

Microalgae for Palm Oil Mill Effluent (POME) Remediation: Future Trends

Nurlydia Mohd Azmil¹, Ali Yuzir¹, Shaza Eva Mohamad¹, Norhayati Abdullah^{2*}, Mostafa El-Sheekh³

¹Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

²Graduate School of Environmental and Information Studies, Tokyo City University, Yokohama 224-8551, Japan

³Botany Department, Faculty of Science, Tanta University, 31527 Tanta City, Egypt

*Correspondence: norhayati@utm.my

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ABSTRACT: Microalgae-based remediation of palm oil mill effluent (POME) grew rapidly, yet evidence remained dispersed across methods and outcomes. This study undertook bibliometric mapping to organise research growth, thematic structure, and actionable pathways aligned with SDGs 6, 7, 12, and 14. A Scopus database of 124 articles (2008–2025) was analysed with VOSviewer to produce keyword co-occurrence and temporal overlays, complemented by impact indicators and close reading of highly cited studies. Output increased from a formative phase to a peak in 2021, with 3275 citations overall and influence that was concentrated yet broad ($h = 35$; $g = 51$; $m = 1.944$). The network resolved into a central focal point (POME, microalgae, effluent/wastewater), surrounded by two related fields: pollutant metrics (COD, nitrogen, phosphorus), which supported treatment claims, and valorisation (biomass, lipid, biofuel), which linked remediation to product streams. Temporal overlays showed a progression from feasibility and nutrient polishing to method-rich optimisation (kinetics, immobilisation) and, more recently, to cultivation realism, phycoremediation, and sustainability. These patterns indicated practical levers for mill-scale deployment, including on-site cultivation with boiler CO₂, microalgae–bacteria partnerships for robustness, and combined pond–photobioreactor systems that balanced cost and control. Together, these combinations delivered cleaner effluents (SDG 6), low-carbon energy vectors (SDG 7), circular nutrient and residue reuse (SDG 12), and reduced land-based marine pollution (SDG 14). Remaining priorities included harmonised reporting of removals and yields, techno-economic and life cycle assessments at mill cluster scale, resilient process control and safety for multi-stage systems, and biomass quality assurance to safeguard downstream uses.

KEYWORDS: POME; sustainability; bibliometric; microalgae

1. Introduction

Microalgae-based remediation of POME emerged as a viable and innovative solution to environmental challenges posed by the palm oil industry. POME, a by-product of palm oil

extraction, was characterised by high organic loads, often displaying Chemical Oxygen Demand (COD) values exceeding 70,000 mg L⁻¹, making it a significant environmental pollutant if not treated properly [1]. Each ton of Crude Palm Oil (CPO) production generated approximately 2.5 to 3.0 m³ of POME, leading to an estimated annual generation of 50 to 65 million tonnes of POME in Malaysia alone [2]. The palm oil industry was integral to the economies of many tropical nations, yet the disposal of POME remained a critical environmental concern, as untreated effluents caused ecological disruption, including water pollution and biodiversity loss. In addition, traditional POME treatment methods such as open ponding systems or anaerobic digesters often faced issues related to hydraulic retention time, land area requirements, and odour management. Open ponds typically required extensive land use (45 to 60 days of retention) and released unpleasant odours, complicating operations near residential areas [3, 4].

Efforts to optimise POME treatment often included combining biological and chemical methods. However, achieving a balance that maximised pollutant removal while maintaining cost efficiency posed ongoing challenges [5]. Microalgae, known for high photosynthetic efficiency, offered a promising alternative for mitigating the environmental impacts of POME through bioremediation and biomass-based biofuel production [6]. This dual potential of microalgae as both a waste treatment agent and a source of bioenergy enhanced the sustainability of palm oil processes [7]. Furthermore, the treatment process reduced COD and biochemical oxygen demand (BOD) and restored pH levels to neutral [8].

Over the past two decades, research on microalgae–POME systems expanded from laboratory batch trials to pilot integrations with anaerobic digestion, open ponds, photobioreactors, bioflocculant-assisted harvesting, and product valorisation pathways. Microalgae utilised nutrients such as nitrogen and phosphorus in POME, which were commonly associated with eutrophication in aquatic systems [9, 10]. Studies showed that species such as *Chlorella vulgaris* and *Spirulina platensis* thrived in POME, absorbing pollutants and improving water quality while producing biomass [11]. Integrating microalgae cultivation into POME management enabled sustainable biomass production that could be converted into biofuels, addressing wastewater issues while contributing to renewable energy solutions [7]. This was particularly relevant as the global community moved towards more sustainable agricultural and industrial practices aligned with the United Nations Sustainable Development Goals (SDGs), particularly those related to clean water and sanitation, responsible consumption, and climate action [6, 12, 13]. In this context, this study (i) analysed publishing patterns based on the number of publications, and (ii) systematically analysed keyword co-occurrences to uncover emerging trends related to the cultivation of microalgae in wastewater for nutrient removal. Throughout, we connected findings to implementation needs in tropical settings and to SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water)).

