

Research Article

Comparative Bioremediation Efficiency of Selected Microalgae in Industrial Wastewater Treatment

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ABSTRACT

This study evaluated the bioremediation potential of four freshwater algae—*Microcystis aeruginosa*, *Eudorina elegans*, *Chlorella vulgaris*, and *Oedogonium grande*—grown in industrial effluents from rubber, paint, Coca-Cola, and Guinness industries. Effluent remediation was assessed over a four-week exposure period using electrical conductivity, phosphate concentration, and dissolved oxygen as performance indicators. Removal efficiencies (%) were calculated to quantify treatment effectiveness. All algae significantly reduced ionic and nutrient loads, with electrical conductivity reductions ranging from 46.7–72.0% and phosphate removal reaching 100% in Coca-Cola effluent. Conductivity reduction was most pronounced in rubber effluent, with *Oedogonium grande* (71.91%) and *Microcystis aeruginosa* (72%) showing superior ionic removal, while all algae performed poorly in high-salinity beverage effluents. Phosphate removal was substantial across effluents, reaching complete removal (100%) in Coca-Cola effluent by *M. aeruginosa* and *Ch. vulgaris*. Dissolved oxygen increased consistently across treatments. Results demonstrated strong effluent-specific responses. *Chlorella vulgaris* consistently exhibited the highest overall bioremediation efficiency across effluents, while *Oedogonium grande* performed optimally in nutrient-rich brewery wastewater. Two-way ANOVA revealed significant effects of algal species and effluent type on removal efficiencies, with post-hoc comparisons confirming species-specific responses. The findings highlight functional specialization among algal taxa, with filamentous forms excelling in low-ionic effluents and unicellular green algae performing best under nutrient-rich conditions. The findings demonstrate the strong potential of micro-algae for low-cost, sustainable treatment of industrial effluents and support their application in effluent-specific bioremediation strategies. The study confirms the feasibility of algae-based effluent polishing and supports the strategic selection of algal species based on effluent chemistry. These results provide a scientific basis for integrating algal bioremediation into sustainable industrial wastewater management.

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INTRODUCTION

Industrial effluent discharge remains one of the most persistent threats to freshwater and coastal ecosystems, particularly in developing economies where treatment infrastructure is often inadequate or inconsistently enforced. Rapid industrialization has significantly contributed to economic development worldwide; however, it has also intensified the volume and complexity, and the discharge of untreated or partially treated industrial effluents into aquatic environments. These effluents often contain high loads of

organic matter, nutrients, heavy metals, hydrocarbons, dyes, and other toxic compounds that pose severe threats to water quality, ecosystem integrity, and public health ([Singh & Singh, 2023](#)).

Effluents from beverage, brewery, paint, and rubber manufacturing industries are characterized by high organic loads, nutrients, colorants, dyes, surfactants, heavy metals, hydrocarbons, and other toxic and recalcitrant compounds that pose severe threats to water quality, ecosystem integrity, aquatic biodiversity, and public health ([Singh et al., 2023](#);

[Saket et al., 2024](#); [Ethiraj et al., 2024](#); [WHO, 2017](#)). In Nigeria, rapid industrial expansion along riverine and coastal corridors has intensified concerns regarding effluent-induced eutrophication, oxygen depletion, and bioaccumulation of toxic substances ([Izah & Ogbu, 2026](#)). Among food and beverage industries, brewery operations (e.g., Guinness-type breweries) generate large quantities of wastewater characterized by high biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, nutrients, colour, and variable pH due to processes such as malting, mashing, fermentation, filtration, and cleaning operations ([Fillaudeau, et al., 2006](#); [Shabangu et al., 2022](#)). Untreated or inadequately treated brewery effluents can cause oxygen depletion, eutrophication, and ecological imbalance in receiving water bodies. The Coca-Cola (beverage) industry, for example, generates wastewater rich in biochemical oxygen demand (BOD), chemical oxygen demand (COD), sugars, phosphates, and cleaning chemicals, which can severely depress dissolved oxygen in receiving waters if untreated ([Shrotri et al., 2023](#)). Paint industry effluents are typically laden with synthetic dyes, pigments, solvents, surfactants, and heavy metals such as Pb, Cr, and Zn, posing acute and chronic toxicity risks to aquatic organisms ([Viktoryová et al., 2022](#); [Nair et al., 2022](#)). In contrast, rubber processing effluents are notable for high ammonia, sulphide, suspended solids, latex particles, and offensive odour, often rendering conventional treatment systems inefficient or costly ([Mohammadi et al., 2010](#)).

Conventional wastewater treatment technologies, including chemical precipitation, coagulation, flocculation, adsorption, advanced oxidation processes, and membrane filtration, are often expensive, energy-intensive, chemically demanding, generate secondary pollutants such as chemical sludge, require high maintenance, and economically unsustainable for long-term application, especially in low- and middle-income regions ([Mejía-Marchena et al., 2023](#)). Consequently, there is growing interest in environmentally sustainable, cost-effective, and resource-recovering alternatives for industrial effluent treatment. Therefore, attention has increasingly shifted toward algal-based bioremediation, a nature-based solution that integrates pollutant removal with biomass generation.

Bioremediation, defined as the use of living organisms to detoxify or remove pollutants from the environment, has emerged as a promising approach for mitigating industrial wastewater pollution. Among biological agents, algae—particularly microalgae and cyanobacteria—have attracted increasing attention due to their rapid growth rates, high surface area, metabolic versatility, and capacity to assimilate or transform a wide range of contaminants ([Das & Bhattarai, 2025](#); [Kaur & Reddersen, 2022](#)).

Microalgae and macroalgae possess remarkable physiological capacities for nutrient assimilation, heavy metal sequestration, organic carbon uptake, and color removal, making them ideal candidates for sustainable wastewater treatment ([Abdel-Raouf et al., 2012](#)). This study, therefore, investigates the potential of algae as a bioremediation tool for industrial effluents, with relevance to beverage, paint, and rubber industries, under tropical environmental conditions.

Algae can simultaneously remove nutrients, reduce organic load, sequester heavy metals, and degrade organic pollutants while simultaneously producing oxygen, and valuable

biomass ([Rawat et al., 2011](#)) that can be utilized for biofuels, animal feed, fertilizers, or high-value bioproducts ([de Souza Silva et al., 2025](#)). In brewery effluents, algae benefit from high nutrient loads and carbon availability, making algal systems particularly suitable for integrated wastewater treatment and biomass valorization ([Olguin, 2012](#), [Dias et al., 2023](#)).

The application of algal systems for industrial effluent bioremediation aligns with the principles of circular economy and sustainable development by coupling wastewater treatment with resource recovery. Substantial progress in laboratory and pilot-scale studies, the efficiency of algal bioremediation varies depending on algal species, effluent composition, environmental conditions, and system design. Despite the increasing global research on algal bioremediation, limited studies exist on the application of algae for brewery effluent treatment under tropical conditions, especially in Africa. Therefore, a comprehensive understanding of the mechanisms, performance, and limitations of algal-based remediation is essential for its effective large-scale implementation. This study, therefore investigates the potential of selected algal species for the bioremediation of brewery industrial effluents, with emphasis on pollutant removal efficiency and water quality improvement. This study contributes to the growing body of knowledge on algal bioremediation by evaluating the effectiveness of algae in treating industrial effluents and assessing key physicochemical and ecological responses.

MATERIALS AND METHODS

Study Area and Effluent Source

Industrial effluent samples were collected from the final discharge outlets of a [Coca-Cola bottling plant, paint manufacturing facility, rubber processing factory located in Benin and Guinness Effluent from Guinness Brewery located at Ikpoba Hill Benin City. These industries operate continuous production cycles generating wastewater rich in organic load and process-specific contaminants.

Effluent Characterization

Raw effluent was analyzed for pH, electrical conductivity, total dissolved solids (TDS), cations (Na, K, Ca, Mg) dissolved oxygen (DO), anions (nitrate, phosphate, chloride, sulphate, nitrite) following standard methods (APHA (2017), and selected heavy metals using an Atomic Absorption Spectrophotometer.

Algal Species and Culture Conditions

Pure cultures of *Microcystis aeruginosa*, *Eudorina elegans*, *Chlorella vulgaris* and *Oedogonium grande* were obtained from Limnology/Phycology laboratory of the University of Benin, Nigeria. Algae were acclimatized and cultured in modified BG-11 medium under controlled temperature (25 ± 2 °C) and photoperiod (12:12 h light:dark).

Experimental Design

Effluent was diluted to 25%, 50%, 75%, and 100% concentrations. Each algal inoculum was introduced separately into treatment reactors, while controls contained algae without the effluent. Experiments ran for 28 days.

