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Impact of Linear Alkylbenzene Sulfonate on Microalgae: a Systematic Review of Toxicity and Removal Strategies

Nathália Bandeira Carvalho dos Santos[1]; Vanessa Sousa da Costa[2]; Bruna Kelly de Oliveira Silva[2]; Joelithon de Lima Costa[3]; Thamires Moura[4]; Sávia Gavazza[5]; Raquel Pedrosa Bezerra[6]; Fabrício Motteran[7]

[1]Doutoranda do Programa de Pós-graduação em Ciências Biológicas, Universidade Federal de Pernambuco, Recife, PE, Brasil. e-mail: nathalia.bandeira@ufpe.br. [2]Doutoranda do Programa de Pós-graduação em Ciências Biológicas, Universidade Federal de Pernambuco, Recife, PE, Brasil. e-mail: vanessa.sousac@ufpe.br; bruna.kelly@ufpe.br. [3]Doutorando do Programa de Pós-graduação em Engenharia Civil, Universidade Federal de Pernambuco, Recife, PE, Brasil, e-mail: joelithon.costa@ufpe.br.[4]Doutoranda do Programa de Pós-graduação em Engenharia Civil, Universidade Federal de Pernambuco, Recife, PE, Brasil, e-mail: tccmoura@gmail.com.[5]Professora do Programa de Pós-graduação em Engenharia Civil e Ambiental, Universidade Federal de Pernambuco, Recife, PE, Brasil, e-mail: savia@ufpe.br.[6]Professora do Programa de Pós-graduação em Biociência Animal e na Rede Nordeste de Biotecnologia, Universidade Federal Rural de Pernambuco, Recife, PE, Brasil, e-mail: raquel.pbezerra@ufrpe.br.[7]Professor do Programa de Pós-graduação em Ciências Biológicas e de Engenharia Civil e Ambiental, Universidade Federal de Pernambuco, Recife, PE, Brasil, e-mail: fabricio.motteran@ufpe.br .

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A B S T R A C T

Linear alkylbenzene sulfonate (LAS) is a widely used anionic surfactant and is frequently detected in aquatic environments, where it is considered an emerging contaminant. This study aimed to conduct a systematic literature review on the effects of LAS on microalgae, with emphasis on toxicity, tested concentrations, evaluated species, and reported removal efficiencies. The systematic search, conducted in accordance with PRISMA guidelines, resulted in the selection of 17 studies published between 2005 to 2023. The evaluated surfactants concentrations ranged from 0.001 to 1,000 mg·L⁻¹. Sublethal and lethal toxic effects were observed at concentrations as low as 0.01–0.02 mg·L⁻¹, with reductions exceeding 90% in cell viability in sensitive species such as *Chaetoceros* sp. IC_{50} values ranged from 0.332 to 8.46 mg·L⁻¹, indicating high interspecific variability. In contrast, *Chlorella* sp. and *Scenedesmus* sp. maintained growth at concentrations of up to 100 mg·L⁻¹. Axenic microalgal systems exhibited removal efficiencies between 61.7% and 73.3%, whereas algae–bacteria consortia achieved removals above 90%, with a maximum efficiency of 97.2%. It is concluded that LAS poses a ecotoxicological risk; however, microalgae, particularly in symbiotic systems, represent promising alternatives for its bioremediation.

Keywords: Anionic surfactant; LAS; Water pollution; Bioremediation; Microalgae.

Impacto do Alquilbenzeno Sulfonato Linear sobre Microalgas: uma Revisão Sistemática da Toxicidade e das Estratégias de Remoção

R E S U M O

O alquilbenzeno sulfonato linear (LAS) é um surfactante aniônico amplamente utilizado e frequentemente detectado em ambientes aquáticos, onde é considerado um contaminante emergente. Este estudo teve como objetivo realizar uma revisão sistemática da literatura sobre os efeitos do LAS em microalgas, com ênfase na toxicidade, nas concentrações testadas, nas espécies avaliadas e nas eficiências de remoção reportadas. A busca sistemática, conduzida de acordo com as diretrizes PRISMA, resultou na seleção de 17 estudos publicados entre 2005 a 2023. As concentrações de surfactantes avaliadas variaram de 0,001 a 1.000 mg·L⁻¹. Efeitos tóxicos subletais e letais foram observados em concentrações tão baixas quanto 0,01–0,02 mg·L⁻¹, com reduções superiores a 90% na viabilidade celular em espécies sensíveis, como *Chaetoceros* sp. Os valores de IC_{50} variaram de 0,332 a 8,46 mg·L⁻¹, indicando elevada variabilidade interespecífica. Em contraste, *Chlorella* sp. e *Scenedesmus* sp. mantiveram crescimento em concentrações de até 100 mg·L⁻¹. Sistemas com microalgas apresentaram eficiências de remoção entre 61,7% e 73,3%, enquanto consórcios microalga-bactéria alcançaram remoções superiores a 90%, com eficiência máxima de 97,2%. Conclui-se que o LAS representa um risco ecotoxicológico; entretanto, as microalgas, especialmente em sistemas simbióticos, constituem alternativas promissoras para sua biorremediação.

Palavras-chave: Surfactante aniônico; LAS; Poluição da água; Biorremediação; Microalgas.

Introduction

Emerging contaminants, especially surfactants, have attracted increasing attention from the scientific community due to their potential environmental impacts and risks to public health (Montagner et al., 2019). Among these compounds, linear alkylbenzene sulfonate (LAS) stands out as one of the most widely used anionic surfactants in cleaning products, household and industrial detergents, and personal care items. Constituting one of the main components of surfactants used on a global scale (Luo et al., 2023). Its presence in various aquatic matrices, resulting from the improper disposal of domestic and industrial effluents, has raised significant concerns regarding its effects on aquatic ecosystems and environmental health (Pandey et al., 2020).

Recent studies demonstrate that LAS can cause significant toxicity in aquatic organisms, particularly microalgae. As primary producers, microalgae are central targets of environmental contaminants such as herbicides and detergents, directly affecting the dynamics of aquatic ecosystems (Franklin et al., 2002; Tu et al., 2020). Exposure to LAS may interfere with gas exchange dynamics (air-water interactions), alter membrane permeability, enzymatic activity, and tissue structure, and even affect the genetic material of microorganisms and higher animals (Zhang et al., 2021). According to Ogbulie et al. (2008), these surfactants reduce water surface tension, impair aquatic organism reproduction, damage the protective mucous layer of fish, and cause severe gill injuries. These effects are associated with the overproduction of reactive oxygen species (ROS), which directly damage lipids, proteins, and cell DNA (Bragadin et al., 2010).

The removal of LAS in wastewater treatment plants can occur through physicochemical and biological processes. In this context, the Upflow Anaerobic Sludge Blanket reactor (UASB) reactor promotes removal primarily via adsorption of the compound onto anaerobic sludge, while the polishing pond contributes through adsorption onto suspended solids and biological degradation. However, these approaches present limitations, including high operational costs and the potential formation of toxic by-products (Silva et al., 2017).