2. Materials and Methods

A bibliometric study offered a rigorous way to synthesise this diffusion. Rather than narrating selected advances, bibliometric mapping systematically mined indexed literature to reveal the structure of the field through co-authorships, topic occurrences and clusters, theme evolution, and leading journals and institutions that contributed to the expanding research landscape. This

strategic, data-driven perspective complemented conventional reviews by quantifying patterns and blind spots that were otherwise difficult to detect, which was particularly valuable in an application domain shaped by tropical contexts, industrial realities, and SDG imperatives.

2.1. Bibliometric tools and parameters.

Keyword co-occurrence, clustering, and overlay visualisations were generated in VOSviewer v1.6.20 using full counting and association strength normalisation. Unless specified, parameters were as follows: minimum keyword occurrences = 5, largest connected component = 1.00, cluster resolution = 1.00, minimum cluster size = 5, and overlay metric = average publication year. Data cleaning and result analysis were performed using Microsoft Excel with the aid of BiblioMagika® by Aidi Ahmi [14].

2.2. Bibliometric analysis.

The bibliometric design followed a single-database strategy using Scopus due to its broad coverage in engineering and environmental sciences. Records were retrieved in August 2025 using the advanced query: “TITLE-ABS (microalgae OR algae OR microalga OR alga) AND TITLE-ABS (‘palm oil mill effluent’ OR POME) AND PUBYEAR > 1999.” After restricting research articles and removing duplicates by title or DOI, 133 records remained. The inclusion criteria required that palm oil mill effluent be the matrix studied, whether in raw, treated, modified form, or as a co-feedstock, with microalgae serving as the primary agent through processes such as cultivation, biosorption, or algae–bacteria consortia. In addition, the article needed to report at least one performance outcome, such as chemical oxygen demand (COD), nitrogen, phosphorus, biomass production, or lipid content. In contrast, articles were excluded if they did not include experiments or data specific to palm oil mill effluent, lacked sufficient metadata for mapping (such as missing keywords), or showed weak coupling to the central remediation theme even if POME or microalgae were mentioned in the text. Following screening, 9 records were excluded, leaving 124 articles for analysis.

2.2.1. Analysis of keyword co-occurrences.

Data were cleaned by deduplication (DOI or title) and by harmonisation of terminology using a thesaurus file. The initial dataset contained 1026 recognised keyword terms. Pre-processing included manual curation, diacritic removal, and singular/plural harmonisation. Acronyms were expanded and unified; for example, “palm oil mill effluent” and its variants were mapped to “POME.” Chemical terminology was normalised so that “chemical oxygen demand” became “COD,” while “CO₂ fixation” and “CO₂ fixation” became “carbon sequestration.” Spelling and hyphenation variants were merged. Ambiguities were addressed using a rule-then-review approach. For example, “algae” and “microalgae” were standardised to “microalgae” when organism-level studies were intended. In addition, “biofuel” was used as an umbrella term to represent “biogas” and “biodiesel.” “Wastewater treatment” was kept distinct from “wastewater” to preserve the difference between process and matrix. After cleaning, 1003 keywords remained, and 41 of these met the minimum occurrence threshold for inclusion in the co-occurrence analysis. A thesaurus file was created for these keywords and uploaded to VOSviewer for the mapping process. The data were viewed in overlay visualisation mode to observe the temporal trends of keyword occurrences.

3. Results and Discussion

3.1. Publication output.

The final query string yielded a total of 124 documents spanning from 2008 to 2025, as shown in Figure 1. These publications were produced by 602 authors, averaging 4.85 authors per paper. This level of collaboration suggested multi-institutional projects and cross-site validation, which likely supported the rapid scale-up observed after 2017. Nearly all outputs were cited, as 122 of 124 papers (98%) received citations, reinforcing the impression that the literature had immediate relevance within wastewater remediation.

Output was sparse during the formative period (2008–2012). This low activity marked an exploratory phase during which foundational methods were trialled, explaining why the citation curve remained close to the baseline in these years. Publications on the topic rose steadily from 2013 and accelerated through 2017–2021, when the field reached its publication peak. This surge indicated the consolidation of protocols and broader uptake across research groups. The total citation curve peaked shortly after, between 2020 and 2022, reflecting the time needed for new work to diffuse and accumulate citations.

