

Screening of Eight Aquatic Macrophytes for Phytoremediation of Sugar Industry Effluent: A Comparative Physico-Chemical Assessment

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ABSTRACT

Untreated sugar-mill effluent is a major contributor to freshwater degradation in agro-industrial regions, yet low-cost polishing options remain under-studied for many locally available macrophytes. This study screened eight aquatic macrophytes — *Pontederia crassipes*, *Ipomoea aquatica*, *Marsilea quadrifolia*, *Pistia stratiotes*, *Nelumbo lutea*, *Epipremnum aureum*, *Salvinia minima* and *Hydrilla verticillata* — for their capacity to improve the physico-chemical quality of diluted sugar-mill effluent over a 15-day static exposure. Baseline effluent was warm (41 °C), mildly acidic (pH 6.4), poorly oxygenated (dissolved oxygen, DO, 1.27 mg L⁻¹) and heavily loaded with organic and dissolved-solid contaminants (BOD 90 mg L⁻¹; COD 345 mg L⁻¹; TDS 2740 mg L⁻¹; chloride 201 mg L⁻¹; sulphate 648 mg L⁻¹). All eight species raised DO and lowered temperature, BOD, COD, TDS, chloride and sulphate, but with markedly different efficiencies. *P. crassipes* was the most effective species overall, raising DO to 2.71 mg L⁻¹ and cutting BOD by 43%, COD by 36%, TDS by 32% and sulphate by 52%, followed closely by *I. aquatica*; *E. aureum* and *H. verticillata* were consistently the weakest performers. Colour lightened from dark brown to yellowish-brown/grey and the effluent's characteristic odour was markedly reduced in all treatments. These findings identify rapid growth, high biomass and extensive fibrous root architecture — traits shared by *P. crassipes* and *I. aquatica* — as key determinants of remediation efficiency, and support the use of these two locally abundant macrophytes as low-cost, low-technology polishing agents for sugar industry effluent ahead of discharge or reuse.

Keywords: sugar mill effluent; aquatic macrophytes; phytoremediation; *Pontederia crassipes*; *Ipomoea aquatica*; water quality

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1. INTRODUCTION

Rapid industrialization has sharply increased the volume of wastewater entering natural water bodies, often with little or no prior treatment, degrading water quality and threatening aquatic ecosystems and public health. Among industrial sources, effluents from sugar and paper mills are recognized as particularly damaging to surrounding ecosystems and agricultural land^{1,2}, carrying high organic and inorganic loads that alter the physico-chemical character of receiving waters and impair seed germination and crop growth in irrigated fields downstream³.

Conventional physico-chemical treatments — ion exchange, membrane filtration, electro-coagulation, flotation and adsorption — remain energy-intensive, costly and generate secondary sludge, limiting their use as sustainable long-term solutions⁴. This has driven interest in biological alternatives, particularly phytoremediation, which exploits the intrinsic capacity of plants to degrade, assimilate, metabolize and detoxify contaminants at comparatively low cost and operational complexity^{5,6}. Aquatic macrophytes are especially well suited to this role: their extensive root systems facilitate pollutant uptake and storage, and they have been used successfully to remediate a wide range of polluted waters worldwide^{7,8}.

A recurring challenge in applying phytoremediation at scale is identifying species — and even individuals within species — that combine strong pollutant tolerance with high uptake efficiency, since these traits vary considerably and are shaped by root architecture, photosynthetic capacity and growth rate under contaminated conditions^{9,10}. Species selection is therefore central to designing an effective system¹¹, and indigenous species are often preferred for their superior local adaptability and survival under environmental stress¹². Barriers to wider commercial adoption include an incomplete inventory of hyperaccumulator species and unresolved questions around process optimization^{28,29}, and work on phytoremediation in India remains comparatively limited, underscoring the need for region-specific screening studies.

The present study was carried out in Vizianagaram district, Andhra Pradesh, India, a hub of sugar-mill activity whose untreated effluent accumulates in local freshwater bodies without prior remediation research. Eight locally occurring aquatic macrophytes were screened over a 15-day exposure period for their ability to improve the temperature, colour, pH, dissolved oxygen, BOD, COD, TDS, chloride and sulphate of diluted sugar-mill effluent, with the goal of identifying the most efficient,

locally adapted candidates for practical, field-level polishing of this effluent stream.

