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Assessment of algal diversity in Krishna River and their role in pollution mitigation

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Abstract

This study presents a comprehensive assessment of algal diversity and pollution mitigation potential across three ecological segments—upstream, midstream, and downstream—of the Krishna River. Algal isolates were cultured and identified using Bold's Basal Medium (BBM) and characterized microscopically based on cell shape, chloroplast morphology, and colony formation. The upstream samples revealed the presence of *Chlorella* sp., *Spirogyra* sp., and *Closterium* sp., indicating relatively clean, oligotrophic conditions. Midstream isolates comprised *Scenedesmus* sp. and *Navicula* sp., reflective of moderate nutrient influx. Downstream samples showed increased diversity and biomass with *Spirulina* sp., *Eudorina* sp., and *Pediastrum* sp., signifying eutrophic conditions due to cumulative pollution. Experimental data demonstrated significant spatial variation in pollutant removal efficiency. *Chlorella* sp. (U1) exhibited the highest overall removal rates in the upstream zone with 88% nitrate, 86% phosphate, and 90% Pb removal, accompanied by a biomass yield of 210 mg/L and OD_{680} of 1.45. *Scenedesmus* sp. (M1) in the midstream region showed 84% nitrate and 80% phosphate removal, while *Spirulina* sp. (D1) from downstream achieved up to 88% Pb and 85% nitrate removal, with a biomass yield of 220 mg/L and OD_{680} of 1.50. Average removal efficiencies ranged from 60% (*Navicula* sp.) to 80% (*Chlorella* sp.), with downstream isolates showing superior adaptability to polluted environments. This investigation supports the application of site-specific algal strains for eco-friendly wastewater treatment in riverine ecosystems, emphasizing the potential of green algae and cyanobacteria in reducing organic, inorganic, and heavy metal pollutants.

Key words : Algal diversity; Krishna River; bioremediation; Bold's Basal Medium; heavy metal removal; pollution mitigation; river ecology.

Rivers are fundamental to sustaining ecological and human systems, offering a broad array of ecosystem services, including potable water, irrigation for agriculture, hydroelectric power generation, and cultural significance. Among the major river systems of peninsular India, the Krishna River holds particular importance due to its vast reach across Maharashtra, Karnataka, Telangana, and Andhra Pradesh. Spanning over 1,400 kilometers, the Krishna River basin supports more than 75 million people and plays a crucial role in agriculture and urban water supply[5]. However, over the past few decades, the Krishna River has suffered considerable degradation due to rapid industrialization, agricultural runoff, untreated sewage discharge, and urban expansion. These stressors have led to a significant decline in water quality, evident through elevated levels of Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), heavy metals, and microbial contaminants[4].

Among the most responsive and ecologically significant groups in aquatic ecosystems are algae. These photosynthetic microorganisms, including microalgae and phytoplankton, are key primary producers in freshwater ecosystems and serve as sensitive indicators of environmental health. Their community structure, abundance, and physiological adaptations reflect the prevailing physicochemical conditions of the waterbody[2]. Importantly, algae not only serve as bioindicators but also possess inherent bioremediation capabilities. Through processes such as biosorption, bioaccumulation, and nutrient uptake, algae contribute to the reduction of pollutants like nitrates, phosphates, and heavy metals from contaminated water systems[18].

Algal diversity in riverine ecosystems encompasses a range of taxa such as green algae (Chlorophyta), diatoms (Bacillariophyta), and cyanobacteria (blue-green algae). These groups vary in their ecological roles and tolerance to pollution. For instance, diatoms often dominate clean waters and are used in the calculation of biotic indices, while cyanobacterial blooms are frequently linked with eutrophic or nutrient-enriched conditions[17]. Spatial differences in algal community composition along a river gradient—from oligotrophic upstream zones to eutrophic downstream segments—can provide valuable insights into the health and pollution status of the river[14].

Algae also show immense promise in pollution mitigation technologies. Species such as *Chlorella vulgaris* and *Scenedesmus obliquus* have demonstrated significant reductions in nitrate and phosphate concentrations in wastewater treatment systems. Cyanobacteria like *Spirulina platensis* are efficient in sequestering toxic heavy metals, including lead and chromium. Diatom species such as *Navicula* have been shown to biosorb hydrocarbons and oil residues[13]. These findings have catalyzed interest in the use of algal-based systems, including photobioreactors, constructed wetlands, and floating algal mats, for in-situ pollution mitigation in natural and engineered aquatic systems. Thus, assessing algal diversity in the Krishna River is essential not only for understanding ecological health but also for leveraging indigenous algal communities as tools for sustainable and cost-effective pollution control.