The persistence of LAS in the environment, due to its recalcitrance under natural conditions, aggravates its potential for bioaccumulation and chronic toxicity (Wu et al., 2023). Moreover, chronic and sublethal toxicity from LAS has been observed even at low concentrations. Studies (Venhuis & Mehrvar, 2004) report that concentrations ranging from 0.02 to 1.0 $mg.L^{-1}$ can already cause gill damage in fish, behavioral changes in mollusk larvae, and impacts on crustaceans. Additionally, Mungray and Kumar (2008) reported that even after treatment, a residual fraction of LAS (between 1% and 5%) may remain in treated effluents, being partially removed in receiving waters through processes such as biodegradation, sorption onto suspended particles, and sedimentation. However, the continuous discharge of untreated effluents can lead to contamination of marine and coastal environments.

Given this scenario, studies suggest that symbiotic systems between microalgae and bacteria may offer a sustainable alternative. In such systems, microalgae produce oxygen via photosynthesis, while bacteria degrade organic compounds into CO_2 and smaller molecules that are reused by algae, creating an energy-efficient functional cycle (Quijano et al., 2017; Zhang et al., 2021; Wu et al., 2026). Additionally, Su et al. (2011) highlighted that the combined use of microalgae and aerobic bacteria in treatment systems can reduce operational costs, since the oxygen generated by microalgae during photosynthesis is used by bacteria in organic matter degradation.

In tropical climates like Brazil, favorable climatic conditions, such as high temperatures and intense solar radiation (Satiro et al., 2025), promote microalgal proliferation. However, the irregular discharge of domestic sewage and industrial wastewater containing LAS into water bodies has exacerbated the contamination of these ecosystems, negatively affecting aquatic biodiversity and water quality (Tu et al., 2020). Microalgae thus stand out as bioremediation agents due to their ability to remove pollutants through active mechanisms (such as biodegration in living cells) and passive mechanisms (such as biosorption onto living or dead cell surfaces) (Volesky & Holan, 1995). The sponge *Amoebocytes* which contain eukaryotic microalgae of the genus *Chlorella* sp., proved to be representative indicators for assessing the impact of anionic surfactants (Nikonova et al., 2023). These microorganisms perform processes such as biodegradation, membrane transport, precipitation, complexation, and redox reactions, demonstrating their efficiency in remediating contaminated environments (Veglio & Beolchini, 1997; Beceiro-González et al., 2000; Dias et al., 2019; Wu et al., 2020). The efficiency of these processes can be enhanced by the formation of syntrophic biofilms, which exhibit structural stability, resistance to high loads, ease of automation, and high pollutant removal efficiency (Quijano et al., 2017; Abinandan et al., 2018).

Nevertheless, the interaction between LAS and microalgae remains poorly understood, especially regarding the mechanisms of toxicity, degradation, and removal mediated by different microalgal species (Pandey et al., 2020). This knowledge gap is even more relevant considering that most studies address either organic or metal pollution separately, with few investigating the combined presence of contaminants such as LAS and metal ions like zinc (Zn^{2+}) (Morales-Muñoz et al., 2004).

The variability in microalgal responses to LAS, influenced by factors such as cell morphology, nutrient availability, and environmental conditions, underscores the need for more in-depth studies on the physiological and biochemical effects of this surfactant (Wu et al., 2023). Furthermore, the formation of biofilms by microalgae in association with bacteria such as *Pseudomonas* sp. and *Alcaligenes* sp. has been identified as an effective mechanism for the biodegradation of organic compounds, including anionic surfactants like LAS (Wu et al., 2023). This syntrophic process enhances contaminant removal in wastewater treatment ponds and activated sludge systems, widely used in tropical countries (Dias et al., 2019).

Despite the potential of microalgae for the remediation of contaminated waters, technical challenges persist, such as species-dependent variability in removal rates and the need for continuous environmental monitoring (Peng et al., 2017). According to Zhou et al. (2020) and Schnurr and Allen (2015), factors such as pH, C/N ratio, temperature, hydraulic retention time, dissolved oxygen, and light intensity strongly influence the growth, activity, and function of the microalgae and bacteria involved in biofilms. Satiro et al., 2025 present systems using microalgae-bacteria consortia are promising nature-based solutions (NbS) that require no artificial aeration and can produce valuable products.

Moreover, the study by Zhu et al. (2016) demonstrates that initial cell density and competitive interactions among species may significantly affect microalgal responses to LAS, emphasizing the importance of an integrated approach that considers ecological variables and environmental contexts. Among the most studied species is *Spirulina platensis*, a cyanobacterium with a well-known capacity for removing heavy metals and organic compounds (Ciferri, 1983).

Regarding the chemical fate and biodegradation pathways of this contaminant in aquatic environments, further investigation is needed. Although aerobic biodegradation shows high efficiency (Liu et al., 2013), the surfactant exhibits persistence under anaerobic conditions, which is relevant for effluent management and the contamination of ecosystems such as estuaries (Penteado et al., 2006). The lower biodegradation efficiency in anaerobic pathways, where removal occurs mainly through adsorption and/or precipitation (Silva et al., 2017), highlights the need for more studies focused on microalgae-mediated degradation in these environments. Although LAS has been structurally optimized for greater biodegradability compared to with alkylbenzene sulfonate (ABS) (Zhang et al., 2021), its toxicity and removal efficiency vary according to the length of the alkyl chain (Lutterbeck et al., 2020).

In Brazil, there is still no specific regulation for the LAS in sanitary effluents discharged into water bodies (Brasil, 2011; Lasek et al., 2019). The Organization for Economic Co-operation and Development (OECD), together with the European Commission, has proposed a regulation under the European Union framework on detergents and surfactants (COM/2023/217). However, it does not establish maximum concentrations for the discharge of surfactants in effluents. The legislation also requires that all surfactants be fully biodegradable according to internationally standardized methods (such as OECD Guidelines 301 and 302), prohibiting the commercialization of products that do not meet this requirement. When conducting a multilevel risk assessment of LAS in aquatic organisms, Luo et al. (2023) produced results that demonstrate the urgency of regulating and controlling the predicted concentrations in order to prevent harm to water resources. Given the above, this work provides the first systematic synthesis of published data on LAS toxicity and removal by microalgae, highlighting species-specific responses, knowledge gaps, and the potential of algal-bacterial systems for bioremediation

Materials and methods

For this study, a systematic investigation model was adopted to map research related to the bioremediation of LAS using microalgae. The methodology followed two main phases: data retrieval from specialized databases (Science Direct, Web of Science, Scopus and Springer) and a systematic literature analysis, in accordance with methodological guidelines for systematic reviews (Tranfield et al., 2003; Snyder, 2019). This approach enabled the identification and critical examination of the most relevant studies on the topic, ensuring a structured review of the scientific output in the field.