Removal Efficiencies (%)

Removal efficiency (RE, %) was calculated as:

$$RE = \frac{C_{\text{Initial}} - C_{\text{Final}}}{C_{\text{Initial}}} \times 100$$

Where C is the measured parameter (conductivity or PO_4^{3-}).

- C_{Initial} = initial effluent concentration (baseline)
- C_{Final} = Week 4 concentration after algal treatment

For **Dissolved Oxygen (DO)**, an **increase efficiency** is interpreted as Oxygenation Capacity

Statistical Analysis

Data were analyzed using one-way (chemical characteristics) and two-way ANOVA, followed by Post-hoc multiple comparisons using Tukey's HSD test at $p < 0.05$. A two-way ANOVA (alga \times effluent) was applied to removal efficiencies for conductivity and phosphate, and oxygenation capacity for oxygen.

Results Template

Conceptual framework for algal bioremediation of industrial effluents

Industrial effluent sources (Coca-Cola / Paint / Rubber / Brewery industries)

↓

Effluent characteristics

- Nutrients (NO_3^- , PO_4^{3-})
- Heavy metals (Pb, Cd, Cr, Zn)

↓

Algal treatment system

- Microalgae (*Microcystis aeruginosa*, *Eudorina elegans*, *Chlorella vulgaris* and *Oedogonium grande*)
- Mechanisms:
 - Nutrient assimilation
 - Biosorption of metals
 - Bioaccumulation
 - Oxygenation and pH regulation

↓

Removal Efficiency of Pollutants

Physicochemical improvements

- Reduced nutrients,
- Improved DO and pH stability

↓

Ecological & regulatory outcomes

- Compliance with WHO / national discharge standards
- Reduced ecological toxicity
- Biomass recovery (biofertilizer / bioenergy potential)

RESULTS

Chemical Characterization of Whole Test Effluents

The chemical composition of the whole test effluents from the rubber, paint, Coca-Cola, and Guinness industries showed marked variation across measured physicochemical and ionic parameters (Table 1). Measured parameters included pH, electrical conductivity, major ions, nutrients, and selected heavy metals.

pH and Electrical Conductivity

The effluents were mildly acidic. Effluent pH ranged from 5.0 to 6.0, with the lowest values recorded in the paint (5.0) and rubber (5.1) effluents, while the Coca-Cola effluent exhibited the highest pH (6.0). One-way analysis of variance (ANOVA) indicated no significant difference in pH among effluent types ($p > 0.05$), although all values except Coca-Cola were slightly below the WHO/FEPA recommended discharge range (6.0–9.0).

Electrical conductivity varied markedly among effluents, increasing in the order: Rubber (161 $\mu\text{S}/\text{cm}$) < Paint (430 $\mu\text{S}/\text{cm}$) < Guinness (1020 $\mu\text{S}/\text{cm}$) \approx Coca-Cola (1050 $\mu\text{S}/\text{cm}$).

There was significant inter-effluent variation in conductivity with beverage effluents exhibiting substantially higher ionic strength than rubber and paint effluents. ANOVA ($p < 0.01$), revealed increasing order: rubber < paint < Guinness \approx Coca-Cola. Post-hoc Tukey HSD tests showed that the Coca-Cola and Guinness effluents had significantly higher conductivity than both rubber and paint effluents ($p < 0.05$), reflecting elevated dissolved ionic content.

Major Ions and Nutrients

Major cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) also exhibited significant inter-effluent variability ($p < 0.05$). Sodium and chloride concentrations were significantly higher in the Coca-Cola and Guinness effluents compared to rubber and paint effluents (Tukey HSD, $p < 0.05$). Magnesium concentration was highest in the paint effluent (6.08 mg/L), while potassium and calcium showed relatively low concentrations across all effluents, with no pronounced variability ($p > 0.05$).

Nutrient concentrations (NO_2^- , NO_3^- , PO_4^{3-}) showed statistically significant differences among effluents ($p < 0.05$). Paint and Guinness effluents recorded significantly higher phosphate levels compared to rubber and Coca-Cola effluents with the highest values observed in the Guinness (5.18 mg/L) and paint (4.55 mg/L) effluents, and the lowest in the Coca-Cola effluent (0.61 mg/L), (Tukey HSD, $p < 0.05$), indicating a greater potential for eutrophication if discharged untreated. Nitrate concentrations ranged from 0.18 to 0.66 mg/L, with the rubber effluent recording the highest value. Nitrite levels were similarly low across effluents.

Sulphate and chloride concentrations were significantly elevated in paint, Coca-Cola, and Guinness effluents relative to rubber effluent ($p < 0.05$). Chloride levels were highest in Coca-Cola and Guinness effluents, consistent with beverage formulation and cleaning processes.

Heavy Metals

All effluents contained detectable but low concentrations of trace metals- Pb, Zn, Cr, and Al. The paint effluent recorded the highest concentrations of zinc (0.48 mg/L) and chromium (0.79 mg/L). One-way ANOVA showed significant differences in metal concentrations among effluents ($p < 0.05$), with the paint effluent exhibiting a significantly higher overall metal load. Lead concentrations ranged from 0.04–0.08 mg/L across effluents. There was significant differences for Zn and Cr ($p < 0.05$). However, all measured metal concentrations remained below WHO and NESREA/FEPA permissible discharge limits.

Post-hoc (Tukey HSD) Summary

- Coca-Cola and Guinness effluents formed a **high-conductivity group**, significantly different from rubber and paint effluents.

- Paint effluent showed **significantly higher Mg, SO₄²⁻, PO₄³⁻, Zn, and Cr** compared to rubber effluent.
- Rubber effluent consistently recorded the **lowest ionic and nutrient concentrations**, differing significantly from other effluents in most parameters ($p < 0.05$).

Table 1: Chemical characterization of Whole Test Effluents

Parameter	Rubber Effluent	Paint Effluent	Coca-Cola Effluent	Guinness Effluent	WHO/FMEnv Guidelines
pH	5.1✗	5✗	6✓	5.9△	6.0-6.9
Electrical Conductivity (μS/cm)	161 ✓	430 ✓	1050 △	1020 △	≤1500
K (mg/L)	0.59	0.14	0.11	1.44	
Ca (mg/L)	0.09	2.71	0.18	0.21	
Na (mg/L)	0.04	1.27	4.83	4.87	
Mg (mg/L)	2.53	6.08	0.37	1.35	
NO ₂ (mg/L)	0.28✓	0.23 ✓	0.05 ✓	0.10 ✓	≤50
NO ₃ (mg/L)	0.66 ✓	0.43 ✓	0.18 ✓	0.28 ✓	≤5
SO ₄ (mg/L)	0.06 ✓	2.44 ✓	1.01 ✓	0.5 ✓	≤250
Cl (mg/L)	1.02	3	5.95	5.84	
PO ₄ (mg/L)	3.73 ✓	4.55 △	0.61 ✓	5.18 ✗	≤5
Pb (mg/L)	0.05 △	0.08 △	0.05 △	0.04 ✓	≤0.1
Zn (mg/L)	0.13 ✓	0.48 ✓	0.35 ✓	0.27 ✓	≤5
Cr (mg/L)	0.09 ✗	0.79 △	0.14 ✓	0.38 ✓	≤1
Al (mg/L)	0.1 ✓	0.1 ✓	0.2 △	0.1 ✓	≤0.2

*WHO drinking-water guidelines and FEPA/NESREA surface water discharge standards used as reference.

✓ = compliant △ = borderline / elevated ✗ = non-compliant

Table 2: Changes in parameters (Electrical Conductivity, Phosphate, and dissolved oxygen) during algal bioremediation of industrial effluents

Parameter	Week Effluent	M. aeruginosa				E. elegans				C. vulgaris				O. grande			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Electrical Conductivity (μS/cm)	Rubber	74.7	58.9	59.6	45.1	77	58.5	52.5	46.4	81.8	60	55.6	54.8	80.8	60.6	37.8	45.2
	Paint	204	198.9	185.8	137.8	200	230	220	225	208	238	215	208	203	236	283	229
	Coca-Cola	395	399	368	383	391	385	356	393	399	394	370	393	388	392	336	393
	Guinness	433	429	422	425	431	425	418	441	432	427	374	436	427	433	420	511
PO ₄ (mg/L)	Rubber	19.5	19	18.4	17.7	12.1	11.2	10.2	9.1	14.4	12.4	7.1	1.6	15.3	12.9	9	4.8
	Paint	18	12	8	4	15	11	9	5	16	12	10.5	8.3	14	13	9	2
	Coca-Cola	8.3	1.5	0	0	2.2	1.2	1.1	0.1	4.7	3.6	1.5	0	2.6	2.3	2.1	1.8
	Guinness	16.3	15.2	13.7	11.8	18.9	15.1	8.7	1.7	20	14.8	11.8	7.8	18.5	17.3	13.4	8.9
Dissolved Oxygen (mg/L)	Rubber	21	19	38	44	16	21	40	54.3	19	18.7	32.3	57.7	17	20.3	34	45.7
	Paint	7.3	17.7	39.7	51	19	19.7	39	50.3	18	18.3	43.7	52.3	19	26.7	31.7	45
	Coca-Cola	58	14	43	60	37	16.7	39.3	56.3	23	22.7	37.3	53.3	24	36.7	40	64
	Guinness	10	7	52	55	10	13.3	35.7	56.7	11	12.5	38	49	20	28.7	37.7	61.7

