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An Extensive Analysis, Patterns, and Worldwide Viewpoints on the Life Cycle Assessment of Seaweeds: A Bibliometric Study (2004–2024)

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ABSTRACT

Research on seaweed has seen substantial growth in life cycle assessment (LCA) studies in recent decades. This bibliometric study analyzed the literature on the LCA of seaweed published between 2004 and 2024. It employed scientific mapping techniques and performance analysis to reveal trends, frameworks, and patterns in the LCA of seaweed. The study examined related topic clusters, leading authors, influential papers, countries of origin, and the impact of the sustainable development goals (SDGs). Additionally, it highlighted gaps in the current research. Data from relevant articles sourced from the Web of Science were analyzed using VOSviewer software to identify key themes and trends in the field. The findings show a significant expansion in LCA research on seaweed, particularly post-2010, with 62% of the articles published in the last five years. Prominent journals and institutions have played a pivotal role in the rapid development of this research area. Key topics include energy fuels, environmental science, ecology, engineering, and biotechnology. The LCA of seaweed research contributes significantly to SDGs 6 (Clean Water and Sanitation) and 13 (Climate Action).

INTRODUCTION

Global seaweed production has increased significantly, with marine macroalgae yields tripling between 2000 and 2018. In 2018, cultivated seaweeds comprised 97.1% of the 32.4 million tonnes of global seaweed production **(Desai & Reddy, 2023)**. China dominates this industry, contributing 59% of the total global output **(Wang *et al*., 2023)**. Despite this growth, the sector faces several challenges, including disease outbreaks, pollution, climate change, and inadequate compensation for farmers **(Msuya *et al*., 2022)**. These challenges call for careful consideration of the environmental impacts of seaweed cultivation, despite its promising role in mitigating and adapting to climate change. In addition to its potential as a food source and raw material for various industries, seaweed farming may also generate emissions, underscoring the need for a comprehensive ecological assessment using LCA **(Langlois *et al*. 2012; Duarte *et al*., 2022; Nilsson *et al*. 2022; Ayala *et al*. 2023)**.

LCA studies on seaweed have identified several key environmental concerns, such as fuel consumption by boats during sea operations, the environmental impact of using nylon lines and floating objects, and energy consumption at the farm level **(Thomas *et al*., 2024)**. However, seaweed cultivation also holds promise for reducing eutrophication by reusing surplus nutrients, contributing to sustainable resource cycling **(Seghetta *et al*., 2016)**. Additionally, seaweed-based products like bioplastics can help mitigate the environmental impact of plastic production and disposal **(Ayala *et al*., 2023)**. With advancements in cultivation techniques, improved crop yields, and better infrastructure, the negative effects of seaweed farming—especially in food production—could be substantially reduced **(Slegers *et al*., 2021)**. Through LCA, ecological efficiency can be enhanced at every stage of seaweed production, from seed preparation to cultivation, processing, and utilization.

Recent years have seen an increase in LCA studies on seaweed **(Seghetta & Goglio, 2020)**. For example, **Thomas *et al*. (2021)** used LCA to examine the seed preparation, sowing, cultivation, harvesting, and preservation stages. **Seghetta and Goglio (2020)** explored the relationship between the seaweed growing cycle and biofuel production, while **Nilsson *et al*. (2022)** analyzed the cultivation and manufacturing processes of bioplastics and biogas. **Ayala *et al*. (2023)** specifically focused on the cultivation and production cycle of bioplastics. However, a comprehensive bibliometric analysis of LCA research on seaweed is still lacking, making it a valuable area for further investigation.

Bibliometric analysis is a widely used method for assessing trends and research patterns across scientific disciplines, enabling a systematic evaluation of global trends and potential future research directions **(Veiga-del-Baño *et al*., 2023)**. One key tool in bibliometric analysis is co-citation analysis, which helps identify the knowledge base within a research area by analyzing referenced documents, authors, and the origins of references **(Li *et al*., 2022)**. Additionally, co-occurrence and grouping analyses offer insights into emerging research trends by examining key terms **(Kıllı & Kefe, 2024)**. VOSviewer is a popular tool for bibliometric analysis, enabling the examination of marine sciences **(Huang & Chen, 2024; Quan & Jin, 2024)**, agriculture **(Ikhwani *et al*., 2024; Kıllı & Kefe, 2024)**, co-citation and co-occurrence networks across various fields, and including engineering **(Sedira *et al*., 2024; Xu *et al*., 2024)**. By analyzing citation connections and keyword frequencies, bibliometric analysis helps researchers understand progress and patterns in a given field **(Tang *et al*., 2023)**.

This study employed various analytical methods. Quantitative analysis was used to assess the publication dispersion over time and to identify shifting patterns among leading contributing countries. Co-citation analysis provided insights into significant research topics, enhancing our understanding of the academic network. The size of nodes represents the cumulative citation count for specific articles **(Dirpan *et al*., 2023; Huang & Chen, 2024)**. Co-occurrence and group analyses helped identify unified research directions and focal points. Analyzing node sizes, keyword frequency, and grouping patterns revealed key trends and patterns in the literature **(Buber & Koseoglu, 2022; Dirpan *et al*., 2023)**. The bibliometric investigation was carried out using the VOSviewer program, reviewing the research of LCA of seaweed collected from the prestigious Web of Science (WoS) catalogue. This study aimed to provide a concise overview of the research topics and primary areas of focus, identify the unique characteristics of publications, clarify the basics of the areas, and map out the research trajectory in the field of LCA for seaweed.

MATERIALS AND METHODS

1. Data source and processing

This study provides an extensive analysis of trends and global perspectives on Life Cycle Assessment (LCA) of seaweed. Data were sourced from the Science Citation Index Expanded database via the Web of Science, accessed on February 12, 2025. A targeted search query was employed: "TS=("life cycle assessment" AND ((seaweed* or algae*))" yielding 1,423 records. A filter was applied to refine the results based on document type (review article, book chapter, proceeding paper, and early access), language (English), and publication period (2003-2023). The refined search query was as follows: TS=("life cycle assessment" AND ((seaweed* or alga*))) and Article or Review Article or Book Chapters or Proceeding Paper or Early Access (Document Types) and English (Languages) and 2002 (Exclude – Publication Years) and 2001 (Exclude – Publication Years)", resulting in 1,308 articles. The data were processed using OpenRefine version 3.7.9 to eliminate data inconsistencies, including duplicate terms such as "LCA" and "LCA (life cycle assessment)", which were unified under the label "LCA." The total amount of words combined was 300 that were removed. Singular and plural forms of terms like "seaweed" and "seaweeds" were also merged, reducing the data to 67 combined terms.

2. Analytical methods and tools

VOSviewer 1.6.20 was selected for its ability to visualize co-citation networks, while Tableau 2022.2 and SigmaPlot 15.0 were used for statistical analysis and data visualization. Data were exported using Microsoft office. This study combines statistical and content analysis to comprehensively assess developments and trends in LCA-related seaweed research. Statistical analysis was used to quantify trends in the data, while content analysis provided qualitative insights into research topics and keywords. Fig. (1) illustrates the research workflow, which outlines the key stages of the bibliometric analysis process.