The alignment of a publication peak followed by a citation peak was typical of a maturing niche that had achieved methodological stability and application relevance. Output remained comparatively high in 2022–2025, albeit below the peak—an expected levelling for a maturing topic. The impact metrics corroborated the visual trends, with 3275 citations over 17 years and a mean of 192.65 citations annually. The h-index was 35 and the g-index was 51, while the h-core alone accounted for approximately 3115 citations (about 95% of the total), demonstrating that influence was concentrated but not narrow.

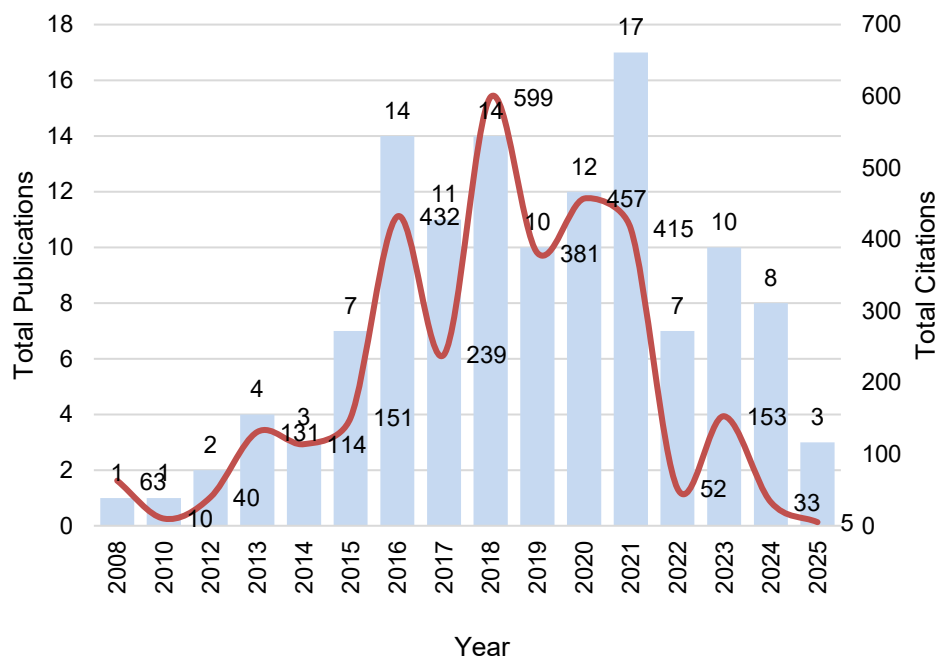


Figure 1. The annual number of publications and total citations from 2008 to 2025.

The ten most-cited papers spanned 2016–2021 and together accounted for 991 citations, representing approximately 30% of all citations in the corpus, as shown in Table 1. Their annual impact was sustained, with a mean citations per year (C/Y) of 14.5 and a median C/Y of about

14.4. Publication timing was concentrated, as nine of the ten papers appeared between 2018 and 2021, aligning with the field's surge in output and the subsequent peak in citations. The venues included journals in environmental engineering and energy, led by the *Journal of Cleaner Production*, *Journal of Water Process Engineering*, *Energy Conversion and Management*, *Algal Research*, *Bioengineered*, *International Journal of Hydrogen Energy*, and the *Journal of Environmental Chemical Engineering*. This distribution signalled cross-disciplinary reach and helped explain the sustained citation momentum.

Table 1. Top ten most cited articles.