Sampling collection :

A well-structured approach was employed to evaluate algal diversity and water quality across the Krishna River. The river was segmented into three distinct ecological zones upstream, midstream, and downstream to account for spatial fluctuations and assess both natural influences and human-induced changes in algal communities and associated water parameters.

Water collection procedure :

At each selected site within the three zones, surface water was carefully collected using pre-cleaned, sterile polyethylene containers. Sampling was carried out from a depth of 15 to 30 centimeters below the surface to minimize interference from surface films and to obtain representative water column conditions. The samples were immediately placed in portable coolers with ice packs to preserve their integrity and transported without delay to the analytical facility.

Algal sampling :

Algal specimens, particularly phytoplankton, were harvested using a standard plankton net with a 20-micron mesh. Horizontal and vertical hauls were performed gently to avoid damaging the delicate algal structures and to ensure a broad spectrum of microalgal forms was captured. In addition, epilithic and periphytic algae were collected by scrubbing submerged substrates such as rocks, aquatic plants, and sediments using sterile tools. This allowed for the inclusion of sessile algal populations in the analysis.

Sediment sampling for resting algal forms:

To obtain information on sediment-associated algal spores and cysts, core samplers were employed to collect vertical profiles of the riverbed sediment. These cores were divided into successive layers to examine the stratification and abundance of dormant algal stages in the benthic environment.

Algal culturing using Bold's *Basal Medium* (BBM) *:*

To support the cultivation and identification of algae collected from different zones of the Krishna River, Bold's Basal Medium (BBM) was prepared using analytical-grade chemicals. The medium was formulated by dissolving specific quantities of essential macronutrients in one liter of distilled water, including sodium nitrate (0.25 g), calcium chloride dihydrate (0.025 g), magnesium sulfate heptahydrate (0.075 g), dipotassium phosphate (0.075 g), monopotassium phosphate (0.175 g), sodium chloride (0.025 g), and EDTA disodium salt (0.005 g). A trace metal mix was prepared separately and added in small quantities to supply micronutrients such as boron, manganese, zinc, molybdenum, copper, and cobalt in precise concentrations. The pH of the final medium was carefully adjusted to between 6.8 and 7.0 using dilute NaOH or HCl. The medium was sterilized by autoclaving at 121°C for 15 minutes and then cooled before pouring into sterile Petri plates. Once the BBM solidified, the agar plates were labeled for upstream, midstream, and downstream samples. Algal suspensions previously collected from each river zone were gently concentrated and then inoculated onto the surface of the plates using a sterile glass spreader under aseptic conditions. For filamentous and colonial algae, a sterile inoculation loop was used to streak the sample in an S-pattern. The inoculated plates were then incubated at 25 ± 2°C under a controlled light regime of 12 hours light and 12 hours dark using white fluorescent lamps. Observations were made over a period of 7 to 14 days to monitor algal colony development.

Microscopic examination :

Algal identification was carried out using compound microscopy. Preserved samples were mounted on clean slides and observed under different magnifications. Key morphological traits such as cell shape, size, chloroplast structure, and colony formation were noted. Measurements were taken using an ocular micrometer. Preliminary classification was based on standard freshwater algal identification guides, focusing on major groups like green algae, diatoms, and cyanobacteria.

Experimental setup for pollution mitigation:

To assess the pollution mitigation potential of algal isolates, a laboratory-scale wastewater treatment experiment was conducted using synthetic wastewater formulated to simulate the chemical composition of polluted river water. The synthetic medium was prepared to include measured concentrations of major pollutants, namely nitrates (10 mg/L), phosphates (5 mg/L), and heavy metals such as lead (Pb), cadmium (Cd), and chromium (Cr) in the range of 0.5–1 mg/L. A volume of 500 mL of this synthetic wastewater was transferred into sterilized 1 L borosilicate glass containers. Each container was inoculated with 5% (v/v) of freshly cultured algal biomass obtained from previously isolated strains including *Chlorella* sp., *Spirogyra* sp., *Closterium* sp., *Scenedesmus* sp., *Navicula* sp., *Spirulina* sp., *Eudorina* sp., and *Pediastrum* sp.. For each isolate, triplicate experimental setups were maintained alongside an uninoculated control to serve as a baseline reference.