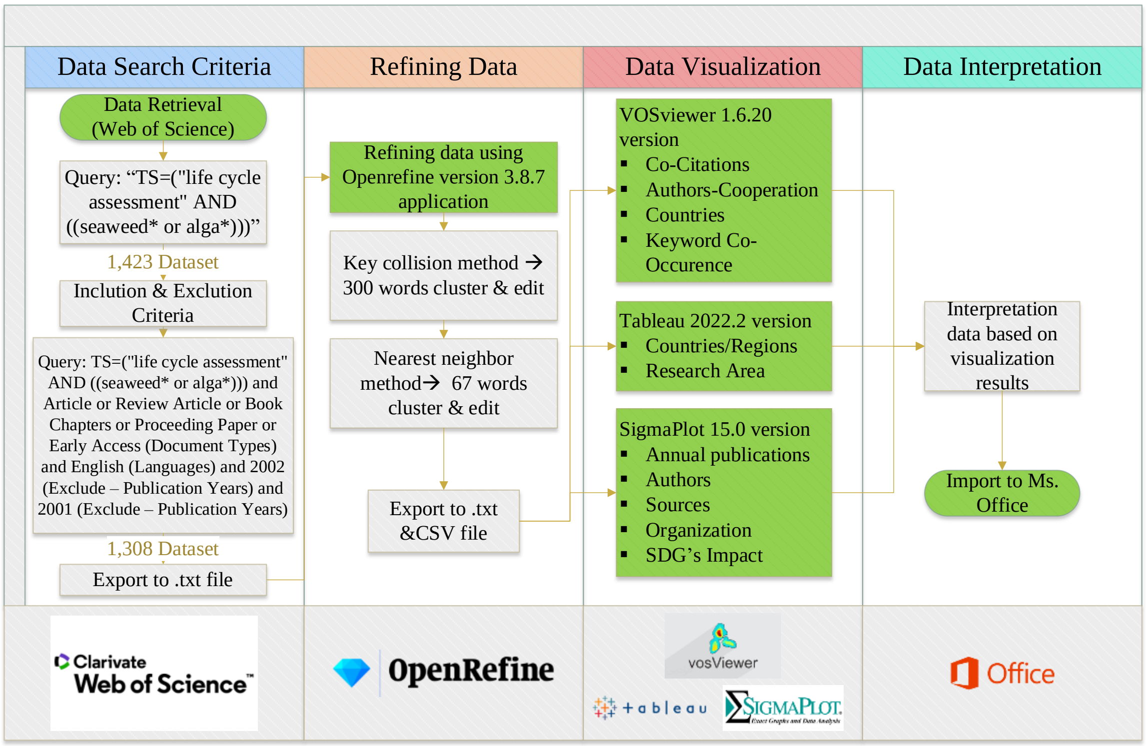

Fig. 1. The Analytical procedure employed in this research

RESULTS

1. Publication distribution analysis

1.1. Analysis of the sequence of publishing year

Since 2003, 1,423 publications on LCA for seaweed have been identified (Fig. 2). Prior to 2013, fewer than 50 publications were released annually, indicating limited academic engagement in this field. Fig. (2) illustrates the annual publication trends in LCA for seaweed, highlighting the significant rise in publications starting in 2014, with annual publications consistently exceeding 100 from 2020 onwards. This trend signifies a sustained increase in research efforts in recent years.

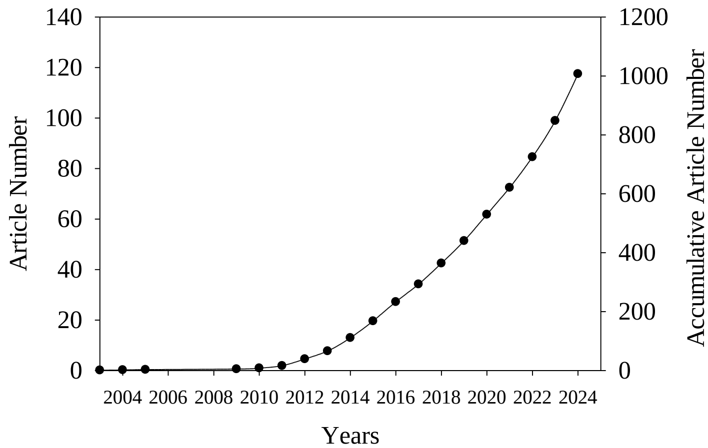

Fig. 2. Statistics for the publishing year

1.2. Analysis of organizations distribution

From 2003 to the present, 1,253 organizations worldwide have contributed to LCA of seaweed research. Tables (1, 2) below present the leading journals and organizations contributing to LCA for seaweed research, helping to identify the key players in this field. Wageningen University Research has been the leading contributor, followed by the Indian Institute of Technology System (IIT) and the U.S. Department of Energy (DOE). Key contributions have also come from prominent institutions across the United States, China, and India, underscoring the global scope and significance of the field. The investigation of LCA for seaweed involved various organizations, particularly several prestigious organizations. The following emphasized its worldwide and decisive scientific standing.

Table 1. The top 10 journal contributions

Ranking	Journal name	Record count	Percentage (%)
1	Bioresource Technology	81	8.482
2	Algal Research Biomass Biofuels and Bioproducts	71	7.435
3	Journal of Cleaner Production	57	5.969
4	Renewable Sustainable Energy Reviews	44	4.607
5	Science of the Total Environment	35	3.665
6	Applied Energy	29	3.037
7	Sustainability	23	2.408
8	Environmental Science Technology	22	2.304
9	Energy	19	1.990
10	Acs Sustainable Chemistry Engineering	17	1.780

Table 2. The top 10 organization contributions

Ranking	Organizations	Record count	Percentage (%)
1	Wageningen University Research	28	2.932
2	Indian Institute of Technology System IIT System	25	2.618
3	United States Department of Energy DOE	25	2.618
4	Council Of Scientific Industrial Research CSIR India	21	2.199
5	De La Salle University	21	2.199
6	Colorado State University	20	2.094
7	INRAE	20	2.094
8	National Cheng Kung University	19	1.990
9	Technical University of Denmark	18	1.885
10	Ghent University	16	1.675

1.3. Analysis of cooperative connections in networks

A total of 1,227 organizations from 78 countries have contributed to the study of LCA for seaweed, publishing 1,423 articles. Out of these, 854 (87.6%) were collaborative works involving multiple institutions, emphasizing the global and cooperative nature of LCA research on seaweed. A co-authorship analysis conducted using VOSviewer revealed two major cooperative clusters, which reflect the geographical and institutional collaboration patterns in the field. Figs. (3, 4) illustrate the collaborative networks in LCA research for seaweed, highlighting key institutions and their connections. These visualizations show that countries such as the United States, China, India, and the United Kingdom have been particularly active in this field. Notably, research on seaweed LCA tends to focus on coastal nations, irrespective of their position as global seaweed producers. The LCA studies also cover geographical regions, including Asia, Europe, and the Americas (Fig. 5).

Fig. (4) displays the intricate collaboration network, comprising 88 key institutions, five distinct groups, and 881 links. The largest group (purple) is centered around Yale and Wageningen University, with 12 direct connections. Leading institutions in terms of publication output include De La Salle University, National Cheng Kung University, Colorado State University, Wageningen University, and the Technical University of Denmark. Collaborative ties between Colorado State University, Cornell University, Yale University, University of Virginia, and Utah State University highlight the depth of cooperation in the field of seaweed LCA.