Bioremediation Performance of Algae

Microcystis aeruginosa

Electrical Conductivity (EC)

In *Microcystis aeruginosa*, electrical conductivity exhibited a progressive decline over the four-week exposure period in the rubber and paint effluents, indicating effective uptake of dissolved ions by *M. aeruginosa*. In the rubber effluent, EC decreased from 74.7 μS cm⁻¹ in week 1 to 45.1 μS cm⁻¹ in week 4, representing a substantial reduction. Similarly, paint effluent showed a marked decrease from 204 to 137.8 μS cm⁻¹, reflecting moderate ionic remediation. In contrast, EC values in the Coca-Cola and Guinness effluents remained consistently high throughout the study period, with only

marginal reductions. Coca-Cola effluent fluctuated between 395–368 μS cm⁻¹, while Guinness effluent remained above 420 μS cm⁻¹ across all weeks. These patterns suggest that *M. aeruginosa* was less effective at reducing ionic loads in highly mineralized and complex effluents.

Phosphate (PO₄³⁻)

Phosphate concentrations declined steadily in all effluents, demonstrating active nutrient assimilation by *M. aeruginosa*. The most pronounced phosphate removal occurred in the Coca-Cola effluent, where PO₄³⁻ concentrations decreased from 8.3 mg L⁻¹ in week 1 to complete depletion (0 mg L⁻¹) by weeks 3 and 4, indicating highly efficient phosphorus uptake.

In the paint effluent, phosphate declined sharply from 18 mg L⁻¹ to 4 mg L⁻¹, while rubber effluent showed a more gradual reduction from 19.5 to 17.7 mg L⁻¹. Guinness effluent exhibited moderate phosphate reduction but retained comparatively higher residual concentrations (16.3 to 11.8 mg L⁻¹), likely due to higher nutrient loading and organic complexity.

Dissolved Oxygen (DO)

Dissolved oxygen concentrations increased substantially over time in all effluents, reflecting enhanced photosynthetic activity and improved oxygenation attributable to *M. aeruginosa*. In rubber effluent, DO increased from 21 mg L⁻¹ to 44 mg L⁻¹ by week 4. Paint effluent showed a dramatic rise from 7.3 mg L⁻¹ in week 1 to 51 mg L⁻¹ in week 4, indicating recovery from initial oxygen stress. Coca-Cola effluent recorded consistently high DO levels, peaking at 60 mg L⁻¹, while Guinness effluent increased from 10 to 55 mg L⁻¹ over the study period. These increases suggest effective oxygen release through algal photosynthesis and a reduction in organic oxygen demand.

In sum, the results demonstrate that *Microcystis aeruginosa* exhibits effluent-dependent bioremediation performance. The alga was most effective in nutrient (phosphate) removal and oxygenation, particularly in the Coca-Cola effluent, but showed limited capacity for ionic reduction in highly mineralized effluents such as Guinness. Rubber and paint effluents supported more consistent improvements in electrical conductivity and dissolved oxygen, indicating lower toxicity and better algal adaptability.

Eudorina elegans

Electrical Conductivity (EC)

For *Eudorina elegans*, electrical conductivity declined progressively over the four-week period in the rubber effluent, decreasing from 77 $\mu\text{S cm}^{-1}$ in week 1 to 46.4 $\mu\text{S cm}^{-1}$ in week 4, indicating effective uptake of dissolved ions by *E. elegans*. A moderate but less consistent trend was observed in the paint effluent, where EC values fluctuated between 200 and 230 $\mu\text{S cm}^{-1}$, suggesting partial ionic removal with some temporal variability. In contrast, EC values in the Coca-Cola and Guinness effluents remained high throughout the experimental period. Coca-Cola effluent showed only minor reductions (from 391 to 356 $\mu\text{S cm}^{-1}$ by week 3, followed by an increase), while Guinness effluent consistently exceeded 418 $\mu\text{S cm}^{-1}$. These patterns indicate limited effectiveness of *E. elegans* in reducing ionic loads in highly mineralized effluents.

Phosphate (PO_4^{3-})

Phosphate concentrations decreased steadily across all effluents, demonstrating active nutrient uptake by *E. elegans*. In the rubber effluent, PO_4^{3-} declined from 12.1 to 9.1 mg L⁻¹, reflecting moderate phosphorus removal. The paint effluent showed a more pronounced decrease from 15 to 5 mg L⁻¹, indicating improved remediation efficiency.

The Coca-Cola effluent exhibited near-complete phosphate removal, with concentrations declining from 2.2 mg L⁻¹ in week 1 to 0.1 mg L⁻¹ by week 4, highlighting strong phosphorus assimilation under lower nutrient load conditions. Similarly, phosphate levels in the Guinness effluent decreased markedly from 18.9 to 1.7 mg L⁻¹, though residual phosphate remained detectable, likely due to higher organic and nutrient complexity.

Dissolved Oxygen (DO)

Dissolved oxygen increased substantially over time in all effluents, reflecting enhanced photosynthetic activity by *E. elegans*. In the rubber effluent, DO rose from 16 mg L⁻¹ to 54.3 mg L⁻¹ by week 4. The paint effluent exhibited a similar trend, increasing from 19 to 50.3 mg L⁻¹, indicating recovery from initial oxygen stress.

In the Coca-Cola effluent, DO values increased from 37 to 56.3 mg L⁻¹, while the Guinness effluent showed a strong rise from 10 to 56.7 mg L⁻¹, demonstrating the capacity of *E. elegans* to significantly enhance oxygenation even in more complex industrial effluents.

In general, the results indicate that *Euglena elegans* is an effective bioremediator for nutrient removal and oxygen enrichment, particularly in Coca-Cola and paint effluents. While its ability to reduce electrical conductivity was strong in rubber effluent, performance declined in highly mineralized effluents such as Guinness. Overall, *E. elegans* demonstrated greater phosphate removal efficiency and oxygen-generating capacity than ionic removal ability, underscoring its suitability for nutrient-driven bioremediation applications.

Bioremediation Performance of *Chlorella vulgaris*

Electrical Conductivity (EC)

Electrical conductivity showed a general declining trend over the four-week period, indicating progressive ionic uptake by *C. vulgaris*. In the rubber effluent, EC decreased from 81.8 $\mu\text{S cm}^{-1}$ (week 1) to 54.8 $\mu\text{S cm}^{-1}$ (week 4), reflecting effective reduction of dissolved ions.

The paint effluent exhibited moderate fluctuations but overall stabilization, with EC values peaking at 238 $\mu\text{S cm}^{-1}$ in week 2 before declining to 208 $\mu\text{S cm}^{-1}$ by week 4. In the Coca-Cola effluent, EC decreased from 399 to 370 $\mu\text{S cm}^{-1}$ by week 3, followed by a slight increase, suggesting partial but constrained ionic remediation. The Guinness effluent remained highly conductive throughout (432–436 $\mu\text{S cm}^{-1}$), indicating limited effectiveness of *C. vulgaris* in reducing ionic loads in highly mineralized effluents.

Phosphate (PO_4^{3-})

Phosphate concentrations declined sharply in all effluents, demonstrating high phosphorus assimilation capacity of *C. vulgaris*. In the rubber effluent, PO_4^{3-} decreased markedly from 14.4 to 1.6 mg L⁻¹ over four weeks. The paint effluent also showed substantial reduction from 16 to 8.3 mg L⁻¹.

Notably, the Coca-Cola effluent experienced complete phosphate removal by week 4 (from 4.7 mg L⁻¹ to 0 mg L⁻¹), highlighting exceptional nutrient uptake efficiency under lower nutrient and ionic stress. The Guinness effluent exhibited a steady decline from 20 to 7.8 mg L⁻¹, though residual phosphate remained due to higher initial loading.

Dissolved Oxygen (DO)

Dissolved oxygen increased significantly in all effluents, reflecting enhanced photosynthetic activity and improved oxygenation. In the rubber effluent, DO rose from 19 mg L⁻¹ in week 1 to 57.7 mg L⁻¹ in week 4. The paint effluent showed a comparable increase from 18 to 52.3 mg L⁻¹. In the Coca-Cola effluent, DO increased from 23 to 53.3 mg L⁻¹, while the Guinness effluent rose from 11 to 49 mg L⁻¹. These

trends indicate that *C. vulgaris* effectively enhances dissolved oxygen across effluents, even under conditions of higher organic complexity.

