the Total Environment | *Chlorella sp.* | Primary sludge | - | Solé-Bundó et al., 2017 |
| 3rd | 91 | Bioresource technology | Microalgae mixture | Sewage sludge | 408 ± 16 $Ncm^3$ g $VS^{-1}$ | Olsson et al., 2014 |
| 4th | 85 | Energy Conversion and Management | *Scenedesmus* | Opuntia maxima | 308 ± 22 $LCH_4$ $kgVS^{-1}$ | Ramos-Suárez et al., 2014 |
| 5th | 82 | Renewable Energy | *Isochrysis galbana & Selenastrum capricornutum* | Sewage sludge | 566 ± 5 mLBiogas/gSV | Caporgno et al., 2015 |
| 6th | 73 | Bioresource Technology | - | Barley straw, beet silage and brown seaweed | 404 $L_N$ $kg^{-1}$ VS | Herrmann et al., 2016 |
| 7th | 62 | Bioresource technology | *Nannochloropsis salina* | Corn silage | 0.33 $m^3$ kg $VS^{-1}$ | Schwede et al., 2013 |
| 8th | 57 | Renewable and Sustainable Energy Reviews | - | - | - | Solé-Bundó et al., 2019b |
| 9th | 56 | Bioresource Technology | *Dunaliella salina* | Olive mill solid waste | 48.1 mL $CH_4$/(g VS day) | Fernández-Rodríguez et al., 2014 |
| 10th | 54 | Waste Management | *Chlorella sp.* | Chicken manure | 31.62 $mL.g^{-1}$ VS | Li et al., 2017 |

potential of other microalgae species in anaerobic digestion. The effect of different microalgae species on methane yield in anaerobic co-digestion systems has not yet been fully studied. In addition, this study was conducted only for the WoS database. Future studies can also be conducted to include other databases.

Table 2 shows the natural habitats of microalgae preferred in the studies obtained as a result of bibliometric analysis. Generally, microalgae species living in freshwater were preferred in the studies. Since they are widely used, the selection of certain microalgae species can affect the efficiency of anaerobic systems. Therefore, it seems that the selection of both microalgae species and waste type in anaerobic co-digestion is important for the efficiency of the systems.

**Preferred pretreatment methods in bibliometric analysis**

Anaerobic digestion processes are more efficient if pretreatment methods are properly determined. Bibliometric analysis shows a range of methods to optimise the treatment of biomass (Figure 4). Thermal pretreatment has been reported as one of the most preferred of the pretreatment methods in the literature (Schwede et al., 2013; Mahdy et al., 2015; Chen et al., 2017; Passos et al., 2017; Wang et al., 2017; Cheng et al., 2018; Solé-Bundó et al., 2018; Passos et al., 2018; Solé-Bundó et al., 2020; Llamas et al., 2021; Vassalle et al., 2021). In comparison to other methods, thermal pretreatment is preferred since it is capable of destroying the structure of the biomass and increasing the amount of biogas produced (Solé-Bundó et al., 2018). However, in the studies, the thermal pretreatment process has not been evaluated in terms of energy usage or sustainability in general. A few studies that have evaluated it have shown that some part of the energy required by the pretreatment process can be maintained from the produced biogas. Carrillo-Reyers et al. (2021) assessed the thermal energy required for thermophilic digestion (50 kWh d-1) and stated that the energy can be provided by the wastewater treatment plant. Vassalle et al. (2022) performed an energy assessment in terms of the energy input and output values for the anaerobic reactor. Another method, alkaline pretreatment, is the second most common approach in five studies (Cheng et al., 2018; Panyaping et al., 2018; Wannapokin et al., 2018; Du et al., 2020; Fardinpoor et al., 2022). Ultrasonication with three papers is the third most common approach (Caporgno et al., 2016; Saleem et al., 2020; Debowski et al., 2022). These methods are useful due to their ability to dissolve organic matter and increase microbial accessibility. Enzymatic pretreatment offers a biotechnological alternative in three studies (Prajapati et al., 2015; Avila et al., 2021; Llamas et al., 2021). Another two studies combine the advantages of thermal and alkaline approaches (Solé-Bundó et al., 2017; Fu et al., 2023). The various pretreatment techniques, each reported in a separate study, illustrate the experimental diversity in the field. Acid hydrolysis (Cheng et al., 2018), autohydrolysis (Arias et al., 2018), urea treatment (Yu et al., 2021), hydrothermal treatments (Bohutskyi et al., 2019), microwave-assisted pretreatments (Feng et al., 2019), and thermo-anaerobic treatment (Damtie et al.,