2. MATERIALS AND METHODS

2.1 Study area

Effluent and plant material were sourced from Vizianagaram district, Andhra Pradesh, India, approximately 18 km inland from the Bay of Bengal and 52 km from Visakhapatnam. The district has a tropical climate with summer (March–May), south-west monsoon (June–August), north-east monsoon (September–November) and mild winter (December–February) seasons, and is drained by the Gosthani, Nagavali and Champavathi rivers. Three sugar mills operate in the district — M/S Vijayarama Gajapathi Co-operative Sugars Ltd., M/S N.C.S. Sugars Ltd. and M/S E.I.D. Parry (India) Ltd. — discharging effluent with minimal prior treatment.

2.2 Collection of plant material and effluent

Eight aquatic macrophyte species — *Pontederia crassipes*, *Marsilea quadrifolia*, *Pistia stratiotes*, *Nelumbo lutea*, *Ipomoea aquatica*, *Epipremnum aureum*, *Salvinia minima* and *Hydrilla verticillata* (two dicotyledons, four monocotyledons and two pteridophytes) — were collected from the banks of the Gosthani River near Korukonda village. These free-floating or rooted-emergent macrophytes are locally abundant, propagate rapidly and tolerate nutrient-rich or polluted water. Untreated sugar-mill effluent — brownish, with a characteristic molasses odour — was collected in 5 L and 10 L containers from the discharge outlet of M/S Vijayarama Gajapathi Co-operative Sugars Ltd. Plant material was rinsed under running tap water to remove soil and debris before use. The study spanned one year (August 2024–August 2025).

2.3 Experimental design

Each species was evaluated independently. Approximately 1 kg of fresh plant biomass (surface moisture removed with filter paper) was introduced into 20 L plastic containers holding 18 L of diluted effluent (10% raw effluent : 90% tap water), maintained under natural sunlight (~10 h day⁻¹) for 15 days, with five replicates per species. Water samples were drawn every 3 days for physico-chemical analysis. Colour and temperature were monitored separately over a 5-day period across all eight species, with colour reduction quantified spectrophotometrically at 430 nm.

2.4 Physico-chemical analysis

Electrical conductivity, pH and turbidity were measured with a calibrated digital pH meter, conductivity meter and the turbidity-tube (nephelometric) method, respectively. Dissolved oxygen and biochemical oxygen demand were determined by the Winkler titrimetric method and chemical oxygen demand by the closed/open dichromate reflux method with potassium dichromate and ferrous ammonium sulphate titration. Total dissolved solids were estimated gravimetrically after filtration and oven-drying at

180 °C. Chloride was determined by argentometric titration, and sulphate turbidimetrically²⁶. All analyses followed standard protocols at each sampling interval throughout the 15-day treatment period.

2.5 Statistical analysis

All measurements were obtained from replicate treatments and expressed as mean values. Data were compared across species by one-way ANOVA with post-hoc tests, with significance set at $p < 0.05$.

3. RESULTS

3.1 Baseline effluent quality

The untreated effluent was warm, mildly acidic, poorly oxygenated and heavily loaded with organic and dissolved-solid contaminants (Table 1). Temperature (41 °C), electrical conductivity (1121 $\mu\text{S m}^{-1}$), BOD (90 mg L^{-1}), COD (345 mg L^{-1}) and TDS (2740 mg L^{-1}) all exceeded WHO/BIS discharge limits, while DO (1.27 mg L^{-1}) was well below the level needed to sustain aquatic life^{13,14}. Turbidity, phosphate and nitrate were below detection; chloride (201 mg L^{-1}) and sulphate (648 mg L^{-1}) were within or moderately above permissible limits, respectively.

Table 1. Physico-chemical characteristics of the sugar-industry effluent prior to treatment (BDL = below detection limit).