No.	Author(s)	Year	Title	Source Title
1	A., Ahmad, Ashfaq; A.H., Bhat, Aamir Hussain; A.B., Buang, Azizul Bin	2018	Biosorption of transition metals by freely suspended and Ca-alginate immobilised with <i>Chlorella vulgaris</i> : Kinetic and equilibrium modeling	Journal of Cleaner Production
2	H.B., Hariz, Harizah Bajunaid; M.S., Takriff, Mohd Sobri; N.H., Mohd Yasin, Nazlina Haiza; et al.	2019	Potential of the microalgae-based integrated wastewater treatment and CO ₂ fixation system to treat POME by indigenous microalgae; <i>Scenedesmus</i> sp. and <i>Chlorella</i> sp	Journal of Water Process Engineering
3	G., Ding, Gongtao; Z., Yaakob, Zahira; M.S., Takriff, Mohd Sobri; J.B., Salihon, Jailani Bin; et al.	2016	Biomass production and nutrients removal by a newly-isolated microalgal strain <i>Chlamydomonas</i> sp in POME	International Journal of Hydrogen Energy
4	W., Cheah, Waiyan; P.L., Loke Show, Pau Loke; J., Juan, Joonching; et al.	2018	Microalgae cultivation in POME for lipid production and pollutants removal	Energy Conversion and Management
5	W., Cheah, Waiyan; P.L., Loke Show, Pau Loke; J., Juan, Joonching; et al.	2018	Enhancing biomass and lipid productions of microalgae in palm oil mill effluent using carbon and nutrient supplementation	Energy Conversion and Management
6	G., Ding, Gongtao; N.H., Mohd Yasin, Nazlina Haiza; M.S., Takriff, Mohd Sobri; K.F., Kamarudin, K. F.; et al.	2020	Phycoremediation of POME and CO ₂ fixation by locally isolated microalgae: <i>Chlorella sorokiniana</i> UKM2, <i>Coelastrella</i> sp. UKM4 and <i>Chlorella pyrenoidosa</i> UKM7	Journal of Water Process Engineering
7	A.F., Mohd Udaiyappan, Ainil Farhan; H., Abu Hasan, Hassimi; M.S., Takriff, Mohd Sobri; et al.	2020	Microalgae-bacteria interaction in palm oil mill effluent treatment	Journal of Water Process Engineering
8	A.S., Japar, Azima Syafaini; M.S., Takriff, Mohd Sobri; et al.	2021	Microalgae acclimatization in industrial wastewater and its effect on growth and primary metabolite composition	Algal Research
9	W., Cheah, Waiyan; P.L., Loke Show, Pau Loke; Y.J., Yap, Yee Jiun; H.F., et al.	2020	Enhancing microalga <i>Chlorella sorokiniana</i> CY-1 biomass and lipid production in POME using novel-designed photobioreactor	Bioengineered
10	J.S.R., Fernando, John Senith Ravishan; M., Premaratne, Malith; D.M.S.D., Dinalankara, Dinalankara Mudiyansele Sineru Dilshan; et al.	2021	Cultivation of microalgae in POME for astaxanthin production and simultaneous phycoremediation	Journal of Environmental Chemical Engineering

The set covered four recurring themes. The most cited article was by [15] in the *Journal of Cleaner Production*, which modelled transition-metal biosorption using freely suspended and Ca-alginate immobilised *Chlorella vulgaris*, addressing biosorption mechanisms through modelling. Second, integrated POME treatment with CO₂ fixation using indigenous or locally isolated microalgae linked remediation to carbon utilisation at mill sites [16, 17]. Third, cultivation for lipid and biomass demonstrated strong “cleanup plus product” performance, incorporating carbon and nutrient supplementation and novel photobioreactors that increased

productivity in POME [18–20]. Lastly, process robustness was addressed through algae–bacteria consortia and acclimatisation in real effluents, while high-value coproducts such as astaxanthin extended the valorisation pathway [21, 22]. The oldest article in the field was published in 2008 by [23]. It investigated marine microalgae cultured in POME as a supplementary diet for rotifer culture. As an early contribution, it established the dual benefits of resource recovery and wastewater mitigation, although limitations were acknowledged due to small scale, the use of modified rather than raw POME, and reliance on a single microalgal taxon.

3.2. Keyword co-occurrences.

Figure 2 shows the bibliometric map in which POME and microalgae were the largest nodes, appearing 97 and 94 times, respectively, and each exhibiting the highest total link strength (TLS = 507). These two terms were tightly connected with effluent (58 occurrences; TLS = 427) and wastewater (39; TLS = 298), producing the thickest and most central edges on the map. This indicated that studies consistently positioned microalgal approaches within both POME-specific and broader wastewater frameworks. The strongest pairwise links quantified this hub: microalgae–POME (weight 71), effluent–microalgae (53), effluent–POME (50), microalgae–wastewater (38), and POME–wastewater (34). Together, these edges underscored a literature that coupled organism, medium, and discharge endpoints within the same design space. Surrounding the centre of the map were two distinct groups of keywords. The first group was product-focused and showed how studies aimed to obtain valuable outputs while treating POME. It included biomass (32 mentions), biofuel (30), lipid (20), and microorganisms (31). The second group was pollution-focused and reflected how treatment success was measured, including chemical oxygen demand (COD) (19), nitrogen (9), phosphorus (6), and bioremediation (19). COD was strongly linked to microalgae (weight 17), POME (16), and wastewater (9), which visually explained why COD reduction was the dominant outcome metric reported, followed by nutrient removal. The lipid node bridged the two groups through its co-links to microalgae (16), POME (18), and wastewater (10), reflecting the recurring narrative that connected remediation to circular economy outcomes. These nodes were located close to both microalgae and POME, with relatively thick links, indicating that performance discussions often extended beyond pollutant removal to include yield and product quality. This pattern was consistent with highly cited articles that treated POME as both a substrate and a platform for energy or chemical recovery.