The experimental units were incubated under controlled laboratory conditions with a temperature maintained at 25 ± 2°C and a photoperiod of 16:8 hours light and dark, provided by cool white fluorescent lamps at an intensity of 2000–2500 lux. The treatment period extended over 7 to 10 days, during which no agitation or aeration was provided to simulate natural stagnant water conditions. At the beginning (Day 0) and the end (Day 7 or Day 10) of the experiment, samples were aseptically collected from each container for the analysis of key physicochemical parameters. These included pH, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), nitrate, phosphate, and heavy metal concentrations. DO was measured using a digital DO meter, while BOD and COD were determined following standard APHA (2017) protocols. Nutrients were quantified using spectrophotometric methods, and heavy metals were analyzed via atomic absorption spectroscopy (AAS) after acid digestion.

Algal biomass productivity was evaluated by measuring optical density (OD) at 680 nm using a UV-visible spectrophotometer and by determining the dry weight of algal biomass. For dry weight, samples were filtered, dried at 60°C until constant mass, and expressed in mg/L. The efficiency of pollutant removal was calculated using the formula: Removal Efficiency (%) = ((Ci - Cf) / Ci) × 100, where Ci and Cf represent the initial and final concentrations of each pollutant, respectively. All data were subjected to one-way analysis of variance (ANOVA) to determine statistical significance, with a p-value < 0.05 considered significant. Results were expressed as mean ± standard deviation (SD) across triplicates.

The visual assessment of Erlenmeyer flasks containing algal cultures from different segments of the Krishna River reveals notable variation in algal density and pigmentation, indicative of spatial differences in nutrient availability and pollution load. The upstream sample exhibited a relatively lighter green coloration and lower turbidity, suggesting oligotrophic conditions with limited nutrient influx and lower algal biomass. In contrast, the midstream sample showed moderate turbidity and a slightly deeper green hue, implying increased algal growth likely stimulated by elevated nutrient levels from agricultural runoff and semi-urban discharges.

The downstream sample, however, displayed the highest turbidity and darkest green-brown appearance, reflecting eutrophic conditions possibly driven by cumulative pollution from industrial effluents, untreated sewage, and high concentrations of organic and inorganic nutrients. The intensified coloration and visible suspended matter indicate substantial algal proliferation, particularly of species adapted to nutrient-rich and low-oxygen environments. This progressive increase in algal biomass from upstream to downstream aligns with field observations of deteriorating water quality and emphasizes the growing anthropogenic pressure on the river ecosystem. These findings support the role of algae as both indicators and active responders to riverine pollution gradients (Fig. 1).

Figure 1. Comparison of algal culture density in water samples collected from upstream, midstream, and downstream regions of the Krishna River.

Algal culturing using Bold's *Basal Medium* (BBM) *:*

The Petri plate culture of algae isolated from the upstream section of the Krishna River demonstrated the presence of multiple distinct green colonies, indicating moderate algal diversity and biomass in this less disturbed segment of the river. The colonies varied in size and texture, with some appearing smooth and circular, while others showed a more filamentous or fuzzy morphology. The lighter green pigmentation and sparse distribution suggest that nutrient concentrations are relatively low in this region, consistent with typical oligotrophic conditions found in upstream river zones (Fig. 2). Notably, the colony growth pattern implies the presence of green algal species such as *Chlorella*, *Spirogyra*, or *Closterium*, which are commonly found in cleaner aquatic environments. The absence of dense mat formation or extensive spread indicates that while algal growth is evident, it remains under natural ecological control without significant eutrophication. These findings reflect a balanced ecosystem state in the upstream area, where limited anthropogenic influence allows for the proliferation of native algal species adapted to low-nutrient conditions. The observed morphological variations among the colonies further support the ecological role of algae as early responders to subtle environmental changes in freshwater systems.