Parameter	Value	Unit
Temperature	41	°C
pH	6.4	—
Electrical conductivity	1121	$\mu\text{S/m}$
TDS	2740	mg/L
Turbidity	BDL	—
Dissolved oxygen (DO)	1.27	mg/L
Biological oxygen demand (BOD)	90	mg/L
Chemical oxygen demand (COD)	345	mg/L
Phosphate	BDL	—
Nitrate	BDL	—
Chloride	201	mg/L
Sulphate	648	mg/L

3.2 Effect of 15-day macrophyte treatment on effluent quality

All eight macrophytes improved every measured parameter over 15 days, but with markedly different efficiencies (Table 2; Figs 1–3). *P. crassipes* was consistently the top performer, raising DO from 1.27 to 2.71 mg L^{-1} and delivering the largest reductions in BOD (90→51 mg L^{-1} , 43%), COD (345→220 mg L^{-1} , 36%), TDS (2740→1876 mg L^{-1} , 32%), chloride (201→168 mg L^{-1}) and sulphate (648→310 mg L^{-1} , 52%). *I. aquatica* ranked second across nearly all parameters. *H. verticillata* showed the weakest pH shift and poorest TDS removal, *P. stratiotes* was least effective at sulphate removal, and *E. aureum* was consistently the poorest performer for DO enhancement and for BOD, COD and chloride removal. Effluent temperature fell from

41 °C to 30–33 °C in all treatments, colour lightened from dark brown to yellowish-brown/grey (most pronounced with *P. crassipes* and *P. stratiotes*), and the raw effluent's unpleasant odour was markedly reduced (Table 3).

Table 2. Effluent quality parameters after 15-day treatment with each macrophyte (pre-treatment: pH 6.4, DO 1.27, BOD 90, COD 345, TDS 2740, Cl⁻ 201, SO₄²⁻ 648).

Species	pH (final)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	TDS (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)
<i>P. crassipes</i>	highest	2.71	51	220	1876	168	310
<i>I. aquatica</i>	2nd highest	2.60	56	230	1887	169	315
<i>M. quadrifolia</i>	3rd highest	2.52	63	253	1940	170	385
<i>S. minima</i>	4th highest	1.92	58	285	1981	174	386
<i>P. stratiotes</i>	5th highest	2.30	64	276	1974	171	390
<i>N. lutea</i>	6th highest	2.21	66	281	2010	173	346
<i>E. aureum</i>	7th highest	1.82	71	300	2110	181	378
<i>H. verticillata</i>	lowest	1.87	70	293	2216	175	365

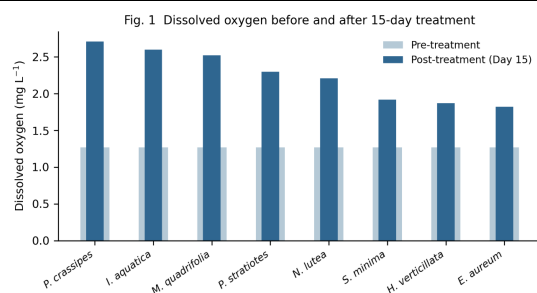


Fig. 1. Dissolved oxygen before and after 15-day treatment across the eight macrophytes.

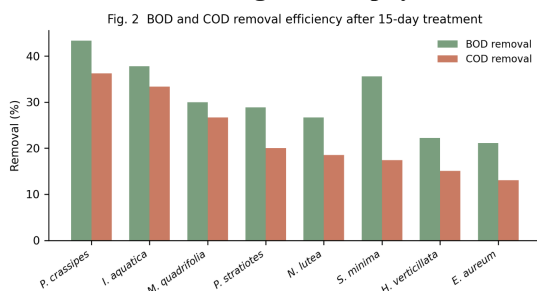


Fig. 2. BOD and COD removal (%) achieved by the eight macrophytes after 15 days.

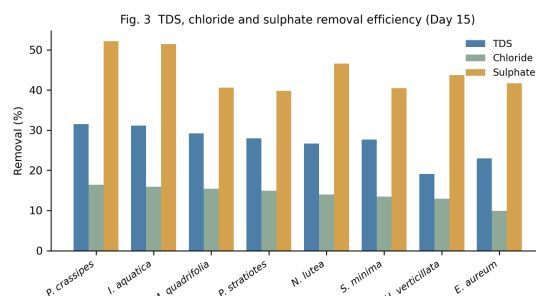


Fig. 3. TDS, chloride and sulphate removal (%) achieved by the eight macrophytes after 15 days.

Table 3. Change in physical characteristics of the effluent after 15-day macrophyte treatment.