**Table 2.** Habitats of microalgae included in the studies used in bibliometric analysis.

| Types of microalgae | Number of documents | Fresh water | Saline water |
|---|---|---|---|
| *Chlorella* | 48 | + | |
| *Scenedesmus* | 23 | + | |
| *Nannochloropsis* | 13 | | + |
| *Tetraselmis* | 4 | | + |
| *Spirulina platensis* | 3 | + | |
| *Chlamydomonas* | 3 | + | |
| *Isochrysis galbana* | 2 | | + |
| *Dunaliella salina* | 1 | | + |
| *Selenastrum capricornutum* | 1 | + | |
| *Pinnularia sp.* | 1 | + | |
| *Synechococcus sp.* | 1 | + | + |
| *Desertifilum tharense* | 1 | + | |

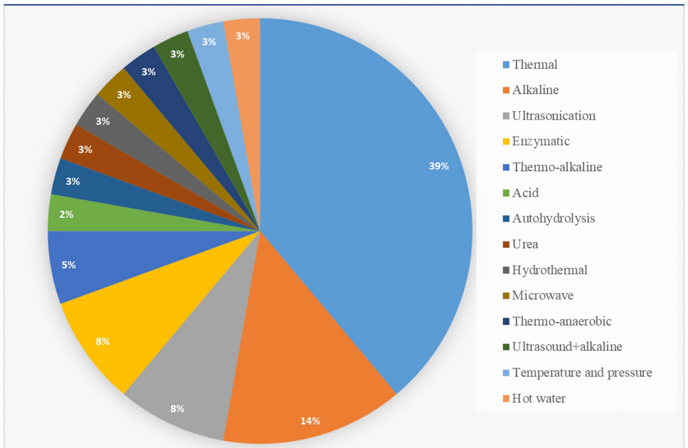


**Figure 4.** Distribution of pretreatment methods used in studies on the role of microalgae in AD.

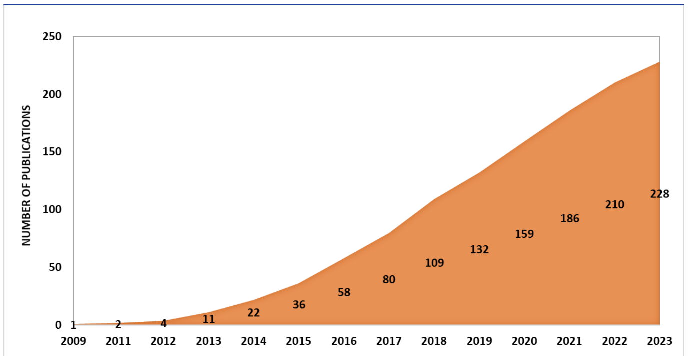


**Figure 5.** Evolution of the number of publications over the years (2009–2023 and 2009–2023).

2021) are some of them. Hybrid strategies utilizing ultrasound and alkaline treatment (Caporgno et al., 2016), as well as variations in temperature and pressure (Arelli et al., 2020), demonstrate novel methods to enhance substrate degradability. Ultimately, hot water pretreatment (Saleem et al., 2020) is evaluated as a cost-effective and eco-friendly solution. This distribution highlights the dynamic and exploratory aspects of pretreatment research on anaerobic digestion.

### Yearly Trends and Keyword Co-Occurrences in Bibliometric analysis

Figure 5 shows data from the WoS related to the distribution trend of all articles on the use of microalgae in AD until the beginning of 2024. The results show a consistent upward trend in research on the use of microalgae in AD from 2009 to 2021. A noticeable decrease in publication output occurred from 2021 to the beginning of 2024. It has been stated that there is a restricted applicability of microalgae in full-scale anaerobic systems (Díez-Montero et al., 2020) and this decrease in the publications may be linked to this situation. In addition, an analysis of studies on microalgae over the last five years shows a strong research focus on bioengineering, ecology and pharmaceutical sciences. A search of the WoS database using the only keyword as "microalgae" revealed nearly 15,000 publications between 2021 and 2025, excluding review articles and book chapters (WoS link for microalgae search). When the research areas were analyzed for the microalgae, the results highlighted not only the continued importance of microalgae in the energy sector but also their growing importance in ecological applications, food production, and pharmaceutical research. Therefore, the observed decline in research publications can also be attributed to a shift in research priorities for microalgae.