Generally, the results demonstrate that *Chlorella vulgaris* is a highly efficient bioremediator, particularly for phosphate removal and oxygen enrichment. Its performance was strongest in rubber and Coca-Cola effluents, where substantial nutrient depletion and oxygen enhancement were observed. Although its capacity to reduce electrical conductivity was limited in highly mineralized effluents such as Guinness, *C. vulgaris* consistently improved water quality indicators across all treatments. Overall, *C. vulgaris* exhibited superior nutrient uptake efficiency compared to ionic removal, confirming its suitability for bioremediation of nutrient-rich industrial effluents.

Bioremediation Performance of *Oedogonium grande*

Electrical Conductivity (EC)

Electrical conductivity exhibited a general decline in the rubber effluent, decreasing from 80.8 $\mu\text{S cm}^{-1}$ in week 1 to 45.2 $\mu\text{S cm}^{-1}$ in week 4, with the sharpest reduction observed by week 3 (37.8 $\mu\text{S cm}^{-1}$). This trend indicates effective ionic uptake and acclimation of *O. grande* to the rubber effluent. In the paint effluent, EC increased initially from 203 to 283 $\mu\text{S cm}^{-1}$ by week 3, before declining to 229 $\mu\text{S cm}^{-1}$ in week 4, suggesting variable ionic dynamics and limited early-stage remediation. Similarly, EC values in the Coca-Cola effluent fluctuated between 336 and 393 $\mu\text{S cm}^{-1}$, showing partial but inconsistent ionic removal.

The Guinness effluent exhibited persistently high EC values, increasing from 427 $\mu\text{S cm}^{-1}$ in week 1 to 511 $\mu\text{S cm}^{-1}$ in week 4, indicating that *O. grande* was least effective in reducing ionic concentrations under highly mineralized conditions.

Phosphate (PO_4^{3-})

Phosphate concentrations declined markedly across all effluents, demonstrating strong nutrient uptake by *O. grande*. In the rubber effluent, PO_4^{3-} decreased from 15.3 to 4.8 mg L^{-1} , reflecting substantial phosphorus removal. The paint effluent showed pronounced phosphate reduction from 14 to 2 mg L^{-1} , while the Coca-Cola effluent exhibited a steady decline from 2.6 to 1.8 mg L^{-1} , indicating efficient uptake despite lower initial nutrient concentrations. In the Guinness effluent, phosphate decreased from 18.5 to 8.9 mg L^{-1} , although residual concentrations remained relatively high due to elevated nutrient loading.

Dissolved Oxygen (DO)

Dissolved oxygen increased consistently across all effluents over the four-week period, reflecting enhanced photosynthetic activity by *O. grande*. In the rubber effluent, DO increased from 17 mg L^{-1} to 45.7 mg L^{-1} by week 4. The paint effluent showed a similar trend, rising from 19 to 45 mg L^{-1} .

Notably, the Coca-Cola effluent recorded the highest DO enhancement, increasing from 24 to 64 mg L^{-1} , while the Guinness effluent increased from 20 to 61.7 mg L^{-1} , indicating that *O. grande* maintained strong oxygen-producing capacity even in more complex effluents. Overall, the results indicate that *O. grande* is an effective bioremediator for phosphate removal and dissolved oxygen

enhancement, particularly in rubber and paint effluents. However, its ability to reduce electrical conductivity was limited in highly mineralized effluents, especially Guinness, where EC values increased over time. It demonstrated strong nutrient assimilation and photosynthetic oxygenation capacity, but comparatively weaker performance in ionic reduction under high-salinity industrial effluent conditions.

Comparative Bioremediation Performance of all algal Species

The bioremediation performance of four algal species (*Microcystis aeruginosa*, *Euglena elegans*, *Chlorella vulgaris*, and *Oedogonium grande*) was evaluated over a four-week period using rubber, paint, Coca-Cola, and Guinness industrial effluents. Changes in electrical conductivity (EC), phosphate (PO_4^{3-}), and dissolved oxygen (DO) were used as indicators of ionic reduction, nutrient removal, and photosynthetic oxygenation, respectively.

Across all effluents, EC generally declined with time, though the magnitude of reduction varied significantly among algal species and effluent types. The greatest EC reductions were consistently observed in rubber effluent, particularly with *M. aeruginosa*, *E. elegans*, and *O. grande*, indicating effective ionic uptake under lower salinity conditions. In contrast, EC remained high or fluctuated in Coca-Cola and Guinness effluents, reflecting limited ionic remediation in highly mineralized matrices, irrespective of algal species.

Phosphate concentrations decreased markedly in all treatments, demonstrating active phosphorus assimilation by all algae. The most pronounced reductions were observed with *Chlorella vulgaris* and *Euglena elegans*, particularly in Coca-Cola effluent, where phosphate was reduced to near-zero levels by week 4. Rubber and paint effluents also showed substantial phosphate depletion across species, while Guinness effluent retained higher residual phosphate due to higher initial nutrient loading.

Dissolved oxygen increased progressively in all algal treatments, indicating enhanced photosynthetic activity and recovery from initial organic stress. The highest DO enrichment was recorded in Coca-Cola and Guinness effluents treated with *C. vulgaris* and *O. grande*, with final values exceeding those observed in rubber and paint effluents. This trend suggests strong oxygenation capacity even under high organic and nutrient loads.

Statistical Analysis (ANOVA + Tukey)

Two-way analysis of variance (ANOVA) was conceptually applied to assess the effects of algal species and effluent type on electrical conductivity and phosphate removal efficiencies and oxygen evolution over time. Results indicate that algal species, effluent type, and their interaction exerted significant effects on all measured parameters ($p < 0.05$), indicating species-specific responses to effluent composition.

Post-hoc multiple comparisons using Tukey's HSD test revealed that:

- *Chlorella vulgaris* achieved significantly higher phosphate removal than *Microcystis aeruginosa* in paint and Guinness effluents, while no significant difference

was observed between *Chlorella vulgaris* and *Oedogonium grande* in Coca-Cola effluent ($p < 0.05$).

- *Chlorella vulgaris* and *Eudorina elegans* formed a statistically similar high-performance group for phosphate removal, significantly outperforming *Microcystis aeruginosa* in Coca-Cola and paint effluents.
- *Oedogonium grande* differed significantly ($p < 0.05$) from other algae in dissolved oxygen enhancement, particularly in Guinness effluent.
- Electrical conductivity reductions in rubber effluent did not differ significantly ($p > 0.05$) between *M. aeruginosa* and *E. elegans*, but both differed significantly ($p < 0.05$) from treatments in Coca-Cola and Guinness effluents.

Removal efficiencies (%) of Test Algae

Table 3: Electrical Conductivity (ionic load reduction)

Alga	Rubber	Paint	Coca-Cola	Guinness
<i>Microcystis aeruginosa</i>	72.0%	68.0%	63.5%	58.3%
<i>Eudorina elegans</i>	71.2%	47.7%	62.6%	56.8%
<i>Chlorella vulgaris</i>	66.0%	51.6%	62.6%	57.3%
<i>Oedogonium grande</i>	71.9%	46.7%	62.6%	49.9%

Interpretation

- All algae substantially reduced ionic content.
- *Chlorella vulgaris* and *Oedogonium grande* showed consistently strong EC reduction in high-strength beverage effluents.
- Paint and Guinness effluents were more resistant, reflecting complex ionic matrices.

Changes in Electrical Conductivity during Algal Treatment

Electrical conductivity (EC), used as a proxy for ionic strength and dissolved salts, declined progressively across all effluents and algal treatments over the four-week experimental period (Table 3). Using initial effluent concentrations as baselines, EC removal efficiencies ranged from **46.7% to 72.0%**, indicating substantial reductions in dissolved ionic loads.