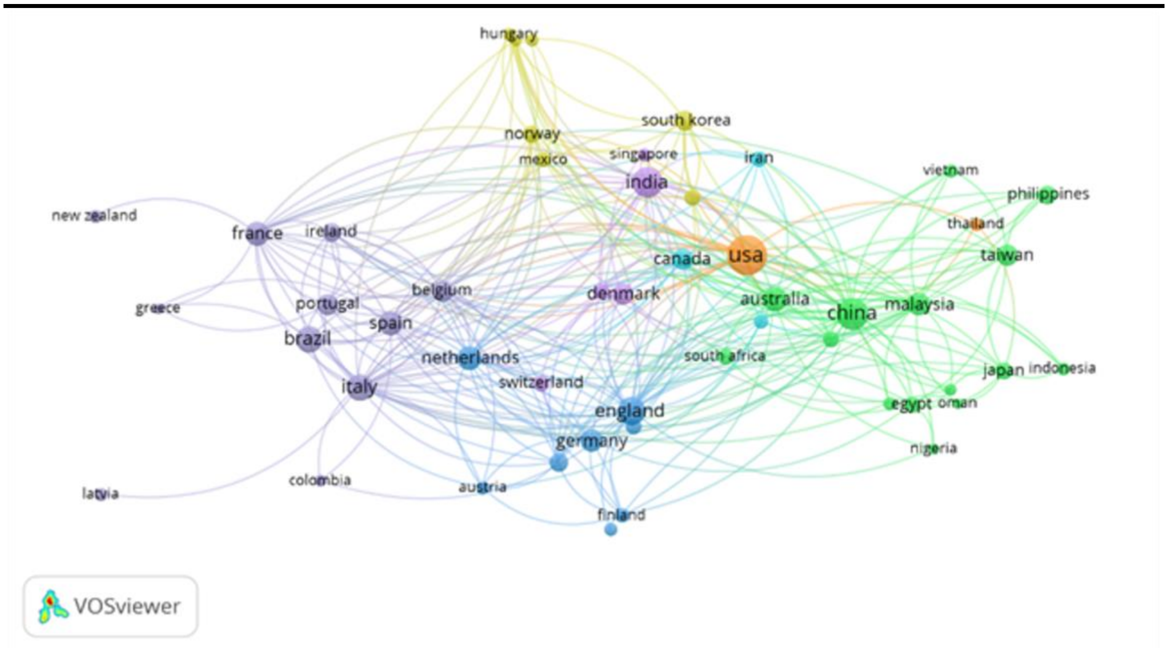

Fig. 3. Collaboration relationships between nations

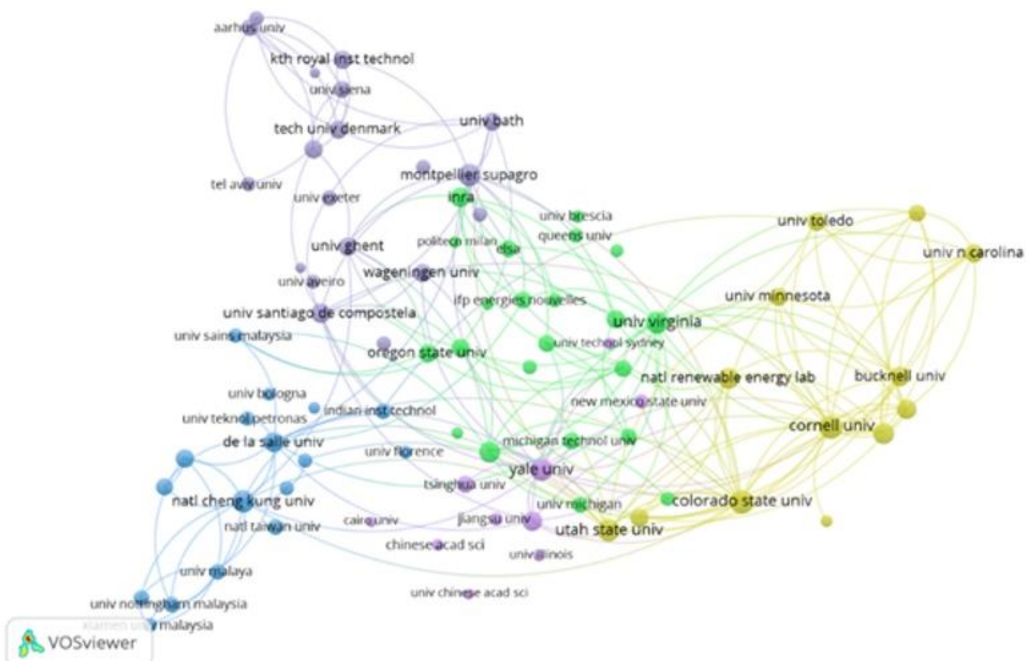

Fig. 4. Collaboration relationships between organizations

Fig. 5. Distribution of countries contributing to research on LCA for seaweed

2. Knowledge base analysis

2.1. Analysis of co-citations from the references cited

Co-citation analysis of the references cited in the selected articles was conducted using VOSviewer (Fig. 6). This analysis focused on evaluating the sources referenced in the articles, including books, journals, conferences, and other relevant materials. Only sources with more than 20 citations were included, resulting in an initial dataset of 13,201 sources, from which 383 sources were selected. Connections between sources represent co-citation relationships, while node size reflects the number of citations linked to a source. The width of the link indicates the strength of the collaboration **(Suban, 2023)**. The analysis identified five distinct groups. Table (3) lists the most influential journals, categorized into five groups, all of which have received over 350 citations. These journals, primarily in Quartile Q1, include Bioresource Technology, Journal of Cleaner Production, Applied Energy, and Environmental Science and Technology. These journals predominantly cover fields such as Energy Fuels, Environmental Sciences, Biotechnology, Green Sustainable Science and Technology, and Environmental Engineering. The integration of knowledge across these disciplines is essential in LCA research on seaweed.