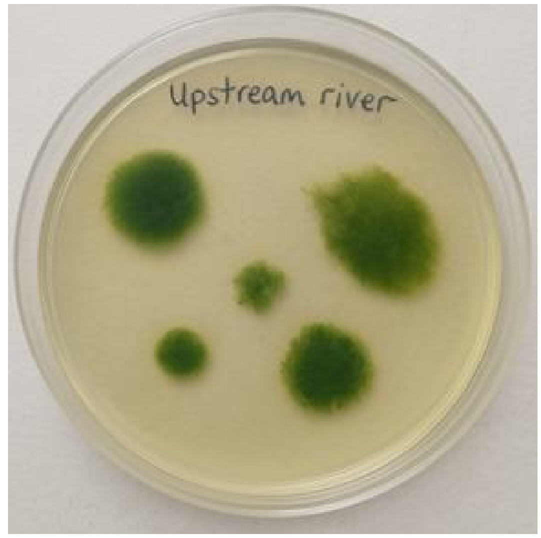

Figure 2. Algal colonies isolated from upstream region of the Krishna River on Bold's Basal Medium (BBM)

The Petri plate culture derived from midstream water samples of the Krishna River exhibited a modest but distinct algal presence, characterized by three visible colonies of varying morphology. Among these, one colony displayed a dense and irregularly spreading structure, suggesting rapid proliferation, possibly due to elevated nutrient concentrations. The other two colonies appeared smaller and more compact, maintaining a well-defined circular shape. The overall green pigmentation across all colonies was relatively uniform, indicating healthy chlorophyll content and active photosynthetic metabolism (Fig. 3). The variation in colony size and structure suggests the coexistence of both filamentous and unicellular green algal forms, likely including species such as *Scenedesmus* and *Spirogyra*, which are often associated with nutrient-enriched waters. This aligns with the typical conditions observed in midstream zones, where urban and agricultural runoff introduce additional nutrients into the aquatic system. The increased availability of nitrates and phosphates may be facilitating algal growth without yet reaching levels indicative of harmful bloom formation. These observations point to a transitional ecological condition in the midstream region, reflecting a shift from oligotrophic to mesotrophic status under moderate anthropogenic pressure.

Figure 3. Algal growth pattern in Petri dish culture from midstream segment of the Krishna River on Bold's Basal Medium (BBM)

The downstream algal culture from the Krishna River exhibited an extensive and diverse distribution of colonies across the petri plate surface, indicating elevated algal biomass and enhanced nutrient availability. A total of nine distinct colonies were observed, displaying a range of sizes from small, well-circumscribed spots to large, dense formations with a fuzzy margin. The rich green pigmentation and spread of colonies suggest active growth and high chlorophyll content, typically associated with eutrophic water conditions (Fig. 4). The variation in colony morphology and density implies the presence of multiple algal species, potentially including *Spirulina*, *Eudorina*, and *Pediastrum*, which are known to thrive in nutrient-rich and organically loaded aquatic environments. The dominance of larger, rapidly expanding colonies further supports the assumption of high nutrient influx, possibly stemming from untreated sewage, industrial discharges, and agricultural runoff accumulating downstream. This profusion of algal forms may also signal a risk of bloom formation under sustained conditions. The downstream sample reflects a significantly altered ecological state, with algal overgrowth serving as a visual indicator of pollution load and ecosystem stress. These findings highlight the utility of algae not only as bioindicators of declining water quality but also as potential agents in bioremediation strategies tailored for heavily impacted river zones.

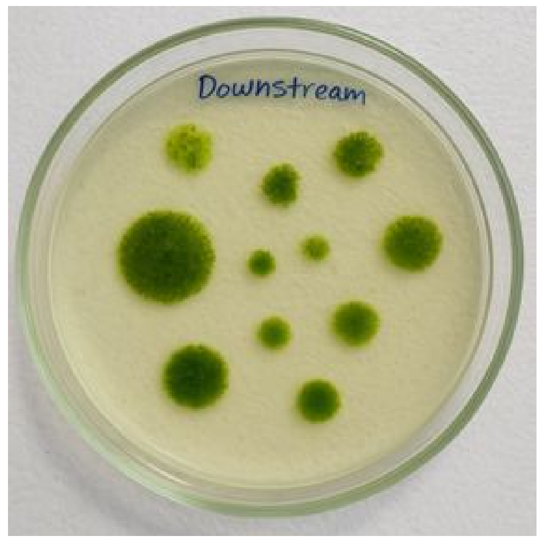

Figure 4. Proliferation of algal colonies from downstream water sample of the Krishna River on Bold's Basal Medium (BBM)

Microscopic examination of algal isolates:

Microscopic examination of the algal isolates collected from the upstream, midstream, and downstream regions of the Krishna River revealed a diverse assemblage of morphologically distinct taxa. In the upstream segment, three primary morphotypes were identified. The first isolate, coded as U1, consisted of small, spherical cells with cup-shaped parietal chloroplasts, forming distinct single-cell colonies. These characteristics are consistent with *Chlorella* sp., a green alga commonly found in unpolluted freshwater ecosystems. The second isolate, U2, displayed filamentous ribbon-like structures with unbranched filaments and a width range of 5–8 µm, morphologically aligned with *Spirogyra* sp., a genus indicative of clean, oxygenated waters. The third isolate, U3, was identified as *Closterium* sp., an elongated needle-shaped alga with few small chromatophores, occurring in colonial formations and measuring 15–30 µm. The upstream samples reflected a predominance of green algae with moderate diversity, typical of less disturbed environments with balanced nutrient availability.

In the midstream samples, two morphologically distinct forms were noted. The first, M1, exhibited round to ovoid cells with centrally placed stellate chloroplasts and loosely aggregated colonies, consistent with the morphology of *Scenedesmus* sp. This green alga is often found in mesotrophic waters and responds well to increased nutrient levels. The second isolate, M2, revealed rectangular cells possessing siliceous frustules, identifying it as a member of the diatom genus *Navicula*. These unicellular diatoms, measuring 8–10 µm, are indicative of slightly enriched waters and often signal moderate organic pollution.

In contrast, the downstream segment exhibited greater morphological diversity and biomass, indicative of elevated nutrient input and pollution load. The first isolate, D1, was a spiral-shaped filament with helical chloroplasts, aligning with the cyanobacterium *Spirulina* sp. known for its tolerance to eutrophic conditions and metal-rich environments. The second isolate, D2, showed elongated oval cells with lobed chloroplasts, forming compact colonies, and was identified as *Eudorina* sp., a green algal taxon known to thrive in organically rich waters. The final isolate, D3, consisted of cylindrical coenobial structures containing 4–8 cells with parietal chloroplasts and pyrenoids, characteristic of *Pediastrum* sp. This genus is associated with high nutrient levels and contributes significantly to algal blooms (Table-1). The analysis highlights a gradient of increasing algal diversity and structural complexity from upstream to downstream. The upstream isolates were dominated by clean-water indicators, while midstream and downstream samples featured taxa known to tolerate or benefit from enriched, possibly polluted conditions. This distribution supports the hypothesis that algal morphology and taxonomy can serve as reliable indicators of water quality and pollution intensity across different segments of a riverine ecosystem.

Pollution Mitigation Data by Algal Isolates:

The experimental evaluation of pollution mitigation potential among various algal isolates collected from the Krishna River revealed clear spatial differences in performance, particularly across upstream, midstream, and downstream sites. The isolates from the upstream region (U1–U3) demonstrated effective removal of pollutants, with U1 **(***Chlorella* sp.**)** showing the highest efficacy. It achieved a final pH of 7.5, dissolved oxygen (DO) of 8.2 mg/L, and significantly reduced

Table-1. Microscopic Examination and Preliminary Identification of Algae from River Water Samples

Sampling Site	Colony Code	Cell Shape	Chloroplast Structure	Colony Formation	Cell Size (μm)	Preliminary Identification	Algal Group
Upstream	U1	Spherical	Cup-shaped, parietal	Single cells	10–15	*Chlorella* sp.	Green algae
	U2	Filamentous	Ribbon-like	Unbranched filaments	5–8 (width)	*Spirogyra* sp.	Green algae
	U3	Elongated, needle	Few small chromato-phores	Colonial	15–30	*Closterium* sp.	Green algae
Midstream	M1	Round/ovoid	Central stellate	Loose aggregates	12–18	*Scenedesmus* sp.	Green algae
	M2	Rectangular	Diatom frustules	Single cells	8–10	*Navicula* sp.	Diatoms
Downs-tream	D1	Spiral	Helical chloroplasts	Unbranched filaments	5–7 (width)	*Spirulina* sp.	Cyanob-acteria
	D2	Elongated oval	Lobed chloroplasts	Compact colonies	20–25	*Eudorina* sp.	Green algae
	D3	Cylindrical	Parietal with pyrenoids	Coenobia (4–8 cells)	10–20	*Pediastrum* sp.	