Database search

In the database search phase, Science Direct, Web of Science, Scopus and Springer were accessed through the CAPES (Coordination for the Improvement of Higher Education Personnel) portal, with the objective of identifying all published studies related to the use of microalgae and/or microalgae consortia for the removal of LAS. To perform the systematic search of articles in the databases, the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was applied, which consists of the stages of identification, screening, eligibility, and inclusion (Page et al., 2021). The search was conducted in January 2024. In the first and second stages (identification and screening), the following terms were jointly searched in the title, abstract, and keywords (title-abs-key) using the Boolean operators "*OR*" and "*AND*": ("linear alkylbenzene sulfonate" *OR* "linear alkylbenzene sulphonate") *AND* ("microalgae" *OR* "algae" *OR* "algae-bacteria") *AND* ("removal" *OR* "biodegradation" *OR* "toxicity"). A total of 267 articles were retrieved: 187 from Science Direct, 27 from Springer, 32 from Scopus and 21 from Web of Science covering the years 2005 to 2023 (Figure 1) presents the aforementioned stages, as well as the number of studies included in each step and the analysis conducted on the selected articles.

In the third stage of the methodological process, corresponding to the eligibility phase, the titles and abstracts of the previously selected articles were analyzed to identify those that did not directly address the research questions. Only studies presenting quantitative experimental data on toxicity, biodegradation, or LAS removal efficiency were considered eligible, including evaluations conducted in microalgal systems or in symbiotic algae–bacteria systems. At this stage, only twenty studies presented relevant information on the use of microalgae in the bioremediation of LAS, with eight articles from the Science Direct database, two from Springer, six from Web of Science and four from Scopus. However, three of these articles were excluded as they consisted exclusively of literature reviews, without experimental data or applied analyses. This exclusion criterion followed methodological guidelines adopted in systematic reviews, as described by Akyüz and Roberts (2002) and Snyder (2019), ensuring greater rigor in the selection of studies.

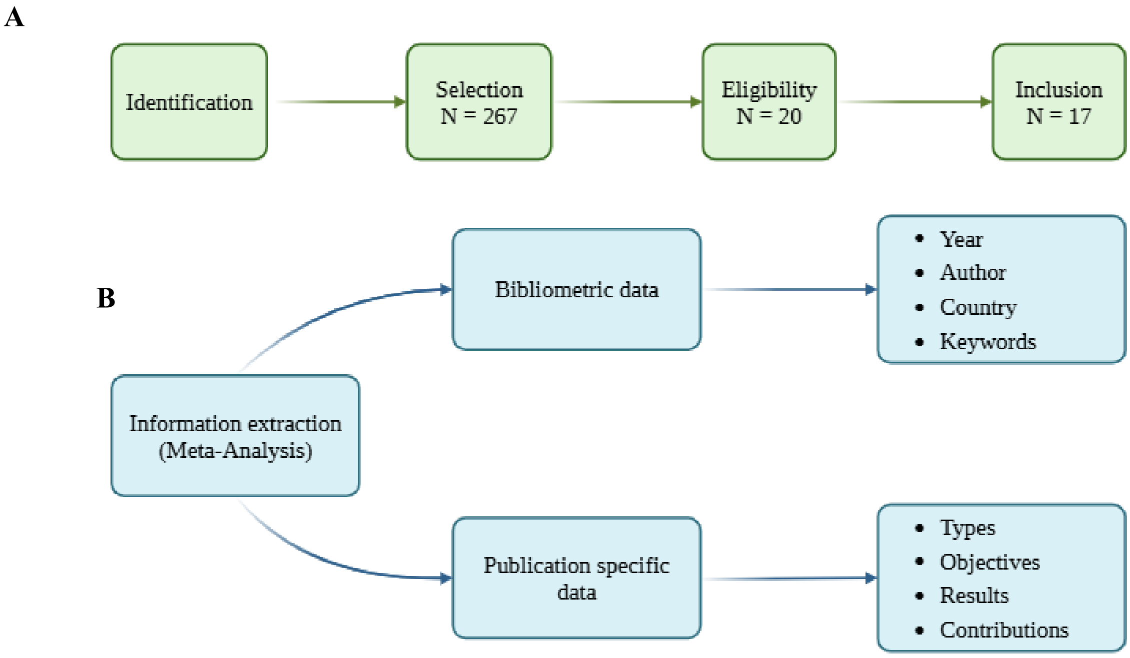

Figure 1. A: Workflow for study selection and evaluation in the meta-analysis. A – Identification and selection of relevant studies; B: Criteria applied for inclusion and analysis in the review.

In the final stage, corresponding to the inclusion phase, the seventeen eligible articles were read in full to ensure that they centrally addressed the proposed topic. After this step, the studies were organized in tabular format to systematize the data. The variation between the initial number of identified studies and the articles ultimately included highlights the importance of careful screening based on the PRISMA model (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), as proposed by Page et al. (2021). This approach contributes to enhancing the precision and reliability of systematic reviews, minimizing the inclusion of out-of-scope research, and ensuring higher quality in the analysis of results (Page et al., 2022), while reducing the likelihood of including irrelevant studies.

Systematic analysis

In the systematic analysis phase, the articles selected from the databases were thoroughly examined to extract and synthesize the most relevant information. To organize the findings, summary tables were developed, systematically compiling data on the investigated anionic surfactants, characterization of the research locations, and the main results obtained. This procedure allowed structuring the available knowledge in the literature and facilitated comparison among different studies, ensuring greater clarity in identifying scientific evidence. The systematization of information followed widely adopted methodological guidelines for systematic reviews, as described by Tranfield et al. (2003) and Akyüz and Roberts (2002), which emphasize the importance of standardizing data organization to enhance the reliability of conclusions.

According to Liu et al. (2020), systematic literature analysis provides a comprehensive overview of the state of the art, enabling the identification of knowledge gaps, key methodological approaches, and emerging trends within the study area. Moreover, this method contributes to the generation of new research hypotheses and the formulation of recommendations for future investigations (Snyder, 2019; Page et al., 2021). Thus, systematic analysis not only consolidates existing findings but also guides scientific development by highlighting aspects that remain underexplored in the investigated field

Results and discussion

Overview of publications: Period, countries, and institutions involved

The selected studies span a publication period from 2005 to 2023, with China being the leading country in the number of publications on this topic, followed by contributions from France, India, and Spain (Figure 2) illustrates the number of publications by country, along with the corresponding references for the published studies.

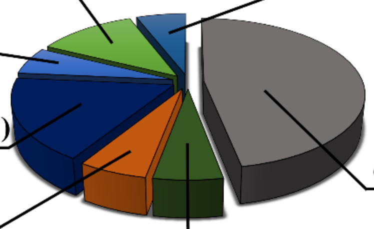

Figure 2. Nationality, number of publications per country, and references of the studies selected in this research.