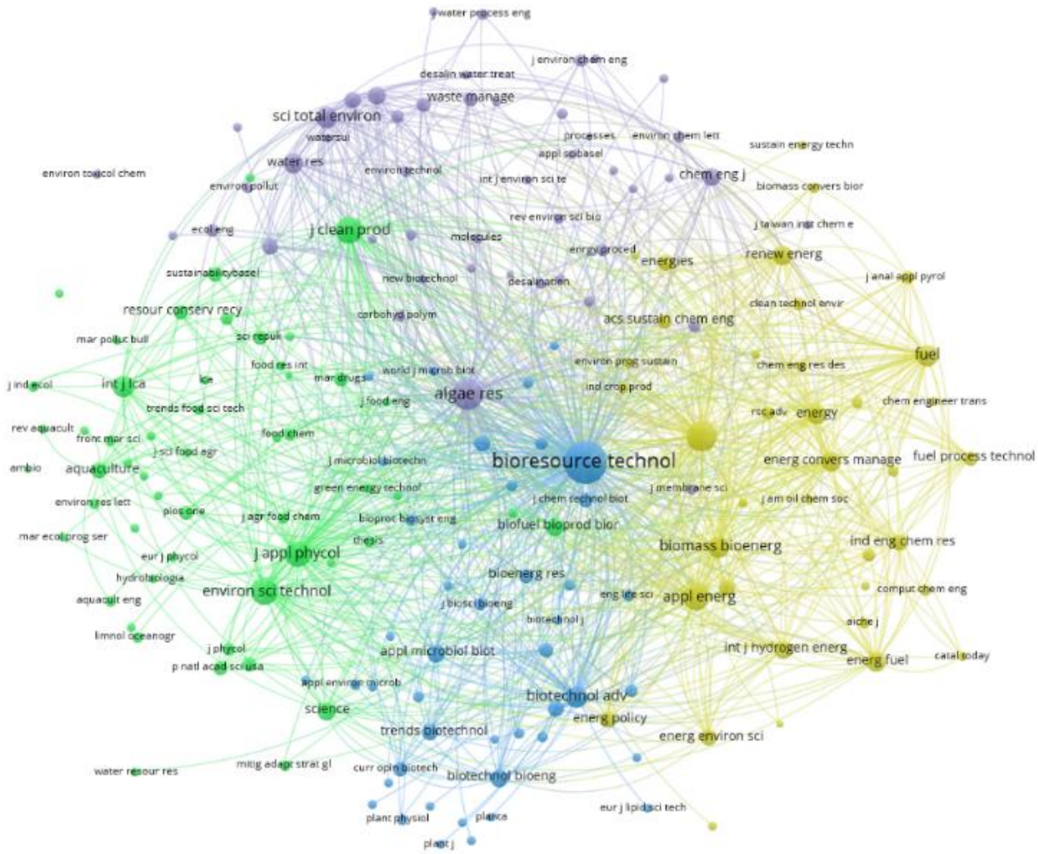

Fig. 6. The co-citations research for the referenced source visualization

Table 3. Ranking of the 10 most frequently referenced sources co-citation

Journal name	x	y	Gro up	Weight <Links>	Weight <TLS>	Weight <Citations>	Journal impact factor	Class
bioresource technology	-0.327	0.151	3	382	821354	8929	2.58	Q1
algae res	-0.035	-0.028	5	382	263796	2740	0.72	Q1
renew sust energ rev	-0.551	0.029	4	382	292327	2738	3.6	Q1
environ sci technol	0.263	0.636	5	382	135098	2089	3.51	Q1
appl energ	-0.437	0.551	4	382	169866	1890	2.82	Q1
j clean prod	0.240	-0.318	1	380	162475	1831	2.06	Q1
j appl phycol	0.329	0.013	1	382	177432	1631	0.61	Q2
biomass bioenerg	-0.542	0.279	4	380	121147	1085	1.11	Q1
sci total environ	0.154	-0.414	2	380	101900	1019	2.00	Q1
biotechnol adv	-0.218	0.669	3	382	95790	1010	2.52	Q1

2.2. Analysis of co-citations from the authors

Fig. (7) displays the visualization of the co-citation assessment of referenced contributors generated using VOSviewer. This selection method offers a straightforward strategy to find top significant academics across many fields of study **(Lin & Himelboim, 2019)**. The writers chosen for this study have accumulated over 20 citations. Among the 50,117 authors in the dataset, only 224 met this criterion. The image exhibits distinct groups, each characterized by a distinct hue. Typically, the writers who exert the most significant effect are commonly linked to four major categories. Fig. (7) illustrates the initial group, represented by the green region, which mainly comprises academics engaged in fundamental research on LCA of bioenergy recovery and biorefinery. **Kannah *et al*. (2021)** conducted research primarily to examine the challenges and potential opportunities for further investigation in the field of integrated algal biorefinery.

Moreover, the ecological ramifications of algal overgrowth and its subsequent transformation into biofuels **(Arashiro *et al*., 2019; Cruce *et al*., 2021)**. The purple area seen in Fig. (7) corresponds to the second group. This group comprises writers specializing in the LCA of seaweed and biofuel manufacturing. The authors of that group are Aldaghi, Jeswani, Yuan, and several others. Their research focused on assessing the ecological consequences of various industrial methods. Furthermore, a sensitivity analysis was conducted to investigate the energy source employed in the manufacturing process explicitly **(Kendall & Yuan, 2013; Jeswani *et al*., 2020; Aldaghi *et al*., 2023)**. The blue zone shown in Fig. (7) represents the 3rd group, comprising researchers demonstrating expertise in Life Cycle Implications. Prominent authors in this group include Agusdinata, Lian, and other individuals. The researchers did extensive research on carbon sequestration and the components of GHG emissions to tackle the issue of the environment **(Agusdinata *et al*., 2011; Quiroz-Arita *et al*., 2019; Lian *et al*., 2023)**. The yellow Group in Fig. (7) represents the fourth group. This group comprises publishers that primarily researched the LCA of agricultural techniques. The group comprises authors such as Langlois, Seghetta, and van Oirschot. Their study investigates several approaches to farming seaweed to address climate change and minimize eutrophication in aquatic habitats by promoting seaweed development. The model improves the precision of measuring ecological services provided through eco-friendly enterprises, hence reinforcing the application of LCA as an instrument for making decisions for long-term seaweed cultivation **(Langlois *et al*., 2012; Seghetta, Marchi, *et al*., 2016; Seghetta, Tørring, *et al*., 2016; van Oirschot *et al*., 2017)**.