This study uses a keyword co-occurrence map to examine the scientific literature on the role of microalgae in AD and biogas production (Figure 6). The VOSviewer software produces a map showing microalgae, biogas, co-digestion, and AD as the main themes explored in the literature. The colour pattern of the map indicates the frequency of terms over a given time period. Blue shades indicate publications from 2014 and earlier. Within this period, the terms 'waste-activated sludge' and 'anaerobic digestion' are prevalent. The green shades highlight topics such as 'biomass', 'methane production' and 'C/N ratio', all of which were analysed from 2016 to 2018. The yellow tones indicate topics that appeared in the literature from 2020 onwards, including the keywords "biomethane potential", "mixture design" and "microalgal biomass". Researchers have investigated methods to optimize processes (C/N ratio, methane potential) and the digestion of microalgae using different biomasses (sewage sludge, chicken manure). The analysis concludes that microalgae are considered an innovative substrate for biogas production and represent a crucial area of research for sustainable energy production.

Figure 7 shows the importance levels of keywords in the bibliometric analysis according to the criteria of "occurrences" (frequency) and "total link strength". This study, when evaluating the role of microalgae in AD and biogas production through keyword analysis, shows that the keyword 'microalgae' is the most frequently found in the literature (n = 25) and has the strongest association strength (114). On the other hand, the term 'biogas' appears 22 times and has a connection strength of 106, suggesting that microalgae play an important role in biogas production. The terms 'co-digestion' and 'anaerobic co-digestion' stand out with n=19 and n=18 occurrences respectively and have high connection values (83-84). This finding indicates that extensive research has been conducted on microalgae in digestion processes with different biomass. On the contrary, the term 'anaerobic digestion' is observed with lower frequency (n=11) and connection strength (55). This indicates that microalgae research is concerned with AD processes, but the main focus is on co-digestion and biogas production. Finally, the study shows that microalgae are an important area of research for biofuel production and sustainable energy systems. They are also very important for biogas production and especially for co-digestion studies.