Species-specific keywords—*C. vulgaris* (18), *C. sorokiniana* (9), and *C. pyrenoidosa* (5)—also appear frequently, with *C. pyrenoidosa* showing the highest average citations per item (42.4). This indicates that these strains are often selected for their robustness. Highly cited studies leveraged these species to demonstrate strong pollutant removal performance and to report reusable data, such as kinetic constants and isotherm capacities for metal uptake, particularly when cells were immobilised in calcium alginate [15]. The keyword map also highlights terms such as kinetics, metabolism, nutrients, and biotechnology positioned at the interface between the product and pollution clusters. This location suggests that method-focused papers, those detailing cultivation duration and optimisation methodologies, are frequently cited and act as a bridge between the two thematic groups. In addition, studies on microalgae–bacteria consortia and strain acclimatisation draw in the keyword microorganisms, keeping it close to the central cluster. These strategies have become common because they

enhance treatment stability and improve product yields [22], reinforcing their importance in the field.

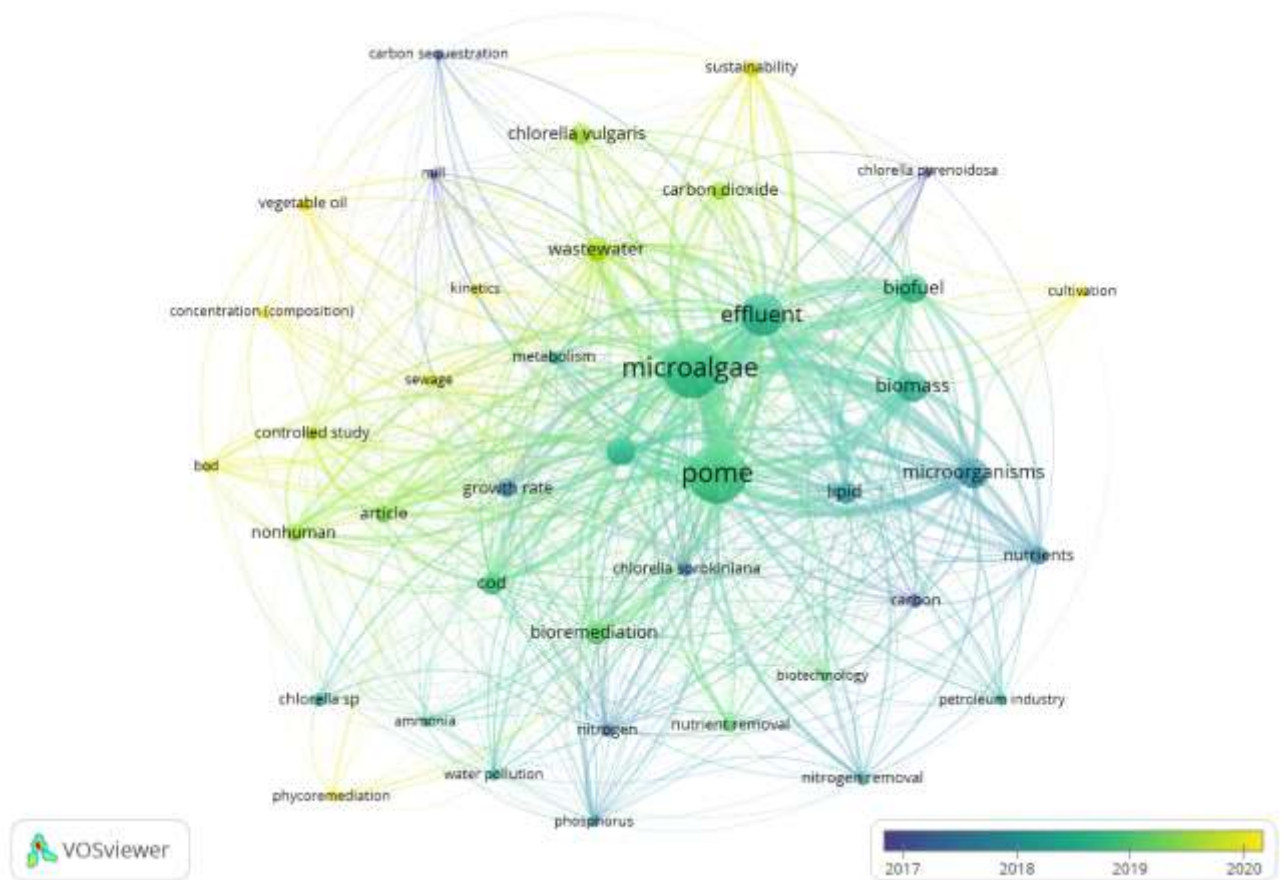


Figure 2. Bibliometric map of keyword co-occurrences. (Online map available: <https://tinyurl.com/23qrk6hk>).