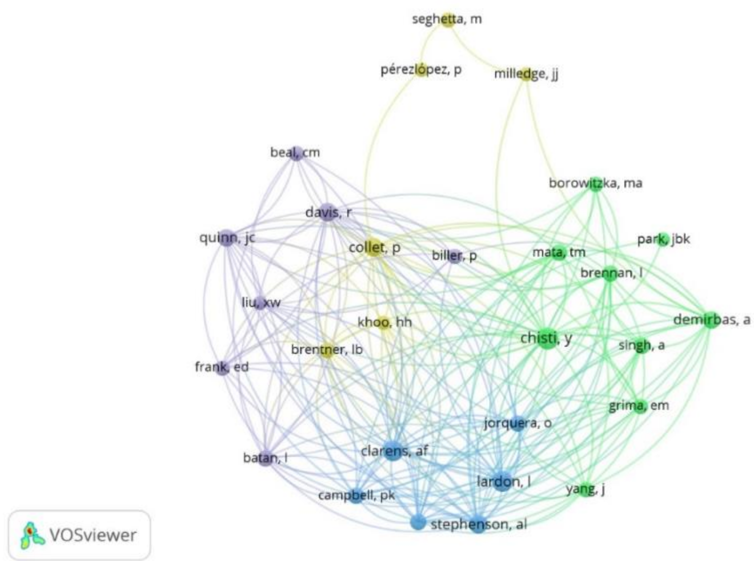

Fig. 7. The co-citations research for the referenced authors visualization

2.3. Analysis of co-citations from the cited references

Fig. (8) illustrates the co-citation analysis performed using the VOSviewer application. VOSviewer uses a network-based approach to identify and visualize the relationships between the sources based on co-citations. This method creates clusters of sources that are frequently cited together, which are represented by nodes and links in the visualization. Only citations that occurred more than 30 times were included in this research. Out of the 50,117 citations in the collection, only 115 satisfied the specified requirements. Table (3) displays the 20 most frequently cited sources, arranged according to their Total Link Strength (TLS) score. This score quantifies the strength of the co-citation relationships, while the Local Citation Score (LCS), which is calculated using VOSviewer, measures the frequency of references within a specific collection of articles obtained from local sources. The Group column in Fig. (8) indicates the exact position of the references. Group 1 relates to the region that is colored red, Group 2 corresponds to the region that is colored green, Group 3 corresponds to the region that is colored blue, and Group 4 corresponds to the region that is colored yellow. Table (4) shows that the main sources, mainly Journal Articles and Reviews, were most prominent from 2008 to 2013, as judged by the TLS indicator value. The references that had a substantial influence were mostly concentrated on three main groups. The red region depicted in Fig. (8) corresponds to the initial Group, with an entire set of three entries in Table (4). The research examined the occurrence and characteristics of LCA on seaweed. The research's primary objective was to investigate biofuel production and environmental effects, namely biodiesel derived from microalgae. The subjects being discussed include LCA, comparative examination of different production methods, environmental impacts, and the possibilities for sustainable biofuel production. The research highlights the importance of factors such as energy conservation, reduction of GHG emissions, and technological advancements in enhancing the environmental efficiency of microalgae-based generation of biofuel. Various research has recorded the computation of LCA indicators for the manufacturing of algal biofuel. Research has demonstrated that incorporating microalgae into the production of biofuels can enhance energy efficiency and alleviate the overall impacts of global warming **(Grierson *et al*., 2013; Sills *et al*., 2013; Adesanya *et al*., 2014; Barlow *et al*., 2016)**. Various literary works offer insights into the progress in microalgae concentrate diets, industrial centrifugation technology, new biosolids management approaches, and microalgal fuel generation procedures. This remark emphasizes the importance of maximizing the lipid content and growth rate in algal biofuel production to save expenses. Furthermore, it highlights the significance of considering sustainability considerations. Research suggests that by improving strain engineering and optimizing production methods, the cost of manufacturing algal oil can be significantly reduced **(Davis *et al*., 2011; Pate, 2013; Woertz *et al*., 2014; Bennion *et al*., 2015; Efroymson *et al*., 2021)**. The green area shown in Fig. (8) represents the second Group, primarily composed of the 13 items listed in Table (3). The articles mostly focused on energy equilibrium, LCA, extraction methodologies, and the ecological consequences of biodiesel. The study examines the discrepancies among different production methods, quantifies the energy used, and evaluates the release of GHG emissions. Moreover, evaluates the potential for sustainability of biofuels obtained from microalgae. Multiple scholarly articles offer comprehensive assessments of the microalgae-to-biodiesel manufacturing process, specifically examining factors such as greenhouse gas emissions, energy usage, economic viability, and environmental impacts. Several studies examine several production scenarios, technologies, and procedures to determine the most efficient and environmentally sustainable approaches for manufacturing algal biodiesel **(Lardon *et al*., 2009; Clarens *et al*., 2010; Sander & Murthy, 2010; Stephenson *et al*., 2010; Campbell *et al*., 2011)**. Multiple research investigations have emphasized the significance of considering energy consumption and CO_2 emissions across the entire production process to improve sustainability and efficiency **(Batan *et al*., 2010; Brennan & Owende, 2010; Collet *et al*., 2011; Jorquera *et al*., 2010)**. Moreover, specific studies highlight the significance of implementing sustainable methods for extensively manufacturing algae biofuels. This research also investigates the environmental repercussions of different approaches **(Clarens *et al*., 2010; Khoo *et al*., 2011; Yang *et al*., 2011)**. The blue area depicted in Fig. (8) corresponds to the third Group, encompassing the four items enumerated in Table (4). These publications highlighted microalgae's capacity in biofuel generation, wastewater purification, and the synthesis of valuable chemical compounds. The importance of improving production efficiency and reducing costs to compete with traditional fuels like petrodiesel is emphasized, as well as the need for advancements in algal biology and bioprocess engineering **(Brennan & Owende, 2010; Harto *et al.*, 2010; Mata *et al.*, 2010; Wijffels & Barbosa, 2010; Slegers *et al.*, 2011)**. Fig. (8) illustrates a small selection of academic articles investigating the practicality of using seaweed farming to produce bioethanol, liquid fertilizers, and fish feed rich in protein. The research objective was to enhance the utilization of renewable resources and evaluate their ecological impacts. This research investigated the impacts of production fluctuations, various seaweed species, and conversion techniques on the feasibility and benefits of seaweed-based biorefinery systems. Many studies examining the positive environmental impacts of seaweed production, such as reducing climate change and decreasing marine eutrophication, fail to adequately study and reference techniques for improving seaweed biomass productivity and material use efficiency.

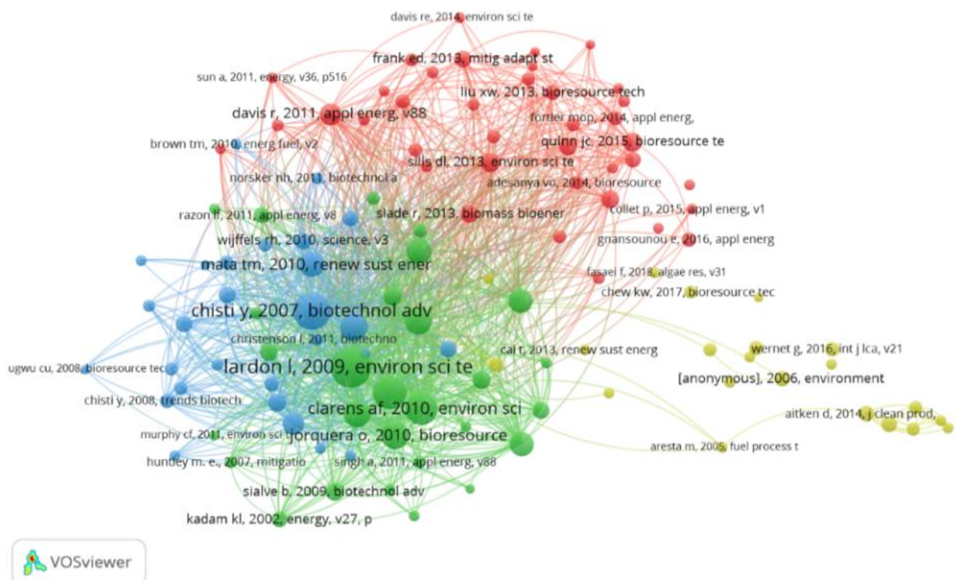

Fig. 8. The co-citations research for the cited references visualization

Table 4. Top 20 references with the highest total link strength

No	Article title	Category	Group	Year	LCS	TLS
1	Life-cycle assessment of biodiesel production from microalgae **(Lardon *et al.*, 2009)**	Article	2	2009	284	3509
2	Biodiesel from microalgae **(Chisti, 2007)**	Review	3	2008	244	3069
3	Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors **(Stephenson *et al.*, 2010)**	Article	2	2010	203	2844
4	Response to comment on "environmental life cycle comparison of algae to other bioenergy feedstocks" **(Clarens *et al.*, 2011)**	Article	2	2011	198	2710