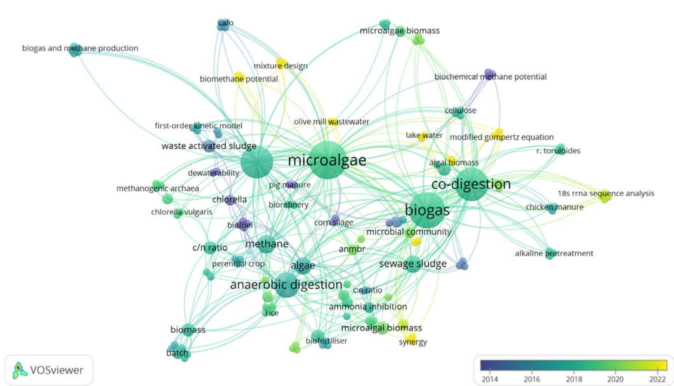


**Figure 6.** Role of microalgae in AD: Bibliometric Keyword Co-Occurrence Network (2009-2023).

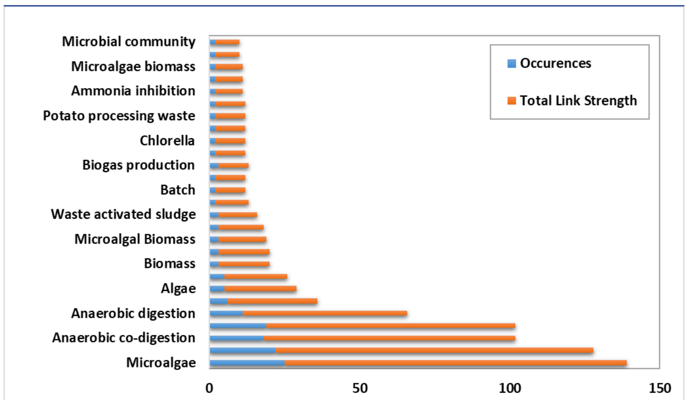


**Figure 7.** Distribution of Keywords by Occurrence and Total Link Strength.

## Alignment of Microalgae and Anaerobic Digestion Studies with SDGs

Figure 8 also illustrates the strong relevance of studies on the role of microalgae in AD to the SDGs. According to the data, a very high proportion (98.25 percent) of studies using microalgae in AD processes were associated with "clean water and sanitation" (SDG 6). For "affordable and clean energy" (SDG 7), AD offers a significant strategy to provide clean energy through biogas production. Additionally, in line with the goals of "responsible production and consumption" (SDG 12), AD supports the recovery of biomass and waste, contributing to responsible consumption targets. Although "climate action" (SDG 13) has a low representation rate of 0.44%, the goal of "increasing climate resilience" stated in SDG 13.2.1 can be supported by the adaptability of microalgae-based anaerobic systems to waste sources and energy security. AD processes provide contributions to this target by providing carbon emission reduction and renewable energy generation. The lack of studies directly related to climate change mitigation provides an opportunity for future research in this field. The underrepresentation of SDG 13 in the context of microalgae and anaerobic digestion research may highlight the gap in carbon footprint studies for microalgae-based systems. Addressing these gaps will require a concerted effort to prioritize research that assesses the environmental impacts of integrating microalgae into anaerobic systems, as well as fostering interdisciplinary collaboration and funding for studies that emphasize climate action. In this way, the potential of microalgae to contribute to sustainable development and climate change mitigation can be more effectively realized.This study is an important resource to assess the contribution of AD and microalgae to sustainable development goals. Future research should focus on further unlocking the potential of AD in the context of climate change and energy efficiency.

To summarise the study in general, this bibliometric analysis covers the studies on this subject in the literature. In addition to other bibliometric analysis data, the study was detailed in terms of microal-

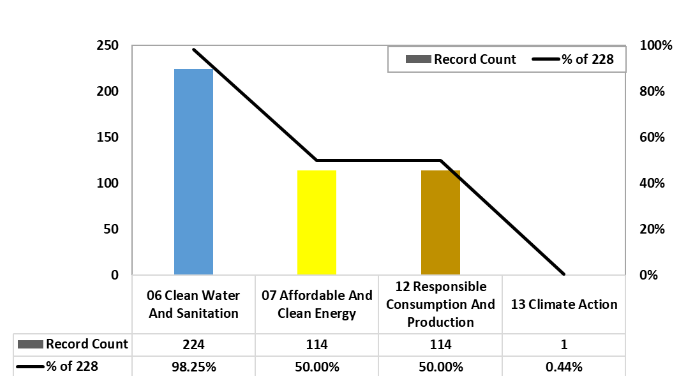


**Figure 8.** SDG Distribution of Microalgae and AD Studies.

gae species used in the studies, pre-treatment methods, and link to the SDGs. Some research gaps were identified in the literature. The primary limitations are that most studies are confined to laboratory-scale experiments, with a focus on certain preferred microalgae species. Additionally, there is a lack of optimization studies, integration of new technologies into existing systems, and sufficient evidence to demonstrate sustainability and economic feasibility. This bibliometric analysis is expected to play an important role in the development of future studies in this field.

## CONCLUSION

This research is a bibliometric analysis of the research on the use of microalgae as co-digestion in anaerobic systems and the resulting biogas production. From the bibliometric analysis, it can be concluded that 70% of the studies on the use of microalgae in anaerobic systems were published until 2021. Most of the research was linked to the SDGs on "clean water and sanitation" (SDG 6), "affordable and clean energy" (SDG 7) and "responsible production and consumption" (SDG 12). The most commonly used microalgae species are *Chlorella, Scenedesmus, Nannochloropsis, Tetraselmis, Spirulina platensis*, and *Chlamydomonas* microalgae. Microalgae living in fresh waters were generally preferred. In some of the anaerobic systems where microalgae were used, pretreatment was preferred. The most commonly used pretreatments were thermal, alkaline, ultrasonication, enzymatic, and thermo-alkaline, respectively.

Given the current findings, future studies should not be limited to lab-scale, and full-scale studies should be attempted. In addition, in anaerobic systems where certain microalgae species are favoured, more comprehensive studies are needed to understand the process mechanism of other microalgae species. Little information is available in the literature on the microalgae-methanogen relationship, and further studies are needed to understand this. Future studies with the integration of advanced technological applications (smart sensor and automation technologies, etc.) may provide more insights into biogas volume and efficiency in these systems.