Additional information about the publications can be observed in Table 1, including type of study (toxicity and/or removal), microalgae species studied, and details regarding LAS.

Table 1. Summary of international studies evaluating the toxicity and/or removal of linear alkylbenzene sulfonate (LAS) using different microalgae species, indicating the country of study, reference (year), type of evaluation performed, microalgae species tested, and the LAS formulation or homologue.

Country	Reference (year)	Evaluation	Microalgae species	Type of LAS used
China	Meng et al. (2012)	Removal and toxicity	*Spirulina platensis*	Not informed
	Wang et al. (2015)	Toxicity	*Microcystis aeruginosa*	C12 homologue
	Liu and Wu (2018)	Toxicity	*Chara vulgaris L.*	C12 homologue
	Zhang et al. (2021)	Toxicity	*Chlorella pyrenoidosa*	C12 homologue
	Wu et al. (2023)	Removal	*Synechocystis*	Synthetic grey water
	Cheng et al.(2021)	Toxicity	*Scenedesmus obliquus*	Not informed
	Zhu et al. (2016)	Toxicity	*Microcystis aeruginosa* *Scenedesmus obliquus*	C12 homologue
	Tu et al. (2020)	Removal	*Scenedesmus dimorphus* (used in the symbiotic system with bacteria)	Not informed
France	Renaud et al. (2011)	Toxicity	*Tetraselmis levis* *Dunaniella tertiolecta* *Thalassiosira pseudonana* *Skeletonema costatum*	C12 homologue

			Prorocentrum minimum	
India	Pandey et al. (2020)	Removal and toxicity	*Chlorella* sp. *Scenedesmus* sp. *Navicula* sp. *Nitzchia* sp. *Stauroneis* sp.	Real laundry effluent
Spain	Debelius et al. (2008)	Toxicity	*Tetraselmis chuii* *Rhodomonas salina* *Chaetoceros* sp. *Isochrysis galbana* *Nannochloropsis gaditana*	C12 homologue
	Moreno-Garrido et al. (2007)	Toxicity	*Phaeodactylum tricornutum*	LAS present in the test sediments
	Garrido-Perez et al. (2008)	Toxicity	*Isochrysis galbana*	C10, C11 and C13 homologues
Netherlands	Lurling (2005)	Toxicity	*Scenedesmus obliquus*	FFD-6 (mono- and didodecyl disulfonated diphenyl oxide, sodium salt, belonging to the LAS class)
Russia	Nikonova et al. (2023)	Toxicity	*Chlorella* sp.	C10, C11, C12 and C13 homologues
	Markina & Aizdaicher (2007)	Toxicity	*Attheya ussurensis*	Not informed
Brazil	Jonsson et al. (2009)	Enzymatic inhibition	*Pseudokirchneriella subcapitata*	Not informed

The research was conducted by different institutions, even within the same country. In China, for example, prominent institutions include the Southern University of Science and Technology (Shenzhen), Wuhan University, and various branches of the Chinese Academy of Sciences (Xiamen and Wuhan). Other studies originated from Guru Jambheshwar University (India), Universidad de Cádiz (Spain), and CNRS - Université de La Rochelle in partnership with IAEA - MEL (France). Additional research contributions came from the A.V. Zhirmunsky Institute of Marine Biology, Far Eastern Branch of the Russian Academy of Sciences (Vladivostok, Russia) and Limnological Institute of the Siberian Branch of the Russian Academy of Sciences, the Department of Biochemistry at the State University of Campinas (Campinas, SP, Brazil), and institutions associated with Aquatic Ecology and Water Quality Management, WIMEK (Netherlands).

Evaluation of Biological Mechanisms: Physiological Responses vs. Removal Efficiency

The analyzed studies highlight that the toxicity of LAS has been the primary focus of research, while the bioremediation capacity by microalgae is frequently addressed as a secondary aspect, as shown in Table 2.

Table 2. Information related to toxicity and/or bioremediation tests of the selected studies.

Reference (year)	**Tested concentrations of LAS ($mg.L^{-1}$)**	**Toxicity highlights**	**Bioremediation highlights**
Lurling (2005)	0.001- 10	Surfactant, FFD-6, induces colony formation at concentrations much lower than those that inhibit growth, potentially altering species interactions and food chain balance, indicating that surfactants at environmental levels may not be harmless to aquatic life	The formation of colonies in *Scenedesmus* was induced by FFD-6 at concentrations several orders of magnitude lower (0.001 a 0.1 $mg.L^{-1}$) than those that inhibited growth (1 a 10 $mg.L^{-1}$)
Moreno-Garrido et al. (2007)	4.77 – 8.46	The EC_{50} value for LAS and *Cylindrotheca closterium* of 4.18 mg LAS kg^{-1}	Not evaluated
Markina &Aizdaicher (2007)	0.1- 10	The microalga *A. ussurensis* exhibits low resistance to the impact of detergents when compared to various aquatic taxa (mollusks, fish, and planktonic microalgae). The Ariel 10 $mg.L^{-1}$ induced the most severe toxic effects, manifested in the reduction of cell number, growth rate, and oxygen productivity. Given its sensitivity, benthic microalgae are suggested as preferred model organisms in the toxicity assessment of effluents	Not evaluated
Garrido-Perez et al. (2008)	2 - 10	The choice of the dilution water and the nutrient concentrations did not affect the toxicity of LAS at threshold levels	Not evaluated
Debelius et al. (2008)	0.1 – 10	High sensitivity to LAS, with growth inhibition	Not evaluated

Jonsson et al. (2009)	0.02-200	The acid phosphatase of *P. subcapitata* is inhibited by both LAS and metal ions. LAS was shown to be the most potent inhibitor in *in vitro* tests, suggesting a mechanism of competitive inhibition via competition of its sulfonate group with the substrate binding site. However, *in vivo*, the inhibitory effect of LAS was inferior to that of Hg^{2+}. The relevance of this finding lies in the indication that pollutants present in effluents can significantly alter this enzyme, which is essential for phosphate homeostasis in algae	*S. obliquus* demonstrates the potential to be a bioremediation agent (due to its resistance and growth), while *A. ussurensis* exhibits the sensitivity necessary to be a toxicity indicator
Renaud et al. (2011)	0.2 – 3.5	Green algae are more resistant to LAS due to their complex cell walls	Adsorption and desorption of LAS were studied, but bioremediation was not the focus
Meng et al. (2012)	0.5 – 4	Toxicity evaluated, but growth stimulated at low concentrations	Synergistic relationship between LAS and Zn^{+2}, with increased Zn^{+2} uptake and LAS biodegradation
Wang et al. (2015)	0.05 – 20	Growth inhibited at 20 $mg.L^{-1}$, but stimulated at lower concentrations	Not evaluated
Zhu et al. (2016)	1-100	Low concentrations of LAS (1 and 20 $mg.L^{-1}$) promoted the growth of *S. obliquus.* But, 20 and 100 $mg.L^{-1}$ of LAS would markedly inhibit the growth of *M. aeruginosa.* Co-culture: Without LAS *M. aeruginosa* dominated	The observed resistance and optimized growth of *S. obliquus* in LAS containing environments suggest that this microalga is a viable candidate for species selection in bioremediation strategies aimed at surfactant mitigation in aquatic ecosystems