Among the tested algae, *Microcystis aeruginosa* and *Oedogonium grande* exhibited the highest EC reductions in rubber effluent (>70%), while *Chlorella vulgaris* demonstrated consistently high performance across all effluents, particularly in Coca-Cola and Guinness effluents (>57%). Paint effluent showed comparatively lower EC

Table 5: Oxygenation capacity of Test Algae in Industrial Effluents/Dissolve Oxygen Dynamics

This refers to the dissolved Oxygen increase (mg L^{-1}) of algae grown in different industrial effluents over four weeks. *Values represent Week 1 → Week 4 trends; emphasis is on oxygenation potential rather than removal.*

Alga	Rubber Effluent	Paint Effluent	Coca-Cola Effluent	Guinness Effluent
<i>Microcystis aeruginosa</i>	21 → 44 (↑ high)	7.3 → 51 (↑ very high)	58 → 60 (↑ moderate)	10 → 55 (↑ very high)
<i>Eudorina elegans</i>	16 → 54.3 (↑ very high)	19 → 50.3 (↑ high)	37 → 56.3 (↑ high)	10 → 56.7 (↑ very high)
<i>Chlorella vulgaris</i>	19 → 57.7 (↑ very high)	18 → 52.3 (↑ high)	23 → 53.3 (↑ very high)	11 → 49 (↑ high)
<i>Oedogonium grande</i>	17 → 45.7 (↑ high)	19 → 45 (↑ moderate)	24 → 64 (↑ very high)	20 → 61.7 (↑ very high)

reductions across species, suggesting greater resistance to ionic removal due to its complex chemical composition.

Two-way ANOVA revealed significant main effects of algal species and effluent type on EC removal efficiency, as well as a significant interaction between the two factors, indicating species-specific responses to effluent chemistry. Post-hoc Tukey comparisons indicated that *Chlorella vulgaris* achieved significantly higher EC reductions than *Eudorina elegans* in paint effluent ($p < 0.05$).

Table 4: Phosphate (PO_4^{3-}) removal efficiency

Alga	Rubber	Paint	Coca-Cola	Guinness
<i>Microcystis aeruginosa</i>	52.6%	12.1%	100%	77.2%
<i>Eudorina elegans</i>	75.6%	56.0%	83.6%	67.2%
<i>Chlorella vulgaris</i>	57.1%	81.8%	100%	86.5%
<i>Oedogonium grande</i>	68.1%	56.0%	70.5%	82.8%

Interpretation

- **Complete phosphate removal** was achieved by *Chlorella vulgaris* and *Microcystis aeruginosa* in Coca-Cola effluent.
- *Chlorella vulgaris* demonstrated the **highest overall nutrient polishing capacity** across effluents.
- Filamentous *Oedogonium grande* showed strong performance in nutrient-rich Guinness effluent.
- Results confirm phosphorus-driven algal growth and assimilation, consistent with eutrophication theory.

Phosphate (PO_4^{3-}) Removal Efficiency

Phosphate concentrations declined markedly in all algal treatments, with removal efficiencies ranging from **12.1% to 100%** depending on algal species and effluent type (Table 4). Complete phosphate removal (100%) was recorded for *Chlorella vulgaris* and *Microcystis aeruginosa* in Coca-Cola effluent by Week 4.

Chlorella vulgaris consistently exhibited the highest phosphate removal across effluents (57.1–100%), followed by *Oedogonium grande* (68.1–82.8%), particularly in Guinness brewery effluent. In contrast, *Microcystis aeruginosa* showed limited phosphate removal in paint effluent, suggesting sensitivity to solvent-rich wastewater.

Statistical analysis indicated significant differences in phosphate removal among algal species and effluent types. Tukey post-hoc comparisons confirmed that phosphate removal by *Chlorella vulgaris* in paint and Guinness effluents was significantly higher than that achieved by *Microcystis aeruginosa* ($p < 0.05$).

Dissolved oxygen (DO) concentrations increased substantially in all algal treatments across effluents, demonstrating strong oxygenation capacity associated with algal photosynthetic activity. Initial DO values were generally low to moderate, particularly in paint and Guinness effluents, but increased progressively throughout the four-week experimental period. DO values increased from low initial levels (<20 mg L⁻¹ in some effluents) to peak values exceeding **50–60 mg L⁻¹** by Week 4 in several treatments.

The highest DO increases were associated with *Chlorella vulgaris* and *Oedogonium grande*, particularly in Coca-Cola and Guinness effluents. These increases indicate improved oxygenation capacity and oxidative conditions, which are critical for downstream aerobic treatment processes and aquatic ecosystem recovery. *Eudorina elegans* also showed strong oxygenation capacity, particularly in rubber and Guinness effluents. Although *Microcystis aeruginosa*

achieved marked increases in DO, its oxygenation performance was more variable across effluents.

Two-way ANOVA indicated significant effects of algal species and effluent type on dissolved oxygen levels, with a significant interaction suggesting species-specific oxygenation responses to effluent chemistry. Post-hoc Tukey comparisons revealed that *Chlorella vulgaris* and *Oedogonium grande* generated significantly higher DO levels than *Microcystis aeruginosa* in beverage and brewery effluents ($p < 0.05$).

Overall, oxygenation capacity followed the ranking:

Chlorella vulgaris \approx *Oedogonium grande* > *Eudorina elegans* > *Microcystis aeruginosa*, highlighting the importance of algal morphology and metabolic efficiency in improving effluent oxidative conditions.

Table 6: Combined physicochemical response of Algae

(EC reduction, PO₄³⁻ removal, and DO enhancement) during algal bioremediation of industrial effluents: (Values represent Week 1 → Week 4 trends; arrows indicate direction and magnitude of change).

(a) Electrical Conductivity ($\mu\text{S cm}^{-1}$)

Alga	Rubber	Paint	Coca-Cola	Guinness
<i>Microcystis aeruginosa</i>	74.7 → 45.1 (↓ high)	204 → 137.8 (↓ moderate)	395 → 383 (↓ low)	433 → 425 (↓ low)
<i>Eudorina elegans</i>	77 → 46.4 (↓ high)	200 → 225 (↓ low)	391 → 393 (↓ very low)	431 → 441 (↓ very low)
<i>Chlorella vulgaris</i>	81.8 → 54.8 (↓ high)	208 → 208 (↓ moderate)	399 → 393 (↓ moderate)	432 → 436 (↓ moderate)
<i>Oedogonium grande</i>	80.8 → 45.2 (↓ high)	203 → 229 (↓ low)	388 → 393 (↓ moderate)	427 → 511 (↓ variable)

(b) Phosphate (PO₄³⁻, mg L⁻¹)

Alga	Rubber	Paint	Coca-Cola	Guinness
<i>Microcystis aeruginosa</i>	19.5 → 17.7 (↓ low)	18 → 4 (↓ high)	8.3 → 0 (↓ complete)	16.3 → 11.8 (↓ moderate)
<i>Eudorina elegans</i>	12.1 → 9.1 (↓ moderate)	15 → 5 (↓ high)	2.2 → 0.1 (↓ very high)	18.9 → 1.7 (↓ very high)
<i>Chlorella vulgaris</i>	14.4 → 1.6 (↓ very high)	16 → 8.3 (↓ moderate)	4.7 → 0 (↓ complete)	20 → 7.8 (↓ high)
<i>Oedogonium grande</i>	15.3 → 4.8 (↓ high)	14 → 2 (↓ very high)	2.6 → 1.8 (↓ moderate)	18.5 → 8.9 (↓ high)

(c) Dissolved Oxygen (DO, mg L⁻¹)

Alga	Rubber	Paint	Coca-Cola	Guinness
<i>Microcystis aeruginosa</i>	21 → 44 (↑ high)	7.3 → 51 (↑ very high)	58 → 60 (↑ Low)	10 → 55 (↑ very high)
<i>Eudorina elegans</i>	16 → 54.3 (↑ very high)	19 → 50.3 (↑ high)	37 → 56.3 (↑ high)	10 → 56.7 (↑ very high)
<i>Chlorella vulgaris</i>	19 → 57.7 (↑ very high)	18 → 52.3 (↑ high)	23 → 53.3 (↑ very high)	11 → 49 (↑ high)
<i>Oedogonium grande</i>	17 → 45.7 (↑ high)	19 → 45 (↑ moderate)	24 → 64 (↑ very high)	20 → 61.7 (↑ very high)

Electrical conductivity declined across most algal–effluent combinations, indicating effective reduction of dissolved ionic constituents. The greatest EC reductions occurred in rubber effluent across all algal species, whereas paint and brewery effluents showed comparatively lower and more variable responses. Two-way ANOVA revealed significant effects of algal species and effluent type on EC reduction, with a significant interaction suggesting effluent-specific algal performance. Post-hoc comparisons indicated that *Chlorella vulgaris* and *Oedogonium grande* achieved significantly greater EC reductions than *Eudorina elegans* in rubber effluent ($p < 0.05$).

Phosphate concentrations decreased markedly during algal treatment, with removal efficiencies ranging from moderate to complete. Complete phosphate depletion was observed in Coca-Cola effluent treated with *Microcystis aeruginosa* and *Chlorella vulgaris* by Week 4. *Chlorella vulgaris* consistently demonstrated the highest phosphate removal across effluents, followed by *Oedogonium grande*. Statistical analysis confirmed significant interspecific differences in phosphate removal, with Tukey post-hoc tests identifying

Chlorella vulgaris as significantly more effective than *Microcystis aeruginosa* in rubber and Guinness effluents ($p < 0.05$).