## REFERENCES

Avila, R., Carrero, E., Crivilles, E., Mercader, M., Vicent, T., & Blánquez, P. (2020). Effects of low temperature thermal pretreatments in solubility and co-digestion of waste activated sludge and microalgae mixtures. Algal Research, 50, 101965.https://doi.org/10.1016/j.algal.2020.101965

Avila, R., Carrero, E., Vicent, T., & Blánquez, P. (2021). Integration of enzymatic pretreatment and sludge co-digestion in biogas production from microalgae. Waste Management, 124, 254-263. https://doi.org/10.1016/j.wasman.2021.01.042

Arelli, V., Juntupally, S., Begum, S., & Anupoju, G. R. (2020). Significance of pretreatment in enhancing the performance of dry anaerobic digestion of food waste: an insight on full scale implementation strategy with theoretical analogy. Processes, 8(09), 1018.https://doi.org/10.3390/pr8091018

Arias, D. M., Solé-Bundó, M., Garfí, M., Ferrer, I., García, J., & Uggetti, E. (2018). Integrating microalgae tertiary treatment into activated sludge systems for energy and nutrients recovery from wastewater. Bioresource technology, 247, 513-519.https://doi.org/10.1016/j.biortech.2017.09.123

Bingül, D. Y., Demirel, Z., & Dalay, M. C. (2021). Chlorella sorokiniana'nın İzolasyonu, Moleküler Tanılanması, Fototrofik, Miksotrofik ve Heterotrofik Üretimi. Journal of Limnology and Freshwater Fisheries Research, 7(2), 128-137. https://doi.org/10.17216/limnofish.703234

Bohutskyi, P., Phan, D., Spierling, R. E., Kopachevsky, A. M., Bouwer, E. J., Lundquist, T. J., & Betenbaugh, M. J. (2019). Production of lipid-containing algal-bacterial polyculture in wastewater and biomethanation of lipid extracted residues: Enhancing methane yield through hydrothermal pretreatment and relieving solvent toxicity through co-digestion. Science of the Total Environment, 653, 1377-1394.https://doi.org/10.1016/j.scitotenv.2018.11.026

Caporgno, M. P., Trobajo, R., Caiola, N., Ibáñez, C., Fabregat, A., & Bengoa, C. (2015). Biogas production from sewage sludge and microalgae co-digestion under mesophilic and thermophilic conditions. Renewable Energy, 75, 374-380. https://doi.org/10.1016/j.renene.2014.10.019

Caporgno, M. P., Clavero, E., Torras, C., Salvadó, J., Lepine, O., Pruvost, J.,& Bengoa, C. (2016). Energy and nutrients recovery from lipid-extracted nannochloropsis via anaerobic digestion and hydrothermal liquefaction. ACS Sustainable Chemistry & Engineering, 4(6), 3133-3139.

Carrillo-Reyes, J., Buitrón, G., Arcila, J. S., & López-Gómez, M. O. (2021). Thermophilic biogas production from microalgae-bacteria aggregates: biogas yield, community variation and energy balance. Chemosphere, 275, 129898.https://doi.org/10.1016/j.chemosphere.2021.129898

Cea-Barcia, G., López-Caamal, F., Torres-Zúñiga, I., & Hernández-Escoto, H. (2018). Biogas purification via optimal microalgae growth: A literature review. Biotechnology progress, 34(6), 1513-1532. https://doi.org/10.1002/btpr.2686

Chen, X., Xiang, X., Dai, R., Wang, Y., & Ma, P. (2017). Effect of low temperature of thermal pretreatment on anaerobic digestion of textile dyeing sludge. Bioresource technology, 243, 426-432.https://doi.org/10.1016/j.biortech.2017.06.138

Cheng, Q., Deng, F., Li, H., Qin, Z., Wang, M., & Li, J. (2018). Nutrients removal from the secondary effluents of municipal domestic wastewater by Oscillatoria tenuis and subsequent co-digestion with pig manure. Environmental technology, 39(24), 3127-3134.https://doi.org/10.1080/09593330.2017.1375020

Collivignarelli, M. C., Abbà, A., Padovani, S., Frascarolo, M., Sciunnach, D., Turconi, M., & Orlando, M. (2015). Recovery of sewage sludge on agricultural land in Lombardy: current issues and regulatory scenarios. Environmental Engineering & Management Journal (EEMJ), 14(7).