Liu & Wu (2018)	0.1 – 5	Toxicity observed, but 5 $mg.L^{-1}$ was not lethal	Not evaluated
Pandey et al. (2020)	Not informed	Green microalgae tolerated up to 100 $mg.L^{-1}$, but diatoms did not grow with LAS	LAS removal was attributed to adsorption, with efficiencies of 61.7% (microalgae) and 100% (consortium)
Tu et al. (2020)	200	Not evaluated	Comparative evaluation of the symbiotic bacteria-algae system versus single cultures (either bacteria or algae) revealed that the consortium system achieved a maximum removal efficiency of 97.2%. In contrast, the axenic cultures of bactéria (*Plesiomonas sp.* e *Pseudomonas sp)* and microalgae (*Scenedesmus dimorphus)* demonstrated lower efficiencies of 82.5% and 73.3%, respectively, highlighting the synergy of the symbiotic system
Cheng et al. (2021)	1000	The results showed that the IC_{50} de 96h of Zero-Valent Iron Nanoparticle (nZVI) and LAS para *Scenedesmus obliquus* was of 2,464 $mmol.L^{-1}$) and 0.332 $mmol.L^{-1}$), respectively	Not evaluated

Zhang et al.(2021)	2.5 – 10	Tolerance to LAS up to 10 mg.L^{-1} with no significant negative effects	LAS is effective in controlling rotifers without affecting microalgae growth
Nikonova et al. (2023)	0.01- 0.02	The acute toxic effect resulted in 97-100% sponge cell death in less than 48h symbiotic microalgae *Chlorella* sp. death over 72h, noted under LAS solution 0.02 mg.L^{-1} exposure during *in vivo* experiments. This includes the cell membrane fatty acid changes, change in the cell sizes, cell swelling and lysis	Long-term exposure to LAS solution 0.01 mg.L^{-1} was reflected in cellular stress (oxidative stress) and was accompanied by malondialdehyde formation (0.0016 – 0.02 mg.L^{-1}) of dry weight) during a 14 day exposure
Wu et al. (2023)	<10	Not evaluated	Removal greater than 90% at different studied stages

This emphasis is related to the emerging nature of LAS as a priority contaminant, present in domestic and industrial effluents at increasing levels, and concerns about its ecotoxicological effects on aquatic organisms. Authors such as Liu and Wu (2018) prioritized the evaluation of physiological effects of LAS on *Chara vulgaris*, observing significant changes in biomass and antioxidant enzymes such as superoxide dismutase (SOD) and peroxidase (POD), with less focus on the plant's recovery capacity. Similarly, Renaud et al. (2011) investigated sorption and toxicity in five microalgal species, emphasizing LAS accumulation kinetics and IC_{50} values, but without addressing degradation mechanisms or active mitigation by the organisms.

These studies reflect a methodological trend to assess immediate environmental risk, often measured by stress biomarkers or lethal/sublethal effects, while the bioremediation capacity of algae, though mentioned, is rarely the central objective. Exceptions such as the study by Zhang et al. (2021), which used *Chlorella pyrenoidosa* in open cultivation and measured the absence of surfactant residues after practical application, remain rare.

The position adopted in this article is that this gap is mainly due to the methodological complexity involved in proving complete biodegradation or effective contaminant removal by microalgae, especially in real systems. Furthermore, many studies use LAS as a model for standardized toxicity tests, which naturally shifts focus on negative effects rather than exploring beneficial uses or technological applications.

Thus, it is argued that there is an urgent need to rebalance the literature by focusing not only on the negative impacts of LAS on aquatic organisms but also on the systematic exploration of microalgae's potential as active bioremediation tools, with studies including enzymatic analyses, monitoring of degradation, and mass flow modeling. This reorientation would not only mitigate the toxic effects of LAS but also transform microalgae into key agents of sustainable environmental treatment.

Despite toxic effects, some studies highlight the potential of microalgae for LAS removal, mainly through adsorption and indirect degradation mediated by associated bacteria. Renaud et al. (2011) demonstrated that LAS sorption is rapid, reaching equilibrium in up to 5 hours, and follows a Freundlich isotherm (n<1), indicating progressive saturation of cell surfaces with increasing contaminant concentration. LAS affinity varied among species, being higher in dinoflagellates and lower in green algae, due to differences in cell wall composition.

Moreover, studies like Zhang et al. (2021) suggest that biological control of contaminants such as rotifers can be achieved without compromising algal biomass and without detectable surfactant residues at the end of cultivation. This evidence points to beneficial interactions between microalgae and associated microorganisms, such as heterotrophic bacteria capable of metabolizing and degrading compounds like LAS, contributing to their removal in symbiotic processes. Although this point is not the central focus of the analyzed articles, it is indirectly suggested in hybrid systems, such as that evaluated by Pandey et al. (2020), where microalgae and activated sludge coexist in treatment reactors and achieve high removal rates of organic matter and nitrogen, indicating potential also for surfactants. However, LAS bioremediation remains a little-explored topic, with most studies focusing on toxicity and microalgal resistance mechanisms to the contaminant (Pandey et al., 2020; Wu et al., 2023).

Most studies concentrate on assessing LAS toxic effects on different microalgal species and submerged aquatic plants. Liu and Wu (2018), for example, analyzed the impacts of different LAS concentrations on *Chara vulgaris*, noting effects on biomass and antioxidant enzymes but without exploring the species' remediation capacity. Similarly, studies by Deberius et al. (2008) and Renaud et al. (2011) deepen the toxicity and sorption mechanisms but do not progress to investigations of complete LAS degradation.

This pattern repeats in studies like Meng et al. (2012), who, although mentioning zinc absorption and LAS degradation by *Spirulina platensis*, mainly focus on co-contamination effects and ecotoxicological risk assessment. Therefore, the evaluated studies reveal a clear gap: the role of microalgae as active agents of LAS bioremediation, either isolated or in consortia with bacteria, still lacks specific and in-depth investigations. This observation reinforces the need for new research integrating physiological, ecological, and biochemical assessments with monitoring of LAS degradation over time, including the importance of microbial communities associated with algal cultures.

The study by Tu et al. (2020) demonstrated that a consortium composed of the microalga *Scenedesmus dimorphus* and LAS-degrading bacteria (*Plesiomonas sp.* and *Pseudomonas sp.*) achieved an average LAS removal efficiency of 94.6%. This superior efficacy is attributed to metabolic synergy, where the microalga supplies essential oxygen to the aerobic degrading bacteria, facilitating the cleavage of the LAS aromatic ring. Molecular ecology analysis using DGGE further confirmed that the strategic addition of specific degrading bacteria, such as *Plesiomonas sp.* and *Pseudomonas sp.*, significantly enhances contaminant removal efficiency.