3.2.1. Research topic and trends.

To make the trajectory of the field explicit, a Sankey-style timeline was created to complement the temporal overlay. Author Keywords were normalised with the thesaurus created and grouped into three conceptual clusters: pollutant metrics (for example COD, nitrogen, phosphorus, metals), valorisation (for example biomass, lipid, biofuel, biogas, pigments, biofertiliser), and systems and sustainability (for example cultivation, photobioreactors, CO₂ fixation, consortia, phycoremediation, acclimatisation, sustainability). For each keyword, the average publication year was calculated and then binned into three eras as shown in Figure 3. Newer edges appear for cultivation (average year 2020.5), phycoremediation (2020.83), sewage (2020.17), concentration (composition) (2020.2), and sustainability (2019.82), suggesting a post-2019 shift toward realistic operating conditions, cross-effluent generalisation, and sustainability framing. The earliest anchors are concepts such as biomass, nitrogen, phosphorus, and carbon sequestration, which reflect proof-of-concept studies demonstrating that microalgae can grow on POME and remove nutrients at measurable rates; this phase is exemplified by work using newly isolated strains to couple growth with nutrient polishing in POME [24]. As the timeline shifted towards 2017–2018, methodology-focused studies begin to brighten on the overlay, keywords like kinetics, isotherms, biosorption, and immobilisation, driven by studies that supplied reusable parameters and modelling frameworks (such as pseudo-second-order kinetics; Langmuir/Freundlich fits).

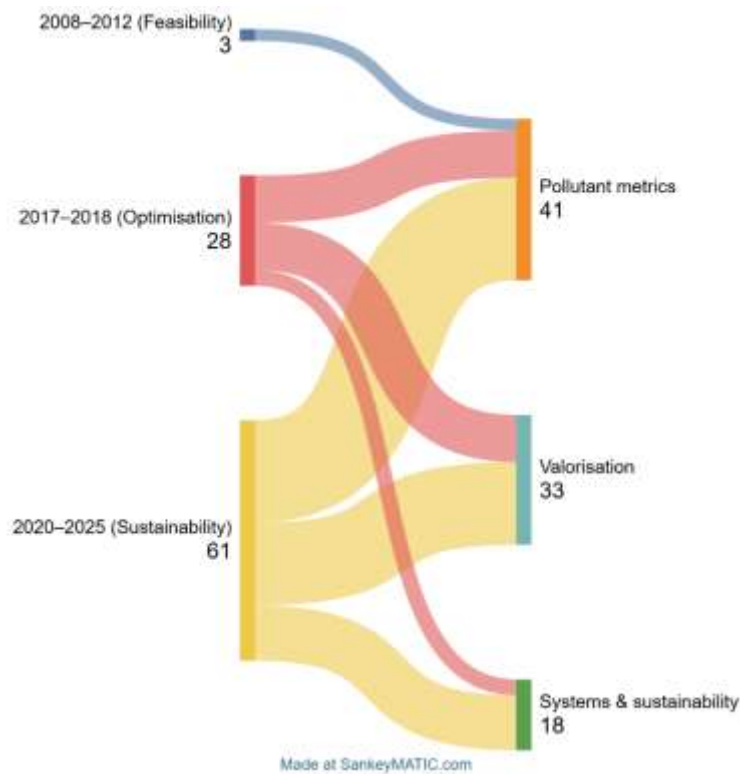


Figure 3. Sankey diagram of topic evolution showing flows from periods (left) to clusters (right) by distinct keyword counts.

The feasibility stage shows only a narrow flow into the pollutant metrics cluster. In 2017–2018, the stream widens equally into both pollutant metrics and valorisation, while systems and sustainability first appear as a smaller but distinct branch. By 2018–2019, the temporal overlay shows blue–green nodes around lipid, biofuel, bioremediation, and CO₂ fixation, marking a pivot from feasibility to co-benefit framing, pollution cleanup paired with resource recovery. During this period, studies cultivating microalgae in POME for lipid production while removing pollutants helped bring lipid and biofuel closer to the core POME–microalgae theme [25,26]. In parallel, CO₂ fixation entered the lexicon as integrated designs using indigenous *Chlorella* and *Scenedesmus* demonstrated simultaneous flue-gas capture and POME treatment, strengthening co-occurrence bridges between microalgal application and climate-related studies [27].