No	Article title	Category	Group	Year	LCS	TLS
5	Life cycle assessment of biodiesel production from microalgae in ponds **(Campbell *et al.*, 2011)**	Article	2	2011	141	2281
6	Life cycle analysis of algae biodiesel **(Sander and Murthy, 2010)**	Article	2	2010	142	2243
7	Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors **(Jorquera *et al.*, 2010)**	Article	2	2010	150	2171
8	Net energy and greenhouse gas emission evaluation of biodiesel derived from microalgae **(Batan *et al.*, 2010)**	Article	2	2010	126	2076
9	Biofuels from microalgae-A review of technologies for production, processing, and extractions of biofuels and co-products **(Brennan and Owende, 2010)**	Review	3	2010	153	1952
10	Combinatorial life cycle assessment to inform process design of industrial production of algal biodiesel **(Brentner *et al.*, 2011)**	Article	2	2011	123	1921
11	Microalgae for biodiesel production and other applications: A review **(Mata *et al.*, 2010)**	Review	3	2010	131	1708
12	Life-cycle assessment of microalgae culture coupled to biogas production **(Collet *et al.*, 2011)**	Article	2	2011	122	1703
13	Techno-economic analysis of autotrophic microalgae for fuel production **(Davis *et al.*, 2011)**	Article	1	2011	103	1503
14	Quantitative uncertainty analysis of life cycle assessment for algal biofuel production **(Sills *et al.*, 2013)**	Article	1	2013	84	1367
15	Environmental life cycle comparison of algae to other bioenergy feedstocks **(Clarens *et al.*, 2010)**	Article	2	2011	79	1335
16	Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance **(Yang *et al.*, 2011)**	Article	2	2011	78	1277
17	Life cycle energy and CO_2 analysis of microalgae-to-biodiesel: Preliminary results and comparisons **(Khoo *et al.*, 2011)**	Article	2	2011	70	1217
18	An outlook on microalgal biofuels **(Wijffels and Barbosa, 2010)**	Review	3	2010	71	1179
19	Assessment of a dry and a wet route for the production of biofuels from microalgae: Energy balance analysis **(Xu *et al.*, 2011)**	Article	2	2011	73	1152
20	Algae biodiesel life cycle assessment using current commercial data **(Passell *et al.*, 2013)**	Article	1	2013	76	1105

DISCUSSION

1. Research direction analysis

This study employed VOSviewer to conduct a co-occurrence analysis about 1,423 papers in the field of Life Cycle Assessment (LCA) of seaweed. Prior to finalizing the analysis, the dataset were thoroughly cleaned, and keywords were consolidated using OpenRefine. Keywords that co-occurred more than five times were selected, resulting in 108 keywords from the 1,889 entries. Fig. (9) illustrates the co-occurrence network of these keywords, in VOSviewer, nodes represent research terms, while links between them indicate the strength of their association in published papers, and colors indicating related groups. Fig. (9) shows the network visualization of co-occurring research terms within the LCA of seaweed.

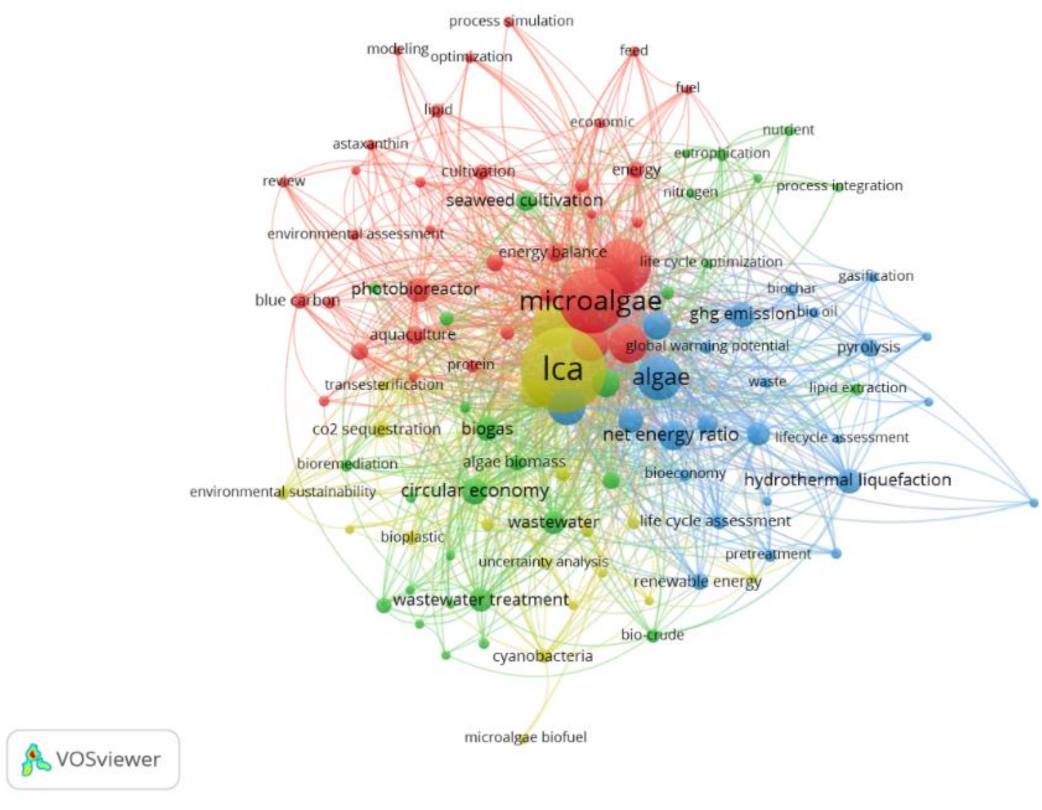

Fig. 9. The co-occurrence research for the author keywords visualization

Fig. (9) highlights key areas of research, which are further broken down in Table (5). Using VOSviewer, the research field of LCA for seaweed is divided into four main categories. These four clusters emerged as key areas of research based on the most frequently co-occurring terms, indicating the primary research trends within LCA for seaweed.

1.1. Group 1 (Red): Biorefinery and environmental assessment of microalgae

This group, the largest with 34 keywords, is centered on the environmental assessment of microalgae biorefinery. "Microalga" had the highest Total Link Strength (TLS) with a value of 541, appearing 217 times. This group marks the initial research focus in the field of seaweed LCA.

1.2. Group 2 (Green): Circular economy and environmental impact with life cycle assessment

Comprising 30 terms, this group is focused on the relationship between circular economy practices and environmental impact assessments using LCA. "Environmental impact" is the most prominent term, appearing 40 times with a TLS of 100.

1.3. Group 3 (Blue): The life cycle of algae/seaweed

This group, consisting of 25 terms, emphasizes the LCA of algae and seaweed. The terms "Algae" and "Seaweed" had the highest TLS values, with "Algae" appearing 104 times and "Seaweed" 68 times, showing a strong connection to studies focusing on the life cycle of these organisms.

1.4. Group 4 (Yellow): LCA of biodiesel and biofuel production

Comprising 19 terms, this group focuses on LCA in the context of biodiesel and biofuel production from seaweed and algae. The term "LCA" had the highest TLS value of 807, appearing 360 times, indicating the central role of LCA in biofuel research.