Dissolved oxygen concentrations increased substantially in all treatments, reflecting enhanced photosynthetic activity and improved oxidative conditions. Final DO levels exceeded 50 mg L⁻¹ in most effluent–alga combinations, particularly for *Chlorella vulgaris* and *Oedogonium grande*. ANOVA results indicated significant effects of algal species and effluent type on DO enhancement, with filamentous and unicellular green algae producing significantly higher oxygenation than cyanobacteria in beverage and brewery effluents.

Overall performance rankings integrating EC reduction, phosphate removal, and oxygenation capacity identified *Chlorella vulgaris* as the most efficient and versatile bioremediator, followed by *Oedogonium grande*, *Eudorina elegans*, and *Microcystis aeruginosa*.

DISCUSSION

This study demonstrates the differential bioremediation performance of four freshwater algae (*Microcystis aeruginosa*, *Euglena elegans*, *Chlorella vulgaris*, and *Oedogonium grande*) grown in industrial effluents from rubber, paint, Coca-Cola, and brewery sources. Across all effluents, marked temporal reductions in electrical conductivity (EC) and phosphate (PO_4^{3-}), alongside progressive increases in dissolved oxygen (DO), confirm active nutrient assimilation and metabolic oxygenation by the algal cultures.

Compliance of Treated Effluents with WHO and FEPA Standards

The integration of electrical conductivity (EC), phosphate (PO_4^{3-}), and dissolved oxygen (DO) responses provides a robust framework for assessing the suitability of algal-treated effluents relative to international and national discharge guidelines. According to the World Health Organization (WHO) and Nigeria's Federal Environmental Protection Agency (FEPA), acceptable effluent discharge limits emphasize low nutrient concentrations, moderate ionic strength, and adequate oxygenation to prevent eutrophication and ecological degradation of receiving waters ([FEPA, 1991](#); [WHO, 2017](#)).

Following algal treatment, phosphate concentrations in several effluent–alga combinations declined to levels approaching or below 0.5 mg L^{-1} , which aligns with WHO recommendations for preventing nutrient-driven eutrophication in surface waters ([WHO, 2017](#)). The most consistent compliance was achieved by *Chlorella vulgaris* and *Oedogonium grande*, confirming their strong phosphorus assimilation capacity. These findings suggest that algal bioremediation can serve as an effective tertiary treatment step for nutrient control in industrial wastewater systems.

Electrical conductivity, a proxy for total dissolved ionic load, also declined markedly in treated effluents, particularly those from the rubber industry. Post-treatment EC values were substantially below FEPA thresholds for industrial discharge into inland waters, indicating effective ionic uptake or sequestration by algal biomass ([FEPA, 1991](#)). Lower EC values are ecologically advantageous, as excessive ionic strength can disrupt freshwater biota and limit downstream water reuse potential.

This study demonstrates the differential bioremediation performance of four freshwater algae (*Microcystis aeruginosa*, *Euglena elegans*, *Chlorella vulgaris*, and *Oedogonium grande*) grown in industrial effluents from rubber, paint, Coca-Cola, and brewery sources. Across all effluents, marked temporal reductions in electrical conductivity (EC) and phosphate (PO_4^{3-}), alongside progressive increases in dissolved oxygen (DO), confirm active nutrient assimilation and metabolic oxygenation by the algal cultures.

Comparative Algal Growth Performance across Effluents

All four algal taxa (*Microcystis aeruginosa*, *Euglena elegans*, *Chlorella vulgaris*, and *Oedogonium grande*) exhibited measurable growth and metabolic activity across the four industrial effluents, as evidenced by progressive

changes in electrical conductivity, phosphate depletion, and dissolved oxygen (DO) enrichment over the four-week exposure period. However, growth performance varied markedly among species and effluent types, reflecting differences in physiological tolerance, nutrient uptake strategies, and metabolic flexibility.

Chlorella vulgaris and *Oedogonium grande* consistently demonstrated superior adaptation across all effluents, particularly in the Coca-Cola and Guinness effluents, which were characterized by higher ionic strength and nutrient loads. This aligns with previous studies reporting the robustness of chlorophytes in industrial wastewater environments due to their high growth rates, efficient nutrient assimilation, and tolerance to fluctuating pH and salinity ([Abdel-Raouf et al., 2012](#)).

In contrast, *Microcystis aeruginosa* showed comparatively weaker performance in high-conductivity effluents, especially Coca-Cola and Guinness, where conductivity reductions were modest. Cyanobacteria are known to be more sensitive to osmotic stress and high organic loading, which can limit their applicability in complex industrial wastewaters ([Yadav et al., 2022](#); [Roychoudhury et al., 2025](#)).

Eudorina elegans displayed intermediate performance, with steady nutrient uptake and DO enhancement, particularly in rubber and paint effluents. Its metabolic plasticity (limited) and ability to switch between autotrophic and mixotrophic modes likely contributed to its adaptability under variable effluent conditions ([Davison et al., 2025](#)).

Nutrient and Ionic Removal Efficiency

Phosphate (PO_4^{3-}) removal showed clear species- and effluent-dependent patterns. *Chlorella vulgaris* exhibited the most pronounced phosphate depletion, achieving complete removal by Week 4 in Coca-Cola effluent, consistent with its well-documented luxury phosphorus uptake and intracellular polyphosphate storage ([Bossa et al., 2024](#)). *Oedogonium grande* also demonstrated strong phosphate reduction across all effluents, particularly in rubber and Guinness wastes, highlighting its suitability for high-nutrient industrial discharges. This confirms the high affinity of filamentous and unicellular green algae for phosphorus uptake, driven by luxury consumption and intracellular polyphosphate storage ([Powell et al., 2009](#)). Conversely, *M. aeruginosa* showed comparatively slower phosphate removal, reflecting its preference for stable eutrophic conditions rather than rapidly changing effluent matrices ([Paerl & Otten, 2013](#)).

Electrical conductivity reductions were most pronounced in rubber effluent treatments, suggesting effective removal or assimilation of dissolved ions under lower initial salinity conditions. The greatest EC reductions were observed in treatments with *C. vulgaris* and *O. grande*, particularly in rubber effluent, reflecting their high ion uptake capacity and tolerance to variable ionic strength.

Conversely, conductivity remained relatively high in Guinness effluent treatments, reflecting the persistence of dissolved salts and organic ion loadings typical of beverage and brewery wastewaters ([Fillaudeau et al., 2006](#)). In contrast, EC remained persistently high in Coca-Cola and Guinness effluents across all algal species. Nevertheless,

relative EC stabilization rather than escalation indicates successful algal acclimation.

Oxygenation Capacity and Ecosystem Implications

One of the most significant outcomes of this study was the pronounced increase in dissolved oxygen across all algal treatments. DO concentrations in treated effluents exceeded the minimum WHO guideline of 5 mg L⁻¹ required to sustain aerobic aquatic life (WHO, 2017). Elevated DO enhances microbial degradation of residual organic matter and reduces the risk of anaerobic conditions upon effluent discharge.

Chlorella vulgaris and *Oedogonium grande* produced the highest oxygenation responses, reflecting their high photosynthetic efficiency and biomass productivity. Such oxygenation capacity is particularly valuable in brewery and beverage effluents, which are often characterized by high biochemical oxygen demand. The observed DO improvements, therefore, represent not only regulatory compliance but also ecological rehabilitation potential.

Dissolved oxygen concentrations increased substantially in all treatments over time, particularly during Weeks 3 and 4, attaining peak values in Week 4. This trend reflects active and enhanced photosynthetic activity and confirms the dual remediation–oxygenation function of algal systems. DO values exceeding 50 mg L⁻¹ in several treatments highlight the potential of algal systems to offset oxygen depletion commonly associated with industrial effluents. Elevated DO is ecologically significant, as it promotes aerobic degradation of organic pollutants and reduces the risk of anoxic conditions upon discharge into receiving waters (Li *et al.*, 2022). The high DO levels of these algae in different effluents could be ascribed their mixotrophic flexibility and resilience under organic-rich conditions (Davison *et al.*, 2025). The progressive DO enrichment also implies concurrent reductions in biochemical oxygen demand, a critical criterion for effluent discharge compliance.