From 2020 onward, the yellow nodes on cultivation, phycoremediation, sustainability, sewage, and other cross-effluent descriptors indicate a shift toward realistic operating conditions, broader transferability, and system-level optimisation. Novel photobioreactor configurations and process tuning (carbon or nutrient supplementation) push *cultivation* language to the fore and draw cultivation–lipid–biomass triads closer to the centre. Cultivation/application studies using *Scenedesmus* sp. connect product profiles to treatment performance [28, 29]. In parallel, microalgae–bacteria consortia and strain acclimatisation emerge as stabilisation tools under industrial conditions, keeping microorganisms (31; 2017.87) tightly linked to the central and pollutant topics. The appearance of phycoremediation and a stronger sustainability lexicon aligns with studies pairing remediation with high-value coproducts (astaxanthin) and circular economy framing, which attract broader audiences and help explain the persistent connection between product and performance nodes [30–32].

Following the Sankey diagram, Table 2 summarises how the thematic emphasis matured across the three clusters and how each map to specific SDG outcomes. The pollutant metrics

cluster originated in 2008–2012, when proof-of-concept studies demonstrated that microalgal uptake and biosorption could reduce COD, nitrogen, and phosphorus in POME. Feasibility works also explored optional polishing for colour and metals, leading to safer reuse. This exploratory phase aligns directly with SDG 6.3 (pollution reduction), SDG 6.4 (recycling and reuse), and SDG 14.1 (reduced land-based pollution to aquatic systems) [33–35].

Next, the valorisation cluster peaked in 2017–2018, when treatment was framed as “cleanup plus product”, and biomass, lipids, biogas, pigments, and biofertilisers were demonstrated as recoverable streams that offset costs and advance SDG 7.2, SDG 12.2, and SDG 12.5 through renewable energy vectors and circular nutrient use [18, 25, 36, 37]. This stage represents the optimisation period, focused on the dual function of microalgae for bioremediation and valorisation.

From 2020–2025, the centre of gravity shifts to systems and sustainability, where reactor configuration, CO₂ integration, consortia/co-culture, acclimatisation, and process optimisation are used to enhance robustness and scale readiness. When paired with basic techno-economic assessment (TEA), life cycle assessment (LCA), and product quality checks, these studies enable integrated progress across SDGs 6, 7, 12, and 14, translating bibliometric themes into deployment pathways for tropical palm oil mill clusters [22, 38–40].

Table 2. Clusters mapped to SDGs based on keyword cluster and year of study.

Cluster	Representative keywords	Year of Study	Mechanism → outcome pathway	SDG targets	Example studies
Pollutant metrics	COD, BOD, nitrogen, ammonia, nitrate, phosphorus, phosphate, bioremediation, metals	2008–2012	Microalgae uptake/assimilation and biosorption lower organic and nutrient loads in POME, with optional polishing for colour/metals before discharge or reuse, improved receiving-water quality and safer reuse	SDG 6.3 (reduce pollution), 6.4 (increase recycling/reuse), 14.1 (reduce land-based marine pollution)	Feasibility/benchmark and acclimatisation studies [33–35]
Valorisation	biomass, lipid, biofuel, biogas, pigments (e.g., astaxanthin), biofertiliser, residue reuse	2017–2018	Biomass and product streams are generated while treating POME to as renewable energy carriers and circular nutrient return reduce waste and offset OPEX/CAPEX	SDG 7.2 (renewable energy share), 12.2 (resource efficiency), 12.5 (waste reduction)	Cleanup + lipid/product, high-value coproducts [18, 25, 36, 37]
Systems & sustainability	cultivation, photobioreactor (PBR), HRAP/raceway, CO ₂ fixation, consortia/co-culture, acclimatisation, phycoremediation, sustainability, process optimisation	2020–2025	Reactor choice, CO ₂ coupling, and microbial strategies improve robustness and scale readiness. TEA/LCA and QA frameworks evidence sustainability and risk controls. Integrated delivery of water-quality, low-carbon energy, circularity, and marine-pollution prevention	SDG 6.3/6.4, SDG 7.2, SDG 12.2/12.5, SDG 14.1	CO ₂ -integrated systems, novel PBRs, consortia/acclimatisation [22, 38–40]

3.2.2. Future trends toward sustainability.

The scalability posed challenges due to the need for optimized conditions for microalgae growth and effective harvesting methods. The treatment efficiency of microalgae was influenced by various factors such as light availability, temperature, pH, and nutrient balance

[41]. Although microalgae systems presented opportunities for treating POME, operational costs associated with managing and maintaining these systems could hinder large-scale deployment. Research indicated that enhanced methodologies, including the integration of membrane technologies or the use of immobilized algal systems, could lead to increased efficiencies and lower long-term costs [42, 43].