Costa, J. A. V., Bezerra, P. Q. M., Moreira, J. B., Molina, A. N., & de Morais, M. G. (2022). Biogas from microalgae: Production approaches and strategies for process optimization. Role of Microbes in Industrial Products and Processes, 305-329. https://doi.org/10.1002/9781119901198.ch12

Damtie, M. M., Shin, J., Jang, H. M., Cho, H. U., Wang, J., & Kim, Y. M. (2021). Effects of biological pretreatments of microalgae on hydrolysis, biomethane potential and microbial community. Bioresource Technology, 329, 124905.https://doi.org/10.1016/j.biortech.2021.124905

Dębowski, M., Kazimierowicz, J., Świca, I., & Zieliński, M. (2022). Ultrasonic Disintegration to Improve Anaerobic Digestion of Microalgae with Hard Cell Walls—Scenedesmus sp. and Pinnularia sp. Plants, 12(1), 53.https://doi.org/10.3390/plants12010053

Díez-Montero, R., Vassalle, L., Passos, F., Ortiz, A., García-Galán, M. J., García, J., & Ferrer, I. (2020). Scaling-up the anaerobic digestion of pretreated microalgal biomass within a water resource recovery facility. Energies, 13(20), 5484.https://doi.org/10.3390/en13205484

Dolganyuk, V., Belova, D., Babich, O., Prosekov, A., Ivanova, S., Katserov, D., & Sukhikh, S. (2020). Microalgae: A promising source of valuable bioproducts. Biomolecules, 10(8), 1153. https://doi.org/10.3390/biom10081153

Du, X., Tao, Y., Liu, Y., & Li, H. (2020). Stimulating methane production from microalgae by alkaline pretreatment and co-digestion with sludge. Environmental technology.https://doi.org/10.1080/09593330.2018.1540665

Fardinpoor, M., Perendeci, N. A., Yılmaz, V., Taştan, B. E., & Yılmaz, F. (2022). Effects of hydrodynamic cavitation-assisted NaOH pretreatment on biofuel production from Cyanobacteria: promising approach. Bioenergy Research, 15(1), 289-302.https://doi.org/10.1007/s12155-021-10286-0

Feng, R., Zaidi, A. A., Zhang, K., & Shi, Y. (2019). Optimisation of microwave pretreatment for biogas enhancement through anaerobic digestion of microalgal biomass. Periodica Polytechnica Chemical Engineering, 63(1), 65-72.https://doi.org/10.3311/PPch.12334

Fernández-Rodríguez, M. J., Rincón, B., Fermoso, F. G., Jiménez, A. M., & Borja, R. (2014). Assessment of two-phase olive mill solid waste and microalgae co-digestion to improve methane production and process kinetics. Bioresource Technology, 157, 263-269. https://doi.org/10.1016/j.biortech.2014.01.096

Greses, S., Gaby, J. C., Aguado, D., Ferrer, J., Seco, A., & Horn, S. J. (2017). Microbial community characterization during anaerobic digestion of Scenedesmus spp. under mesophilic and thermophilic conditions. Algal research, 27, 121-130. https://doi.org/10.1016/j.algal.2017.09.002

Herrmann, C., Kalita, N., Wall, D., Xia, A., & Murphy, J. D. (2016). Optimised biogas production from microalgae through co-digestion with carbon-rich co-substrates. Bioresource Technology, 214, 328-337. https://doi.org/10.1016/j.biortech.2016.04.119

Llamas, M., Magdalena, J. A., Greses, S., Tomás-Pejó, E., & González-Fernández, C. (2021). Insights on the microbial communities developed during the anaerobic fermentation of raw and pretreated microalgae biomass. Chemosphere, 263, 127942.https://doi.org/10.1016/j.chemosphere.2020.127942

Li, R., Duan, N., Zhang, Y., Liu, Z., Li, B., Zhang, D., & Dong, T. (2017). Anaerobic co-digestion of chicken manure and microalgae Chlorella sp.: Methane potential, microbial diversity and synergistic impact evaluation. Waste Management, 68, 120-127. https://doi.org/10.1016/j.wasman.2017.06.028