A wide variety of microalgal species were used in the reviewed studies, including *Spirulina platensis*, *Chlorella* sp., *Scenedesmus* sp., *Tetraselmis chuii*, *Rhodomonas salina*, *Chaetoceros* sp., *Isochrysis galbana*, *Nannochloropsis gaditana*, *Microcystis aeruginosa*, and *Chara vulgaris L*. These species were selected for their ecological relevance and potential application in bioremediation systems. For example, *Spirulina platensis* was used to evaluate LAS biodegradation and zinc (Zn^{+2}) accumulation (Meng et al., 2012), while *Chlorella* sp. and *Scenedesmus* sp. were employed in laundry wastewater treatment systems (Pandey et al., 2020). Moreover, Renaud et al. (2011) used five marine microalgal species to measure LAS sorption and toxicity, observing considerable variation between taxonomic groups: dinoflagellates showed higher affinity to the surfactant, followed by diatoms and green algae, reinforcing the importance of considering cell wall composition in species selection. These species reflect the need to understand how different microalgae respond to LAS in diverse environmental contexts.

Mechanisms of Toxicity and Physiological Responses of Microalgae to LAS

Recent studies demonstrate that LAS can cause significant toxicity in aquatic organisms, particularly in microalgae, which play a fundamental role as primary producers in the dynamics of aquatic ecosystems (Tu et al., 2020). Moreover, the persistence of LAS in the environment, due to its resistance to degradation under natural conditions, exacerbates its potential for bioaccumulation (Wu et al., 2023).

In this context, microalgae emerge as promising agents for bioremediation due to their capacity to perform processes such as biosorption, bioaccumulation, and biodegradation of toxic compounds (Dias et al., 2019; Wu et al., 2023). Although the remediation potential of microalgae is widely supported by the analyzed studies, different approaches reveal important limitations, such as variability in removal rates among species and the need for continuous monitoring of environmental conditions (Peng et al., 2017), indicating that technical challenges persist.

Zhu et al. (2016) indicate that initial cell density and competitive interactions among species can significantly influence the response of microalgae to LAS, highlighting the importance of an integrated approach that considers ecological variables and environmental contexts. For example, Liu and Wu (2018) observed the effects of LAS on *Chara vulgaris* in a two-week experiment, noting significant changes in antioxidant enzyme activities (SOD and POD), as well as plant biomass. The study suggests that, despite partial resistance of the species, concentrations of 5 $mg.L^{-1}$ already cause oxidative stress, limiting the organism's tolerance to LAS.

Debelius et al. (2008) demonstrated that the response of microalgae to LAS depends on the initial cell density, proposing the concept of toxic cellular quota to explain sensitivity variation among different species. This metric relates the toxic concentration to the number of exposed cells, offering an innovative approach for toxicity studies in aquatic systems.

Nikonova et al. (2023) found that the toxic effects of LAS on the sponge *Lubomirskia baikalensis* and its symbiotic microalgae *Chlorella* sp. were observed at low concentrations in *in vitro* experiments. An acute toxic effect of LAS was detected at a concentration of 20 $\mu g.L^{-1}$, while oxidative stress in the sponges in response to LAS exposure was identified at concentrations as low as 10 $\mu g.L^{-1}$.

Studies also indicate that the behavior of LAS in the environment depends on ecological factors such as medium composition, presence of nutrients, and other pollutants. For example, Zhang et al. (2021) demonstrated that the surfactant sodium dodecylbenzene sulfonate (SDBS) can be effectively used to eliminate contaminant rotifers in cultures of *Chlorella pyrenoidosa* without compromising algal biomass. This shows that, under certain conditions, LAS or its derivatives can be exploited as an ecological management tool in addition to being a remediation target.

The study by Lurling (2005), for example, demonstrated that the surfactant FFD-6 can induce colony formation in *Scenedesmus* sp. at concentrations significantly lower than those required for growth inhibition. This suggests that these compounds have the capacity to affect interspecific interactions, survival, and energy flow along the food chain, thereby refuting the assumption that environmental surfactant concentrations are harmless to aquatic life.

Moreno-Garrido et al. (2007) established a direct correlation between the LAS content in the sediment and algal inhibition. Interestingly, the immobilization of algal cells in a calcium alginate matrix conferred protection against the xenobiotic, indicating the influence of the cellular/extracellular matrix on toxicity. Contaminant sensitivity is also influenced by environmental conditions, as Garrido-Perez et al. (2008) observed that the marine microalga *Isochrysis galbana* is more susceptible at natural nutrient concentrations and in marine waters from polluted areas.

The toxicity of LAS was further detailed by Cheng et al. (2021), who noted the growth inhibition of *Scenedesmus obliquus* even at low concentrations of the isolated surfactant. However, the Zero-Valent Iron Nanoparticle (nZVI) exhibited a dual effect, promoting growth at low doses (< 0.714 $mg.L^{-1}$) but causing inhibition at higher doses. The ecological consequence of LAS presence was evidenced by Zhu et al. (2016), who demonstrated the reversal of algal competition in freshwater ecosystems, resulting in the replacement of the susceptible cyanobacterium (*Microcystis aeruginosa*) by the more resistant green alga (*Scenedesmus obliquus*).

The effect of detergents varies among species, with Markina and Aizdaicher (2007) concluding that the microalga *Amphora ussurensis* is less resistant to the impact of detergents (such as Ariel 10 $mg.L^{-1}$) compared to some other aquatic organisms. In this context, parameters such as cell number, growth rate, and oxygen productivity proved to be the most sensitive indicators of toxicity.

From a biochemical perspective, Jonsson et al. (2009) identified LAS and metals as inhibitors of acid phosphatase in *Pseudokirchneriella subcapitata*. LAS was the most potent inhibitor *in vitro*, suggesting competitive inhibition due to the interaction of its sulfonate group with the substrate. This highlights that pollutants like LAS in sewage sludge can alter the activity of this enzyme, which is vital for algal phosphate metabolism. In contrast to toxicity, the mitigation potential is promising, as Tu et al. (2020) demonstrated that a symbiotic system involving *Scenedesmus dimorphus* and bacteria achieved a high LAS removal rate (97.2%) at a concentration of 200 mg.L^{-1}.

Therefore, although studies confirm the viability of microalgae in mitigating surfactants such as LAS, they also reveal that its application requires attention to interspecies variation, sublethal effects, and the environmental dynamics of aquatic systems. Approaches integrating physiological, biochemical, and kinetic analyses are recommended to maximize the effectiveness of bioremediation processes.