In tropical mills, on-site remediation was favoured by warm temperatures, high irradiance, and continuous POME generation. The co-occurrence structure between COD, nitrogen, phosphorus, and the POME–microalgae relationship was reflected in evaluations in which robust freshwater genera were screened directly in POME. Broader taxon portfolios were expected to be studied from estate-isolated microalgae and yeasts, enabling staged removal and valorisation. Early units were populated with fast-growing yeasts to reduce soluble COD and condition the matrix, followed by microalgae polishing that captured nitrogen and phosphorus while generating biomass for lipids, pigments, or biofertiliser. Comparable nutrient removal and growth performance were reported for *Chlorella vulgaris* and *Tetradismus* sp. under mill-relevant conditions, indicating that local strain portfolios could be assembled to buffer seasonal variability and pH fluctuations [44].

Primary polishing of organics and nutrients was complemented by post-treatment steps targeting residual metals and colour. Pelletised microalgae–fungus bioadsorbents and other low-energy sorbents were proposed as retrofit modules upstream of discharge points [45]. Modular post-treatment units for metals and colour were likely to be standardised so they remained operable under monsoon-season hydraulics. POME treatment framed as a “sustainable and green technology approach” was demonstrated with *C. vulgaris*, and this framing was aligned with mill-level reuse options and short residence-time units that were compatible with equatorial throughputs [46]. Where tropical estate integration was intended, applications using *Euglena* sp. were documented in oil-palm contexts, supporting the feasibility of site-adapted strains for post-treatment and water reuse. These findings are collectively aligned with SDG 6 by reducing untreated discharges and improving effluent quality prior to release or recycling [47].

Energy and product linkages that dominated the outer “valorisation” ring in the map were reflected by cultivation designs in which lipid and co-product yields were increased while organics and nutrients were lowered, thereby supporting SDG 7 and SDG 12. Operating windows defined by light quality and carbon supply were expected to be tuned to equatorial irradiance profiles. Spectrum and intensity ranges were set to favour lipid or protein pathways while protecting cultures from midday heat, and carbon supply was matched to boiler-derived CO₂ or bicarbonate dosing to stabilise pH and raise productivity. In mixotrophic and photo-mixotrophic regimes that were compatible with warm, high-light environments, wavelength-tuned LEDs were employed to raise *Nannochloropsis oculata* lipid productivity in POME. The reported parameter windows were used to define mill-practical operating envelopes [37]. Additional implementation flexibility was indicated by heterotrophic biocatalysts, as *Rhodotorula toruloides* cultivated on POME was optimised for COD removal and lipid co-production. This supported hybrid or staged configurations in which algal and non-algal units were combined for robustness and yield [40]. The cumulative effect was a reduction in organic and nutrient fluxes to rivers and estuaries and a lowering of the risk of ecotoxic loads when polishing steps for metals or colour were included, thereby advancing SDG 14 through prevention rather than downstream remediation.

4. Conclusions

Microalgae-based remediation of POME was achieved, showing that output expanded from an exploratory phase to a sustained production phase. Influence remained concentrated yet broad, as indicated by an h-index of 35, a high h-core share of total citations, and an m-index of 1.944. A stable co-occurrence central core (POME–microalgae–effluent/wastewater) was identified, around which pollutant metrics such as COD, nitrogen, and phosphorus anchored evidence of treatment efficacy, while valorisation terms including biomass, lipid, and biofuel linked remediation to product generation. Over time, vocabulary evolved from feasibility and nutrient polishing toward methods and optimisation, including kinetics and immobilisation, and most recently toward cultivation realism, phycoremediation, and sustainability. Implementation in tropical mill clusters was shown to be feasible through year-round irradiance, source-integrated CO₂, hybrid reactor trains, robust strain portfolios, and algae–bacteria consortia. These configurations aligned with SDG 6 through improved effluent quality, SDG 7 through low-carbon energy carriers, SDG 12 through circular nutrient and residue reuse, and SDG 14 through the reduction of land-based pollution to waters. Limitations related to database scope, keyword thresholds, and citation proxies were acknowledged. Future work was identified to benefit from techno-economic analysis and life cycle assessment for tropical deployments, standardised performance reporting for removals and yields, process control and safety for multistage photobioreactors, and biomass quality assurance to support responsible scale-out.

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Author Contribution

Nurlydia Mohd Azmil: Conceptualisation, Methodology, Formal analysis, Investigation, Visualisation, Writing – original draft. Ali Yuzir: Project Administration, Funding, Validation, Writing - review & editing. Norhayati Abdullah: Supervision, Writing - review & editing. Shaza Eva Mohamad: Writing – review & editing. Mostafa El Sheekh: Writing – review & editing.

Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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