Table 5. Theoretical frameworks and current trends in research

Group	Research Direction	Nodes (n=108)
1	Biorefinery and environmental assessment of microalga	Aquaculture, astaxanthin, biofuel, bioproduct, biorefinery, blue carbon, carbon footprint, carbon sequestration, chlorella vulgaris, climate change, coproduct, cultivation, dewatering, economic, emerging technology, energy, energy balance, energy demand, environmental assessment, extraction, feed, fuel, harvesting, life cycle inventory, lipid, microalgae, modelling, open raceway ponds, optimization, photobioreactor, process simulation, protein, review, sustainability.
2	Circular economy and environmental impact with life cycle assessment	Algae biomass, algae biorefinery, alginate, bao-based economy, bio-crude, biogas, bioremediation, circular economy, constructed wetland, economic assessment ecosystem service, environmental impact, eutrophication, high rate algae ponds, life cycle optimization, lipid extraction, nitrogen, nutrient, nutrient recovery, nutrient removal, phycoremediation, process design, process integration, resource recovery, *saccharina latissimi*, seaweed

Group	Research Direction	Nodes (n=108)
		cultivation, sustainable development, value added product, wastewater, and wastewater treatment.
3	The life cycle of algae/seaweed.	Algae, algae biofuel, anaerobic digestion, bio-oil, biochar, bioeconomy, bioethanol, biomass, fermentation, gasification, ghg emission, global warming potential, hydrothermal carbonization, hydrothermal liquefaction, LCA, net energy ration, pretreatment, pyrolysis, renewable energy, seaweed, technoeconomic analysis, valorisation, and waste.
4	LCA of biodiesel and biofuel production	Algae biodiesel, biodiesel, biohydrogen, biomethane, bioplastic, CO_2 sequestration, cyanobacteria, energy efficiency, environmental sustainable, ethanol, industrial ecology, LCA, microalgae biofuel, microalgae biomass, microalgae biorefinery, technoeconomic, transesterification, and uncertainty analysis.

Overall, the most prominent fields of study in the LCA of seaweed include Energy Fuels, Environmental Sciences, Ecology, Engineering, Biotechnology, Applied Microbiology, and Science Technology. These fields dominate LCA research in seaweed, with a significant emphasis on biorefinery and impact assessments of seaweed production. The research direction, therefore, is expected to focus on biotechnology, resource recovery, economic valuation, blue carbon, and optimizing seaweed cultivation, as indicated by the keywords in Fig. (9) and Table (6).

Table 6. Top 10 research area on LCA of seaweed

Research areas	Record count	Percentage (%)
Energy Fuels	372	19.30
Environmental Sciences Ecology	320	16.61
Engineering	311	16.14
Biotechnology Applied Microbiology	265	13.75
Science Technology Other Topics	235	12.20
Agriculture	103	5.35
Chemistry	75	3.89
Thermodynamics	41	2.13
Marine Freshwater Biology	34	1.76
Water Resources	27	1.40

2. Evolution of research topics

As we move through the stages from 2017 to the present, the focus of LCA research has gradually shifted, reflecting the growing complexity of topics such as biorefinery and sustainability in seaweed cultivation. Fig. (10) illustrates the evolution of research topics within the four identified groups in the LCA of seaweed field. Using data from

VOSviewer, we analyzed the mean publishing years for each keyword, starting from 2017. The research trajectory can be divided into four main stages:

2.1. The LCA of biodiesel and biofuel research stage

The relevant terms encompass "algae," "biofuel," and "biodiesel". Before 2017, the initial LCA investigation on seaweed primarily focused on exploring algae's viability as a potential alternative energy source. The works cited by **Adesanya *et al*. (2014)** and **Kern *et al*. (2017)** comprehensively analyze various technologies used in this field, such as anaerobic digestion, photobioreactors, and extraction methods. The LCA effect assessment examines explicitly the process of CO_2 sequestration **(Chandra *et al*., 2018)**. It plays a crucial and essential role in shaping the future trajectory of seaweed LCA research.

2.2. The LCA of the microalga research stage

The terms "LCA" and "microalga" are relevant in this situation. Since 2018, there has been an increasing focus on the LCA of microalgae. Microalgae are well-acknowledged for their exceptional ability to produce energy. A comprehensive investigation was performed on several microalgae species to assess their biofuel production capacity. LCA research has expanded its focus to highlight the evaluation of environmental impacts compared to the previous phase. The analysis has encompassed a range of factors, such as the net energy ratio, greenhouse gas emissions, biomethane production, and climate change impact **(Wu *et al*., 2017; Colzi Lopes *et al*., 2018; Foteinis *et al*., 2018)**. Hydrothermal liquefaction is the prevailing technology in use and is under development **(Sun *et al*., 2019)**.

2.3. The LCA of seaweed cultivation and sustainability research stage

The terms "Seaweed Cultivation" and "Nutrient Recovery" are mentioned. Presently, there is a growing concern surrounding the production of seaweed. Seaweed cultivation is the primary global supply source, requiring meticulous evaluation of cultivation techniques, equipment options, fuel requirements, and other pertinent aspects. The approaches utilized in various countries differ, resulting in distinct outputs, ranging from seed preparation to seaweed diversification **(Anand *et al*., 2018; Parsons *et al*., 2019)**. Tropical countries use less energy for the process of drying in comparison to subtropical countries. There is an increasing focus on retrieving nutrients in connection with environmental issues. Moreover, there is a prevailing inclination towards integrating renewable energy technology with seaweed aquaculture **(Porcelli *et al*., 2020)**.

2.4. The biorefinery and bioproduct research stage

The terms "biorefinery," "environmental impact," and "bioproduct" are pertinent in this context. This step entails performing an LCA analysis on the latest seaweed, hence outlining the direction for further research. Currently, researchers have begun exploring the broader consequences of seaweed, including its potential in biorefinery, the economic aspects associated with the circular economy and blue growth **(Hasan *et al*., 2023; Kiehbadroudinezhad *et al*., 2023; Rose & Hemery, 2023)**. This research has made an essential achievement in comprehending the complex method for seaweed cultivation. The research also highlights bioproducts as the outcome **(Balan *et al*., 2023)**. Seaweed is considered a viable alternative to plastic, a sustainable energy source, and a domain for biotechnological advancements. Nevertheless, the study's findings may partially represent the seaweed research landscape. This limitation arises from the constraints imposed by the article's choosing procedure within the WoS fundamental data retrieval, the constraints in the measurement, and the utilized analytical procedures, acquired examples and analyzed results. Hence, a thorough investigation from multiple viewpoints is needed to attain a complete and profound comprehension of the topic.