Magdalena, J. A., Ballesteros, M., & González-Fernandez, C. (2018). Efficient anaerobic digestion of microalgae biomass: proteins as a key macromolecule. Molecules, 23(5), 1098.https://doi.org/10.3390/molecules23051098

Mahdy, A., Fotidis, I. A., Mancini, E., Ballesteros, M., González-Fernández, C., & Angelidaki, I. (2017). Ammonia tolerant inocula provide a good base for anaerobic digestion of microalgae in third generation biogas process. Bioresource Technology, 225, 272-278. https://doi.org/10.1016/j.biortech.2016.11.086

Muhammad Nasir, I., Mohd Ghazi, T. I., & Omar, R. (2012). Production of biogas from solid organic wastes through anaerobic digestion: a review. Applied microbiology and biotechnology, 95, 321-329. https://doi.org/10.1007/s00253-012-4152-7

Nagarajan, D., Dong, C. D., Chen, C. Y., Lee, D. J., & Chang, J. S. (2021). Biohydrogen production from microalgae—Major bottlenecks and future research perspectives. Biotechnology journal, 16(5), 2000124. https://doi.org/10.1002/biot.202000124

Olsson, J., Feng, X. M., Ascue, J., Gentili, F. G., Shabiimam, M. A., Nehrenheim, E., & Thorin, E. (2014). Co-digestion of cultivated microalgae and sewage sludge from municipal waste water treatment. Bioresource technology, 171, 203-210. https://doi.org/10.1016/j.biortech.2014.08.069

Panyaping, K., Khiewwijit, R., & Wongpankamol, P. (2018). Enhanced biogas production potential of microalgae and swine wastewater using co-digestion and alkaline pretreatment. Water Science and Technology, 78(1), 92-102.https://doi.org/10.2166/wst.2018.077

Prajapati, S. K., Malik, A., Vijay, V. K., & Sreekrishnan, T. R. (2015). Enhanced methane production from algal biomass through short duration enzymatic pretreatment and codigestion with carbon rich waste. RSC advances, 5(82), 67175-67183.

Passos, F., Gutiérrez, R., Uggetti, E., Garfí, M., García, J., & Ferrer, I. (2017). Towards energy neutral microalgae-based wastewater treatment plants. Algal research, 28, 235-243.https://doi.org/10.1016/j.algal.2017.11.006

Passos, F., Cordeiro, P. H. M., Baeta, B. E. L., de Aquino, S. F., & Perez-Elvira, S. I. (2018). Anaerobic co-digestion of coffee husks and microalgal biomass after thermal hydrolysis. Bioresource technology, 253, 49-54.https://doi.org/10.1016/j.biortech.2017.12.071

Rahman, M. H., Mia, S. H., Nessa, A., Badhan, M. A., & Islam, M. A. (2015). Reducing the Volume of Garbage and Production of Biogas through Anaerobic Decomposition. Journal of Environmental Science and Natural Resources, 8(2), 33-36.

Ramos-Suárez, J. L., Martínez, A., & Carreras, N. (2014). Optimization of the digestion process of Scenedesmus sp. and Opuntia maxima for biogas production. Energy conversion and management, 88, 1263-1270. https://doi.org/10.1016/j.enconman.2014.02.064

Saleem, M., Hanif, M. U., Bahadar, A., Iqbal, H., Capareda, S. C., & Waqas, A. (2020). The effects of hot water and ultrasonication pretreatment of microalgae (Nannochloropsis oculata) on biogas production in anaerobic co-digestion with cow manure. Processes, 8(12), 1558. https://doi.org/10.3390/pr8121558

Scarcelli, P. G., Serejo, M. L., Paulo, P. L., & Boncz, M. Á. (2020). Evaluation of biomethanization during co-digestion of thermally pretreated microalgae and waste activated sludge, and estimation of its kinetic parameters. Science of the Total Environment, 706, 135745.https://doi.org/10.1016/j.scitotenv.2019.135745

Schwede, S., Kowalczyk, A., Gerber, M., & Span, R. (2013). Anaerobic co-digestion of the marine microalga Nannochloropsis salina with energy crops. Bioresource technology, 148, 428-435. https://doi.org/10.1016/j.biortech.2013.08.157