Parameter	Before treatment	After treatment (all species)
Colour	Dark brown	Yellowish-brown/grey (palest with <i>P. crassipes</i> , <i>P. stratiotes</i>)
Temperature	41 °C	30–33 °C
Odour	Strongly unpleasant	Mildly unpleasant

4. DISCUSSION

4.1 Pollution status of raw sugar-industry effluent

The elevated temperature, low DO and high organic load recorded for the untreated effluent match the general profile reported for sugar-mill wastewater elsewhere, where suspended and dissolved solids, BOD, COD, chloride and sulphate commonly exceed permissible discharge limits^{15,16}. Because BOD and COD directly deplete receiving-water oxygen, and DO below 3 mg L⁻¹ is generally inadequate to sustain aquatic life, the combination observed here (DO 1.27 mg L⁻¹; BOD 90 mg L⁻¹; COD 345 mg L⁻¹) indicates that untreated discharge would be ecologically damaging^{13,17}. Chloride and sulphate, though elevated relative to drinking-water guidelines, remained within levels unlikely to be acutely toxic to aquatic biota on their own^{14,18}, indicating that organic and oxygen-demand load, rather than salinity, was the dominant hazard in this effluent.

4.2 Comparative phytoremediation performance

Across all endpoints, *P. crassipes* outperformed the other seven species, followed by *I. aquatica*, consistent with previous reports of strong remediation capacity in *Eichhornia crassipes*^{19,20} and in *I. aquatica* for BOD, COD and TDS removal from textile effluent²¹. This advantage is plausibly linked to rapid growth, large biomass and extensive fibrous root/rhizome systems, which increase the surface area available for pollutant sorption and for rhizosphere microbial communities^{22,23}. By contrast, *E. aureum*, the slowest-growing species tested, was consistently the weakest performer, and *H. verticillata*, a fully submerged species with limited surface contact with the bulk effluent, showed the poorest pH modification and TDS removal. These trait–performance associations suggest that growth

rate, biomass accumulation and root architecture — rather than taxonomic grouping alone — are the principal determinants of remediation efficiency among free-floating, submerged and fern macrophytes.

The present ranking diverges from some earlier findings: *P. stratiotes* performed comparatively poorly here despite being highlighted as an effective remediator elsewhere, and *N. lutea* underperformed relative to its reported efficacy in other sugar-effluent trials²⁴. Such discrepancies likely reflect differences in initial effluent composition, plant growth stage, treatment duration and local environmental conditions between studies, underscoring that phytoremediation efficiency is context-dependent and should be verified for the specific effluent and species combination intended for field application.

4.3 Implications for effluent management

These results identify *P. crassipes* and, secondarily, *I. aquatica* as the most promising of the eight macrophytes tested for polishing sugar-industry effluent. Because *P. crassipes* is also a well-documented invasive species capable of forming dense surface mats, its use in open water bodies carries an ecological risk that would need to be managed through contained or engineered wetland-type systems rather than free release²⁵. Within such controlled systems, phytoremediation with these macrophytes offers a low-cost, low-technology polishing step that could reduce the organic load of sugar-industry effluent before discharge or reuse, and process parameters could be further optimized using kinetic modelling approaches developed for constructed wetland systems²⁷. A companion study examines the same two best-performing species — *P. crassipes* and *I. aquatica* — for their phytosorption of heavy metals and synthetic azo dyes, extending this screening to co-occurring pollutants not addressed here.

4.4 Limitations and future work

The trial was conducted over a fixed 15-day window under controlled laboratory conditions with single-species stands, so extrapolation to longer exposure periods, mixed-species systems, seasonal temperature variation and continuous-flow (rather than batch) treatment requires further study.

5. CONCLUSION

All eight aquatic macrophytes tested brought about measurable improvement in sugar-industry effluent quality over 15 days, reducing colour, temperature, BOD, COD, TDS, chloride and sulphate while raising dissolved oxygen and shifting pH toward neutrality. *P. crassipes* and *I. aquatica* consistently performed best, likely aided by rapid growth, high biomass and extensive fibrous root systems that support both direct uptake and rhizosphere microbial activity. Because *P. crassipes* is also a well-known invasive weed, its practical use should rely on controlled cultivation and timely harvesting rather

than open release. Used this way, macrophyte-based phytoremediation — particularly with *P. crassipes* — offers a low-cost, environmentally compatible option for polishing sugar industry and similar industrial wastewaters, best applied alongside, rather than in place of, conventional treatment.

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