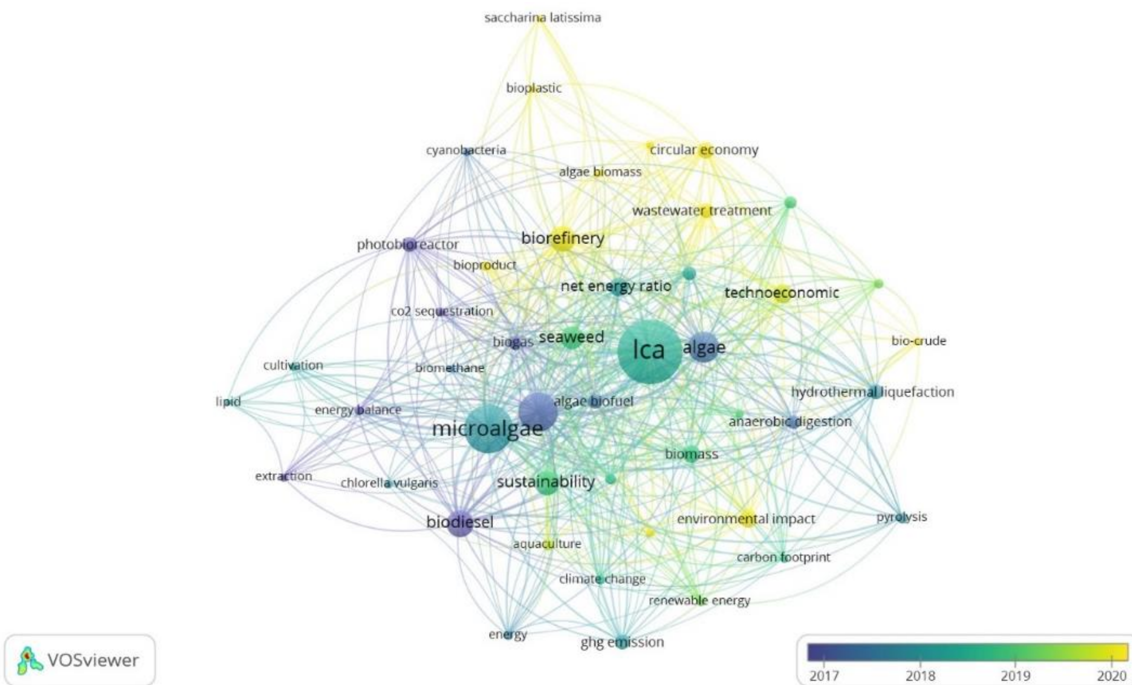

Fig. 10. The mapping of keywords temporal evolution

3. Suggestions on future research of LCA for seaweed

As highlighted earlier, there are limitations associated with the publications retrieved from the WoS Base Obtaining dataset. This section integrates reliable results from graphical analysis with data from various sources and provides several suggestions for advancing research in the LCA of seaweed.

3.1. Enhance Global Collaboration

Collaboration among nations, research institutions, and subsidiaries is essential for advancing LCA studies of seaweed. Currently, geographic bias persists, with the top 10 countries contributing to 88.9% of all related publications. Notably, there is a lack of LCA studies from major seaweed-producing countries, such as Indonesia, South Korea, Japan, and Malaysia. Among the top 10 producers, only China ranks among the top countries conducting LCA research. To address this imbalance, international collaboration should be prioritized, particularly in countries with significant seaweed production. By engaging with stakeholders in these regions, it will be possible to explore the ecological impact, development potential, and circular economy opportunities in seaweed farming. This collaboration will enhance understanding and drive sustainable practices in seaweed production **(Langlois *et al*., 2012; Seghetta & Goglio, 2020; Nilsson *et al*., 2022; Maddalen Ayala, Thomsen & Pizzol, 2023)**.

3.2. Broaden the scope of LCA impact assessment

Expanding the scope of impact assessments in LCA studies is crucial. Many LCA software tools offer various impact categories, including climate change, ozone depletion, acidification, eutrophication, and human toxicity, among others. Incorporating these broader impact categories will enable a more comprehensive evaluation of seaweed LCA, as outlined in the previous section. Linking LCA studies of seaweed to the SDGs, especially SDG 13 (Climate Action) and SDG 14 (Life Below Water) will provide actionable insights into how seaweed production can contribute to global environmental goals, as shown in Table (7).

Table 7. SDGs on LCA of seaweed

SDGs type	Record count	Percentage (%)
06 Clean Water and Sanitation	622	65.131
13 Climate Action	140	14.660
12 Responsible Consumption and Production	118	12.356
07 Affordable and Clean Energy	78	8.168
14 Life Below Water	67	7.016
15 Life on Land	58	6.073
02 Zero Hunger	41	4.293
03 Good Health and Well Being	13	1.361
11 Sustainable Cities and Communities	9	0.942
01 No Poverty	1	0.105

3.3. Focus on LCA of seaweed cultivation

Comprehensive LCA studies on seaweed cultivation are urgently needed, especially considering the varying methodologies, species, and equipment used in seaweed farming. These factors result in different environmental impact estimates. Seaweed cultivation accounts for approximately 97% of seaweed production **(Desai & Reddy, 2023)**, highlighting the need for a thorough environmental impact assessment. A more nuanced understanding of the ecological effects of seaweed cultivation will aid in mitigating pollution in local and regional farming areas **(van Oirschot *et al*., 2017)**. Previous studies that focus on LCA of seaweed cultivation are shown in Table (8).

Table 8. LCA research of seaweed cultivation

No	Seaweed species	Objective	LCA scope	Reference
1	*Laminaria digitata*	Biofuel Production	Cultivation Process	**(Alvarado-Morales *et al*., 2013)**
2	*Gracilaria chilensis* and *Macrocystis pyrifera*	Bioethanol and Biogas	Cultivation Method	**(Aitken *et al*., 2014)**
3	*Sakarina latissima*	Comparison of Two Seaweed Cultivation Systems	Biomass Production, Seeding, etc.	**(Taelman *et al*., 2015)**
4	*Kappaphycus alvarezii*	Production of Biostimulants from Seaweed	Cultivation Process	**(Ghosh *et al*., 2015)**
5	*Sakarina latissima*	Ethanol, Protein and Fertilizer Production	Energy consumption	**(Seghetta, *et al*., 2016)**
6	*Laminaria digitata*	Biomethane Production	Energy consumption	**(Czyrnek-Delêtre *et al*., 2017)**
7	*Enteromorpha prolifera*	Biogas Production	Materials Process	**(Giwa, 2017)**
8	*Sakarina latissima*	Biomass Productivity	Seaweed Cultivation and Processing	**(van Oirschot *et al*. 2017)**
9	Mixed (Red and brown algae)	Biogas Production	Raw Material Variations	**(Ertem *et al*., 2017)**
10	*Gracilaria edulis*	Seaweed Biostimulants	Cultivation Process	**(Vijay Anand *et al*., 2018)**
11	*Sakarina latissima*	Single Cell Oil	Process, Energy Consumption	**(Parsons *et al*., 2019)**
12	*Sakarina latissima*	Bioremediation and Carbon Capture	Seeding, Cultivation, and Drying	**(Thomas *et al*. 2021)**

3.4. Establish a taxonomy for LCA of seaweed

Over the past two decades, LCA research on seaweed has increasingly focused on impact assessments, covering topics such as circular economy, blue carbon, and resource recovery. As technology and methodologies continue to advance, it is recommended to establish a formal taxonomy for the LCA of seaweed. This would provide clear guidelines for future research and foster more structured international cooperation. The current study has contributed to this effort by categorizing research based on time, keywords, references, and authors.

CONCLUSION

This study presents a comprehensive bibliometric review and visual analysis of LCA research in the field of seaweed. The findings reveal a steady increase in the number of publications on this topic over the last 20 years, with China emerging as a major contributor. However, there remains a significant need for global collaboration, particularly with seaweed-producing countries that have not fully engaged in LCA research. The literature identifies five key areas of current research and outlines potential future directions. These include: (1) enhancing global cooperation, (2) expanding the scope of impact assessments, (3) focusing on the LCA of seaweed cultivation, and (4) developing a formal taxonomy for the scientific discipline. Although this study is based on the WoS Core Collection database, future research should address limitations in analytical methodologies and should extend the scope of analysis to encompass a broader range of linked research. This bibliometric exploration relies on the extent of the WoS Core Collection database. Furthermore, addressing inherent flaws in analytical methodologies and mathematical instruments is necessary. Consequently, the information and findings might only encompass part of the range of linked research. An all-encompassing methodology is deemed crucial for comprehensively understanding the subject.

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