Solé-Bundó, M., Cucina, M., Folch, M., Tàpias, J., Gigliotti, G., Garfí, M., & Ferrer, I. (2017). Assessing the agricultural reuse of the digestate from microalgae anaerobic digestion and co-digestion with sewage sludge. Science of the Total Environment, 586, 1-9. https://doi.org/10.1016/j.scitotenv.2017.02.006

Solé-Bundó, M., Salvadó, H., Passos, F., Garfí, M., & Ferrer, I. (2018). Strategies to optimize microalgae conversion to biogas: Co-digestion, pretreatment and hydraulic retention time. Molecules, 23(9), 2096.https://doi.org/10.3390/molecules23092096

Solé-Bundó, M., Garfí, M., Matamoros, V., & Ferrer, I. (2019a). Co-digestion of microalgae and primary sludge: Effect on biogas production and microcontaminants removal. Science of the total environment, 660, 974-981. https://doi.org/10.1016/j.scitotenv.2019.01.011

Solé-Bundó, M., Passos, F., Romero-Güiza, M. S., Ferrer, I., & Astals, S. (2019b). Co-digestion strategies to enhance microalgae anaerobic digestion: A review. Renewable and Sustainable Energy Reviews, 112, 471-482. https://doi.org/10.1016/j.rser.2019.05.036

Solé-Bundó, M., Garfí, M., & Ferrer, I. (2020). Pretreatment and co-digestion of microalgae, sludge and fat oil and grease (FOG) from microalgae-based wastewater treatment plants. Bioresource technology, 298, 122563.https://doi.org/10.1016/j.biortech.2019.122563

Van Eck, N., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. scientometrics, 84(2), 523-538. https://doi.org/10.1007/s11192-009-0146-3

Vargas-Estrada, L., Longoria, A., Arenas, E., Moreira, J., Okoye, P. U., Bustos-Terrones, Y., & Sebastian, P. J. (2022). A review on current trends in biogas production from microalgae biomass and microalgae waste by anaerobic digestion and co-digestion. BioEnergy Research, 15(1), 77-92. https://doi.org/10.1007/s12155-021-10276-2

Vassalle, L., Passos, F., Rosa-Machado, A. T., Moreira, C., Reis, M., de Freitas, M. P., & Mota, C. R. (2022). The use of solar pre-treatment as a strategy to improve the anaerobic biodegradability of microalgal biomass in co-digestion with sewage. Chemosphere, 286, 131929. https://doi.org/10.1016/j.chemosphere.2021.131929

Wang, M., Sahu, A. K., Rusten, B., & Park, C. (2013). Anaerobic co-digestion of microalgae Chlorella sp. and waste activated sludge. Bioresource technology, 142, 585-590.https://doi.org/10.1016/j.biortech.2013.05.096

Wang, M., Lee, E., Dilbeck, M. P., Liebelt, M., Zhang, Q., & Ergas, S. J. (2017). Thermal pretreatment of microalgae for biomethane production: experimental studies, kinetics and energy analysis. Journal of Chemical Technology & Biotechnology, 92(2), 399-407. https://doi.org/10.1002/jctb.5018

Wannapokin, A., Ramaraj, R., Whangchai, K., & Unpaprom, Y. (2018). Potential improvement of biogas production from fallen teak leaves with co-digestion of microalgae. 3 Biotech, 8, 1-18.https://doi.org/10.1007/s13205-018-1084-7

Xue, Z., Yu, Y., Yu, W., Gao, X., Zhang, Y., & Kou, X. (2020). Development prospect and preparation technology of edible oil from microalgae. Frontiers in Marine Science, 7, 402. https://doi.org/10.3389/fmars.2020.00402

Yu, Q., Sun, C., Liu, R., Yellezuome, D., Zhu, X., Bai, R., & Sun, M. (2021). Anaerobic co-digestion of corn stover and chicken manure using continuous stirred tank reactor: The effect of biochar addition and urea pretreatment. Bioresource Technology, 319, 124197.https://doi.org/10.1016/j.biortech.2020.124197

Zhu, Z., Jiang, J., & Fa, Y. (2020). Overcoming the biological contamination in microalgae and cyanobacteria mass cultivations for photosynthetic biofuel production. Molecules, 25(22), 5220. https://doi.org/10.3390/molecules25225220