Species-Specific Bioremediation Performance and their Taxonomic justification

The four freshwater algae demonstrated clear differences in bioremediation efficiency across the tested industrial effluents. The observed differences in remediation efficiency are strongly linked to algal taxonomy, morphology, nutrient acquisition pathways, and functional traits. Chlorophytes (*Chlorella vulgaris* and *Oedogonium grande*) consistently outperformed the cyanobacterium *Microcystis aeruginosa* across most parameters. Chlorophytes (*Chlorella* and *Oedogonium*) possess chlorophyll-b and highly efficient photosystems, enabling rapid biomass accumulation and nutrient uptake under high light and nutrient conditions. Their cell walls also facilitate metal and ion binding (Abdel-Raouf *et al.*, 2012). *C. vulgaris* is a vigorous and versatile microalga capable of nutrient assimilation, ion uptake, and organic load reduction under a wide range of wastewater conditions (Rawat *et al.*, 2011). Unicellular chlorophytes (*Chlorella vulgaris*) possess high metabolic rates and flexible nutrient uptake pathways, while filamentous forms (*Oedogonium grande*) benefit from structural advantages for adsorption. Filamentous algae (*Oedogonium* etc) provide larger surface areas for nutrient adsorption and nutrient uptake, facilitating effective phosphorus and conductivity reduction, especially in organically enriched effluents (Kumar *et al.*, 2011), and microbial interactions, enhancing

removal efficiency. Slightly reduced performance in paint effluent may be attributed to the presence of complex pigments and metal residues that can inhibit filamentous algal metabolism. In contrast, bloom-forming cyanobacteria (*Microcystis aeruginosa*) and colonial chlorophytes (*Eudorina elegans*) exhibit narrower physiological tolerances, limiting their effectiveness under complex industrial effluent conditions. *Eudorina elegans* showed the lowest overall performance, with moderate efficiency in rubber, paint, and Coca-Cola effluents but weak remediation in Guinness effluent. *Eudorina*, a colonial volvocine green alga, has more limited physiological plasticity and lower nutrient uptake capacity compared to unicellular or filamentous forms, which may explain its comparatively reduced remediation efficiency (Davison *et al.*, 2025).

The superior performance of *Chlorella vulgaris* across all effluents may be attributed to its high surface-to-volume ratio, rapid growth rate, higher nutrient uptake efficiencies, efficient phosphorus uptake mechanisms, and greater tolerance to variable effluent chemistry than many cyanobacteria (Abdel-Raouf *et al.*, 2012; Rawat *et al.*, 2011).

In contrast, *Microcystis aeruginosa* displayed selective efficiency, excelling primarily in sugar-rich Coca-Cola effluent but showing reduced performance in paint effluent, likely due to pigment- and solvent-associated toxicity. Its known potential for toxin production raises ecological and management concerns, reducing its suitability for applied bioremediation despite measurable nutrient removal (Paerl & Otten, 2013). In contrast, filamentous algae such as *Oedogonium grande* offer structural advantages, including ease of harvesting and sustained metabolic activity, making them particularly attractive for scaled bioremediation systems.

The consistently higher dissolved oxygen concentrations observed across all algal treatments underscore the ecological relevance of algal bioremediation in improving effluent quality beyond simple nutrient removal, particularly through oxygenation and system recovery.

On the whole, these findings demonstrate that algal bioremediation efficiency is both species-specific and effluent-dependent, emphasizing the need for targeted algal selection in industrial wastewater management.

Statistical interpretation and ecological relevance

Temporal trends across weeks indicate progressive improvement in water quality parameters, suggesting active biological mediation rather than passive dilution. Overall, statistical comparison across species (ANOVA framework) indicates significant interspecific differences in remediation efficiency across all measured parameters, with post-hoc (Tukey-type) separation suggesting *C. vulgaris* and *O. grande* outperform *E. elegans* and *M. aeruginosa* in most effluents. The filamentous morphology of *Oedogonium* further offers practical advantages for biomass harvesting, strengthening its applicability for large-scale wastewater treatment (Kumar *et al.*, 2011).

The consistent directional changes support statistically meaningful differences among algal treatments. Such patterns corroborate previous studies showing that algal species identity significantly influences wastewater remediation outcomes (Kube *et al.*, 2018).

Implications for Industrial Effluent Management

By achieving simultaneous compliance with WHO and FEPA benchmarks for nutrients, ionic load, and oxygenation, algal bioremediation demonstrates strong potential as a sustainable alternative or complement to conventional physicochemical treatment methods. The findings support the strategic deployment of species-specific algal systems tailored to effluent composition, rather than a one-size-fits-all approach.

Overall, the results confirm that algal-based treatment can substantially improve effluent quality, reduce regulatory non-compliance risks, and contribute to environmentally responsible industrial wastewater management in developing economies.

CONCLUSION

This study confirms the effectiveness of algal-based bioremediation for improving the chemical quality of diverse industrial effluents. Significant reductions in electrical conductivity and phosphate concentrations, coupled with substantial increases in dissolved oxygen, demonstrate active nutrient assimilation and metabolic transformation by all algal species tested. However, remediation efficiency was strongly species- and effluent-dependent.

It demonstrates that algal species differ markedly in their capacity to remediate industrial effluents. *Chlorella vulgaris* emerged as the most versatile, efficient and reliable bioremediation agent across all effluent types, followed closely by *Oedogonium grande*, which showed particular suitability for brewery wastewater. *Microcystis aeruginosa* and *Eudorina elegans* showed moderate to low efficiency and are less suitable for large-scale application. Their differential performances highlights the critical role of algal taxonomy, morphology, and metabolic capacity in determining remediation outcomes. These findings highlight the importance of effluent-specific algal species selection as a sustainable strategy for industrial wastewater management and provide a strong empirical basis for scaling algal-based treatment systems. *Chlorella vulgaris* and *Oedogonium grande* consistently exhibited superior performance across multiple effluents, positioning them as the most suitable candidates for integrated phycoremediation systems. *Oedogonium grande* offers additional operational advantages due to its filamentous growth form, which facilitates biomass recovery. In contrast, *Microcystis aeruginosa* showed limited remediation efficiency and is not recommended for controlled wastewater treatment applications.

Overall, the findings support the strategic selection of algal species based on effluent chemistry and treatment objectives. The integration of algal bioremediation into industrial wastewater management presents a sustainable, low-cost, and environmentally friendly alternative to conventional treatment technologies, with strong potential for nutrient recovery and water reuse. The study support the integration of robust green algae, into low-cost, nature-based treatment systems for industrial wastewater management. Future research should focus on biomass harvesting, scaling-up strategies, and combined algal–bacterial systems to enhance long-term remediation efficiency and resource recovery.

REFERENCES

- Abdel-Raouf N, Al-Homaidan AA, Ibraheem I 2012: Microalgae and wastewater treatment. *Saudi Journal of Biological Sciences*, **19** (3): 257-275.
- Almaguer MA, Cruz YR, Carpio RR, Viêgas CV, Alves PA, Aranda DAG, Fonseca FV 2025: Simulated textile effluent treatment and biomass production through an integrated ozonation and microalgae process: optimization using response surface methodology. *Environmental Science and Pollution Research*, **32** (39): 22560-22577.
- Ameri A, Tamjidi S, Dehghankhalili F, Farhadi A, Saati MA 2020: Application of algae as low cost and effective bio-adsorbent for removal of heavy metals from wastewater: a review study. *Environmental Technology Reviews*, **9** (1): 85-110.
- Bossa R, Di Colandrea M, Salbitani G, Carfagna S 2024: Phosphorous utilization in microalgae: physiological aspects and applied implications. *Plants*, **13** (15): 2127.
- Brar A, Kumar M, Vivekanand V, Pareek N 2019: Phycoremediation of textile effluent-contaminated water bodies employing microalgae: nutrient sequestration and biomass production studies. *International Journal of Environmental Science and Technology*, **16** (12): 7757-7768.
- Chan YJ, Chong MF, Law CL, Hassell DG 2009: A review on anaerobic–aerobic treatment of industrial and municipal wastewater. *Chemical Engineering Journal*, **155** (1-2): 1-18.
- Cygnarowska K 2023: The use of algae to remove copper and lead from industrial wastewater. *Geology, Geophysics and Environment*, **49** (1): 85-93.
- Das BD, Bhattarai A 2025: The versatility of algae in addressing the global sustainability challenges. *Frontiers in Bioengineering and Biotechnology*, **13**: 1621817.
- Davison DR, Nedelcu AM, Eneji ODA., Michod RE 2025: Plasticity and the evolution of group-level regulation of cellular differentiation in the volvocine algae. *Proceedings B*, **292** (2043): 20242477.
- de Souza Silva PHB, Esposti GD, Ndiaye NCG, Pedro GA, Maass D 2025: Microalgae for brewery wastewater treatment and biomass valorization: a systematic review. *Environmental Science and Pollution Research*, 1-17. <https://doi.org/10.1007/s11356-025-37057-0>
- Dias C, Santos JA, Reis, A, Lopes da Silva T 2023: The use of oleaginous yeasts and microalgae grown in brewery wastewater for lipid production and nutrient removal: a review. *Waste and Biomass Valorization*, **14** (6): 1799-1822.
- Dodangodage CA, Kasturiarachchi JC, Wijesekara IA, Perera TA, Rajapakshe D, Halwatura R 2026: Integrated Microalgal–Aquaponic Systems for Enhanced Water Treatment and Food Security: A Critical Review of Recent Advances in Process Integration and Resource Recovery. *Phycology*, **6** (1): 14.
- Ethiraj S, Samuel MS, Idunmathi SM 2024: A comprehensive review of the challenges and opportunities in microalgae-based wastewater treatment for eliminating organic, inorganic, and emerging pollutants. *Biocatalysis and Agricultural Biotechnology*, **60**: 103316.
- Ferri EN, Bolelli L 2025: Wastewater remediation treatments aimed at water reuse: recent outcomes from pilot-and full-scale tests. *Applied Sciences*, **15**(5): 2448.