Dynamics of Toxicity and Physiological Responses of Microalgae to LAS

The LAS concentrations evaluated varied widely, ranging from 0.05 mg.L^{-1} to 98 ± 5 mg.L^{-1}, reflecting different environmental contexts and research objectives. Lower concentrations, such as 0.05 mg.L^{-1} and 0.1 mg.L^{-1}, were tested to simulate conditions close to those found in natural environments (Wang et al., 2015; Liu & Wu, 2018), whereas higher concentrations, such as 98 ± 5 mg.L^{-1}, were used in studies on LAS removal from synthetic greywater (Wu et al., 2023). This variation in concentrations allowed a more comprehensive understanding of LAS effects, from toxicity at low concentrations to removal efficiency in wastewater treatment systems.

The microalgae response to contaminants like LAS is not uniform, being influenced by biotic factors specific to each species and abiotic conditions of the cultivation environment. Debelius et al. (2008) evaluated LAS toxicity in five marine microalgae, identifying *Chaetoceros* sp. as the most sensitive genus to LAS. Besides interspecies comparison, the authors found that initial cell density plays a decisive role in microalgae response to LAS exposure. In cultures with higher densities, toxic effects were less pronounced. This occurs, according to the authors, because LAS distributes among a larger number of cells, reducing the contaminant amount available per cell, which dilutes individual impact and helps maintain cell viability. This observation led researchers to propose the concept of toxic cellular quota, an innovative metric relating observed toxicity not only to the environmental pollutant concentration but also to the effective proportion absorbed per cell.

This approach represents an important contribution to ecotoxicological studies with microalgae, as it helps explain divergent results found between species and experiments with different initial densities. Moreover, it provides a methodological basis for planning microalgal cultivation under real bioremediation conditions, where cell density can be adjusted to minimize toxic effects of surfactants such as LAS.

Therefore, initial cell density should not be seen merely as an experimental parameter but as an ecological variable with a direct impact on the toxicity kinetics and toxicity dynamics of contaminants in aquatic systems. This understanding creates a critical conceptual link to the following sections, which address the feasibility of microalgae use in environmental remediation strategies, where mitigating toxic effects is fundamental to successful field applications.

Renaud et al. (2011) studied LAS adsorption and desorption processes in marine microalgae, observing that green algae are more resistant to LAS due to their more complex cell wall structure. The toxic cellular concentration (TCC_{50}), defined as the amount of LAS per gram of algal biomass necessary to inhibit 50% of cells, was determined as 0.38 ± 0.09 mg LAS.g^{-1} of algae. The authors investigated LAS adsorption and desorption in five marine microalgae species across three major taxonomic groups: green algae (*Tetraselmis chuii*), diatoms (*Thalassiosira pseudonana*, *Skeletonema costatum*), and dinoflagellates (*Prorocentrum minimum*). They identified significant differences in LAS sorption among these groups, with green algae showing the lowest affinity for the contaminant, attributed to their thicker and more complex cell wall composed of resistant structures such as glycoproteins and sulfated polysaccharides.

This structural factor limits LAS penetration, reducing its adsorption and consequently cytotoxic effects. As a result, TCC_{50} was estimated at 0.38 ± 0.09 mg.g^{-1} for green algae, indicating greater tolerance compared to diatoms and dinoflagellates, whose values were lower (Renaud et al., 2011).

Cell inhibition or intoxication by LAS occurs primarily through interaction of the surfactant with the plasma membrane, promoting lipid disorganization, increased cell permeability, and release of intracellular contents. Previous studies cited by Renaud et al. also indicate that LAS can impair photosynthesis by affecting thylakoid membrane fluidity, as well as cause oxidative stress affecting antioxidant enzymes essential for maintaining cellular integrity. Therefore, the lower affinity of green algae for LAS not only reflects a physiological characteristic favorable to resistance but may also represent an adaptive strategy relevant in bioremediation systems, where more tolerant species are desirable for pollutant removal without significant biomass loss.

The surfactant FFD-6 (sodium mono- and didodecyl disulfonated diphenyloxide) was shown to induce colony formation in *Scenedesmus* sp. at extremely low concentrations (0.001 - 0.1 mg.L^{-1}) , far below the growth inhibitory doses (1 - 10 mg.L^{-1}, Lurling, 2005). This sublethal effect challenges the assumption of environmental concentrations being harmless, as it can alter interspecific interactions and trophic energy flow. LAS exhibits variable toxicity. Moreno-Garrido et al. (2007) identified that algal inhibition is directly correlated with the LAS content in the sediment. However, cellular immobilization in a calcium alginate matrix offers protection against the xenobiotic. Contaminant sensitivity is species-specific and modulated by environmental factors; for instance, Garrido-Perez et al. (2008) noted that the marine microalga *Isochrysis galbana* is more susceptible in polluted marine waters under natural nutrient concentrations.

The toxicity of isolated LAS to *Scenedesmus obliquus* is significant IC_{50} = 0.332 mg.L^{-1} with its impact contrasted by the dual effect of nZVI, which promote growth at low doses but inhibit it at higher concentrations IC_{50} = 2.464 mg.L^{-1} (Cheng et al*.*, 2021). In terms of ecological impact, increased LAS concentrations (up to 100 mg.L^{-1}) can reverse competitive dominance, favoring the more resistant green alga *S. obliquus* over the susceptible cyanobacterium *Microcystis aeruginosa* (Zhu et al*.*, 2016). The benthic microalga *Amphora ussurensis* proved to be a sensitive toxicity indicator, showing low resistance to detergents overall, with severe effects (reduced growth rate and oxygen productivity) observed at 10 mg.L^{-1} of Ariel (Markina & Aizdaicher, 2007).

Furthermore, the acute toxicity of LAS (0.02 mg.L^{-1}) can induce cell lysis and oxidative stress, even at low concentrations during prolonged exposure (Nikonova et al*.*, 2023). At the molecular level, Jonsson et al. (2009) demonstrated that LAS acts as a potent in vitro inhibitor of acid phosphatase in *Pseudokirchneriella subcapitata*, suggesting competitive inhibition via the sulfonate group. This finding indicates that LAS present in effluents can compromise phosphate homeostasis in algae. Environmental mitigation of LAS is promising through symbiotic systems. The *Scenedesmus dimorphus* and bacteria consortium achieved a maximum LAS removal efficiency of 97.2% (200 mg.L^{-1}) significantly surpassing axenic cultures of both algae and bacteria, thus demonstrating the synergistic potential for bioremediation (Tu et al*.*, 2020).

Meng et al. (2012) investigated LAS biodegradation and Zn^{+2} accumulation by *Spirulina platensis*, revealing a synergistic relationship between LAS and Zn^{+2}. Increased LAS concentration promoted Zn^{+2} uptake, while increased Zn^{+2} enhanced LAS biodegradation. Wang et al. (2015) evaluated the effects of LAS on growth and toxin production by *Microcystis aeruginosa*, concluding that environmental concentrations of LAS can promote algal overgrowth in eutrophic aquatic ecosystems. The authors found that at environmental concentrations up to 10 mg.L^{-1}, LAS not only stimulates algal biomass growth but also significantly increases intracellular and extracellular microcystin levels, potent hepatotoxins that exacerbate water health risks.

Although the authors do not directly specify if this concentration is typical of Brazilian environments, they indicate that the 10 mg.L^{-1} level represents an upper range observed in water bodies contaminated by domestic and industrial effluents in China. Thus, although the Chinese scenario may present variability in pollutant sources and loads, Wang et al. (2015) results are relevant to the Brazilian context, as they show that even moderate LAS concentrations have the potential to aggravate eutrophication and bloom toxicity. This underscores the importance of including surfactants such as LAS in environmental monitoring of tropical aquatic ecosystems like those found in various regions of Brazilian Northeast.

Liu and Wu (2018) investigated LAS effects on growth and antioxidant activities of *Chara vulgaris*, observing that LAS is toxic to the alga, but concentrations up to 5 mg.L^{-1} is non-lethal. The authors noted that LAS exerts significant toxic effects on the species, including reduced growth (dry weight) and altered activities of antioxidant enzymes, especially superoxide dismutase (SOD) and peroxidase (POD), enzymes fundamental to neutralizing reactive oxygen species (ROS) generated by chemical stress.

Nevertheless, results also indicated that LAS concentrations up to 5 mg.L^{-1} are non-lethal for the species, suggesting the existence of physiological resistance mechanisms. According to the authors, this resistance relates to activation of the enzymatic antioxidant system, which reduces ROS accumulation and protects cellular structures from oxidative damage. Additionally, the cell wall structure of *Chara vulgaris*, thick and composed of resistant polysaccharides and proteins, may hinder LAS penetration, limiting its direct effects on intracellular metabolism.

Another important aspect highlighted in the study is that although LAS causes significant metabolic alterations, such as increased malondialdehyde (MDA) content (a lipid peroxidation marker), these effects were reversible or partly compensated by the alga's biochemical defenses at non-extreme concentrations. *Chara vulgaris* thus demonstrated a moderate physiological tolerance profile to LAS, making it an interesting model for bioindicator studies and potential use in bioremediation of environments impacted by surfactants.

Pandey et al. (2020) compared the efficiency of different laundry wastewater treatment systems using green microalgae, diatoms, and symbiotic bacteria. The consortium of diatoms and activated sludge was the most efficient in removing LAS. The study evaluated three configurations: (A) only green microalgae (*Scenedesmus obliquus*), (B) diatom consortium (*Nitzschia palea*) with activated sludge, and (C) isolated activated sludge. The initial LAS concentration in the effluent was approximately 25 mg.L^{-1}, simulating typical domestic detergent effluent discharges.

The most efficient system was the diatom and activated sludge consortium (System B), which achieved complete LAS removal (100%) at the end of treatment. In contrast, the green microalgae system (System A) failed to completely remove LAS, with trace amounts of surfactant still detected in the treated effluent. The superior performance of System B is attributed to functional symbiosis between diatoms and heterotrophic microorganisms (symbiotic bacteria) present in the activated sludge, which enhance aerobic biodegradation processes. Furthermore, the siliceous cell structure of diatoms provides an additional surface for LAS adsorption, increasing initial compound capture and favoring its subsequent degradation.

The study also showed System B was most effective in removing other parameters, such as total nitrogen (90%) and total organic carbon (79%), reinforcing its potential as an integrated and sustainable solution for treating wastewater containing surfactants and excess nutrients. These findings indicate that hybrid systems combining different microbial and algal functionalities can be more effective than monoculture systems, offering advantages both in removal efficiency and operational stability.

Zhang et al. (2021) evaluated the use of surfactants, including LAS, to control rotifer contamination in *Chlorella pyrenoidosa* cultures. LAS was effective in controlling *Syndermata* groups without affecting microalgal growth. Wu et al. (2023) investigated LAS removal in a microalgae-bacteria biofilm reactor, observing removal efficiency exceeding 90%. Microalgae were responsible for oxygen production, facilitating LAS degradation by bacteria. In this setup, microalgae played a key role in continuous dissolved oxygen (O_2) production via photosynthesis. This oxygen-sustained respiratory activity of heterotrophic bacteria adhered to the biofilm, which directly biodegraded LAS, characterizing an algal-bacterial syntrophic process. This metabolic cooperation is essential in non-aerated systems where biochemical oxygen demand (BOD) is high due to organic load in the effluent.

The most abundant bacterial genera identified in the reactor were *Pseudomonas*, *Bacillus*, and *Acinetobacter*, all known for their capacity to degrade emerging compounds like LAS, especially in oxygenated environments. The presence of microalgae favored biofilm formation and stability, as well as nutrient and nitrogen compound removal (ammonium and nitrate), conferring on the system an efficient tertiary treatment profile. Compared to other studies reviewed, most literature still focuses on LAS toxicity in microalgae, with few works actively investigating bioremediation or surfactant degradation by these organisms. Among the eight reviewed articles, only two address LAS bioremediation involving microalgae (Pandey et al., 2008; Wu et al., 2023), while others focus on toxicity, bioaccumulation, or physiological biomarkers.

This discrepancy is also reflected in international scientific production. Publication analysis reveals that while countries like China and Spain lead in the number of LAS-related articles, studies integrating microalgae within bioremediation contexts remain scarce and concentrated in few research groups. This gap highlights a significant scientific opportunity for tropical countries such as Brazil, only one article, where native microalgal diversity and challenges with domestic effluents make applied bioremediation research with microalgae a promising and underexplored strategy.

Conclusions

This systematic review demonstrates that linear alkylbenzene sulfonate (LAS) poses a significant ecotoxicological risk to aquatic ecosystems, inducing concentration-dependent physiological, biochemical, and morphological effects in microalgae. Toxic responses, including oxidative stress, enzyme inhibition, membrane damage, and growth suppression, were observed even at low concentrations, highlighting the sensitivity of microalgae as bioindicators of environmental contamination.

The reviewed studies revealed marked interspecific variability in LAS tolerance, with sensitive species such as *Chaetoceros* sp. showing severe toxicity, whereas *Chlorella* sp. and *Scenedesmus* sp. exhibited greater resistance. Although most studies focused on toxicity, the findings confirm the potential of microalgae for LAS bioremediation. Axenic systems showed moderate removal efficiencies, while microalgae–bacteria consortia achieved superior performance, exceeding 90% removal due to metabolic cooperation.

Nevertheless, important gaps remain regarding biodegradation mechanisms, resistance pathways, and system performance under real environmental conditions. Future research should focus on tolerant species, integrated mechanistic analyses, and the validation of scalable treatment systems, particularly in tropical environments, to strengthen the application of microalgae as sustainable solutions for wastewater treatment.

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