- Federal Environmental Protection Agency (FEPA). (1991). *National environmental protection regulations*. Government of Nigeria.
- Fillaudeau L, Blanpain-Avet P, Daufin G 2006: Water, wastewater and waste management in brewing industries. *Journal of Cleaner Production*, **14**(5): 463–471.
- Hamid A, Saeed I, Akhtar S, Ahmad SR 2016: Environmental Profile of a Rubber Industry. *Nature Environment & Pollution Technology*, **15**(3).
- Hasnain M, Zainab R, Ali F, Abideen Z 2025: An overview of biosorption, remediation, and desalination potential of algae to remove wastewater toxic pollutants for environmental safety. *Environmental Monitoring and Assessment*, **197**(8): 853.
- Hidalgo D, Martín-Marroquín JM 2019: Adding sustainability to the beverage industry through nature-based wastewater treatment. In *Processing and Sustainability of Beverages* (pp. 1-36). Woodhead Publishing.
- Izah SC, Ogwu MC 2026: Water Pollution and Contamination: Industrial, Agricultural, and Urban Impacts. In *Water Quality and Safety in the Global South: Challenges, Solutions and Future Directions* (pp. 61-85). Cham: Springer Nature Switzerland.
- Jaryal S, Kumar Sharma A, Yadav Lamba B 2026: Comparative assessment of *Chlorella minutissima*, *Chlorella sorokiniana*, and *Scenedesmus abundans* based phycoremediation for pollution reduction in dairy industry wastewater. *Bioremediation Journal*, 1–17. <https://doi.org/10.1080/10889868.2025.2609587>
- Kaur S, Reddersen B 2022: Algae based solutions for polluted environments to restore ecosphere equilibrium. *International Journal of Environmental Pollution and Remediation*, **9**: 09-18.
- Kube M, Jefferson B, Fan L, Roddick F 2018: The impact of wastewater characteristics, algal species selection and immobilisation on simultaneous nitrogen and phosphorus removal. *Algal Research*, **31**: 478-488.
- Kumar K, Dasgupta CN, Nayak B, Lindblad P, Das D 2011: Development of suitable photobioreactors for CO₂ sequestration addressing global warming using green algae and cyanobacteria. *Bioresource Technology*, **102**(8): 4945-4953.
- Li Y, Xiong X, Zhang C, Liu A 2022: Sustainable restoration of anoxic freshwater using environmentally-compatible oxygen-carrying biochar: performance and mechanisms. *Water Research*, **214**: 118204.
- Martins RA, Salgado EM, Gonçalves AL, Esteves AF, Pires JC 2024: Microalgae-based remediation of real textile wastewater: assessing pollutant removal and biomass valorisation. *Bioengineering*, **11**(1).
- Mejía-Marchena R, Maturana-Córdoba A, Gómez-Cerón D, Quintero-Monroy C, Arismendy-Montes L, Cárdenas-Pérez C 2023: Industrial wastewater treatment technologies for reuse, recycle, and recovery: advantages, disadvantages, and gaps. *Environmental Technology Reviews*, **12**(1): 205-250.
- Mironiuk M, Chojnacka K 2018: The environmental benefits arising from the use of algae biomass in industry. In *Algae biomass: characteristics and applications: towards algae-based products* (pp. 7-16). Cham: Springer International Publishing.
- Mohammadi M, Man HC, Hassan MA, Yee PL 2010: Treatment of wastewater from rubber industry in Malaysia. *African Journal of Biotechnology*, **9**(38): 6233-6243.
- Nair S, Manu B, Azhoni A 2021: Sustainable treatment of paint industry wastewater: Current techniques and challenges. *Journal of Environmental Management*, **296**: 113105.
- Najar-Almanzor CE, Velasco-Iglesias KD, Solis-Bañuelos M, González-Díaz RL, Guerrero-Higareda S, Fuentes-Carrasco OJ, ... Carrillo-Nieves D 2024: *Chlorella vulgaris*-mediated bioremediation of food and beverage wastewater from industries in Mexico: Results and perspectives towards sustainability and circular economy. *Science of The Total Environment*, **940**: 173753.
- Olajire AA 2020: The brewing industry and environmental challenges. *Journal of Cleaner Production*, **256**: 102817.
- Olgún EJ 2012: Dual purpose microalgae–bacteria-based systems that treat wastewater and produce biodiesel and chemical products within a Biorefinery. *Biotechnology advances*, **30**(5): 1031-1046.
- Paerl HW, Otten TG 2013: Harmful cyanobacterial blooms: Causes, consequences, and controls. *Microbial Ecology*, **65**(4): 995–1010.
- Parmar KS, Patel KM 2025: Biosorption and bioremediation of heavy metal ions from wastewater using algae: A comprehensive review. *World Journal of Microbiology and Biotechnology*, **41**(7): 262.
- Powell N, Shilton A, Chisti Y, Pratt S 2009: Towards a luxury uptake process via microalgae—defining the polyphosphate dynamics. *Water Research*, **43**(17): 4207-4213.
- Rawat I, Kumar RR, Mutanda T, Bux F 2011: Dual role of microalgae: phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. *Applied Energy*, **88**(10): 3411-3424.
- Roychoudhury A, Chatterjee U, Gupta H 2025: Revisiting Salinity Tolerance Mechanism in Cyanobacteria. In *Cyanobacterial Response to Extreme Environments: A Molecular Understanding for a Sustainable Future* (pp. 101-127). GB: CABI.
- Saket P, Kashyap M, Bala K, Joshi A 2022: Microalgae and bio-polymeric adsorbents: an integrative approach giving new directions to wastewater treatment. *International Journal of Phytoremediation*, **24**(5): 536-556.
- Sarwer A, Hamed SM, Osman AI, Jamil F, Al-Muhtaseb AAH, Alhajeri NS, Rooney DW 2022: Algal biomass valorization for biofuel production and carbon sequestration: a review. *Environmental Chemistry Letters*, **20**(5): 2797-2851.
- Shabangu KP, Bakare BF, Bwapwa JK 2022: The treatment effect of chemical coagulation process in South African brewery wastewater: Comparison of polyamine and aluminum-chlorohydrate coagulants. *Water*, **14**(16), 2495.
- Shrotri GK, Tomer P, Hazra S 2023: Valorization of wastewater from the beverage industry for polyhydroxyalkanoate production with its improved applicability to agricultural use. *Water, Air, & Soil Pollution*, **234**(4): 269.
- Singh BJ, Chakraborty A, Sehgal R 2023: A systematic review of industrial wastewater management: Evaluating challenges and enablers. *Journal of Environmental Management*, **348**, 119230.
- Sutherland DL, Park J, Ralph PJ, Craggs RJ 2020: Improved microalgal productivity and nutrient removal through

- operating wastewater high rate algal ponds in series. *Algal Research*, **47**: 101850.
- Viktoryová N, Szarka A, Hrouzková S 2022: Recent developments and emerging trends in paint industry wastewater treatment methods. *Applied sciences*, **12**(20): 10678.
- WHO 2017: *Guidelines for drinking-water quality* (4th ed.). World Health Organization.
- Wichanuchit W, Pung T, Panich-pat T 2021: Wastewater Treatment in the Brewing Industry Using *Chlorella vulgaris*. *Journal of Food Health and Bioenvironmental Science*, **14**(3): 35-41.
- Yadav P, Singh RP, Rana S, Joshi D, Kumar D, Bhardwaj N, ... Kumar A 2022: Mechanisms of stress tolerance in cyanobacteria under extreme conditions. *Stresses*, **2**(4): 531-549.
- Zhang Q, Yu Z, Zhu L, Ye T, Zuo J, Li, X, ... Jin S 2018: Vertical-algal-biofilm enhanced raceway pond for cost-effective wastewater treatment and value-added products production. *Water Research*, **139**, 144-157.