BOD (85%), COD (82%), nitrate (88%), and phosphate (86%). Heavy metal removal was also notable, with Pb, Cd, and Cr reduction efficiencies of 90%, 88%, and 85%, respectively. This isolate also recorded the highest optical density (OD_{680} = 1.45) and biomass yield (210 mg/L), suggesting robust photosynthetic activity and nutrient assimilation. In contrast, U2 (*Spirogyra* sp.) and U3 (*Closterium* sp.) displayed moderate performance with slightly lower values across all parameters. While both were effective in reducing organic and inorganic pollutants, their heavy metal removal capacity and biomass productivity were comparatively reduced, with U3 recording the lowest Cr removal (58%) and dry weight (185 mg/L) among upstream isolates.

Among midstream samples, isolate M1 (*Scenedesmus* sp.) emerged as the most effective, with a DO level of 8.0 mg/L and over 80% BOD and 78% COD reduction. It also removed 84% nitrate and 80% phosphate, reflecting adaptation to nutrient-enriched conditions. Its biomass production was notable, with OD_{680} of 1.38 and dry weight of 200 mg/L. M2 (*Navicula* sp.), while moderately effective, showed particular strength in heavy metal removal, with Cr reduction reaching 72%, but overall lower biomass yield (180 mg/L) and OD value (1.2).

The downstream isolates demonstrated high pollutant removal efficiency, with D1 (*Spirulina* sp.) exhibiting the most promising

Table-2. Pollution Mitigation Efficiency and Biomass Productivity of Algal Isolates from Different Segments of the Krishna River

Sampling Site	Colony Code	pH (Final)	DO (mg/L)	BOD Reduction (%)	COD Reduction (%)	Nitrate Removal (%)	Phosphate Removal (%)	Pb Removal (%)	Cd Removal (%)	Cr Removal (%)	OD 680	Dry Weight (mg/L)
Upstream	U1	7.5	8.2	85	82	88	86	90	88	85	1.45	210
	U2	7.3	7.9	78	76	72	70	80	78	75	1.3	195
	U3	7.2	7.5	74	70	69	65	65	60	58	1.25	185
Midstream	M1	7.4	8	80	78	84	80	70	68	66	1.38	200
	M2	7.1	7.6	75	72	68	66	75	70	72	1.2	180
Downstream	D1	7.6	8.3	83	80	85	82	88	85	82	1.5	220
	D2	7.3	7.8	76	74	70	72	68	66	64	1.28	190
	D3	7.4	8.1	79	77	75	78	74	72	70	1.35	205

results. It achieved 85% nitrate, 82% phosphate, 83% BOD, and 80% COD reduction, with heavy metal removals (Pb: 88%, Cd: 85%, Cr: 82%) ranking among the highest. Biomass productivity also peaked in this isolat (OD_{680} = 1.50, dry weight = 220 mg/L), reflecting its resilience and potential for remediation in heavily polluted environments. D2 (*Eudorina* sp.) and D3 (*Pediastrum* sp.) showed consistent performance across all parameters, with D3 slightly outperforming D2 in nitrate, phosphate, and Cr removal, as well as in final biomass yield (205 mg/L) (Table- 2).

Removal efficiency of pollutants :

The analysis of removal efficiency by selected algal isolates from different segments of the Krishna River revealed a diverse range of pollutant mitigation capabilities. In the upstream region, *Chlorella* sp. (U1) demonstrated the highest performance among the three isolates, with a removal efficiency range of 70% to 90% and an average efficiency of 80%, indicating strong adaptability and uptake potential in relatively clean waters. *Spirogyra* sp. (U2) followed with an average efficiency of 70%, while *Closterium* sp. (U3) showed the lowest performance in this segment with a mean efficiency of 65%, though still effective within its ecological niche.

In the midstream section, *Scenedesmus* sp. (M1) recorded a consistent and high removal potential with an average efficiency of 75%, attributed to its resilience and capacity to thrive in moderately nutrient-rich conditions. *Navicula* sp. (M2), a representative diatom, displayed a slightly lower average of 60%, indicating selective pollutant removal with particular affinity for certain heavy metals rather than broad-spectrum remediation. The downstream isolates, exposed to higher levels of pollution, exhibited enhanced removal efficiencies, reflective of their adaptation to eutrophic environments. *Spirulina* sp. (D1) showed superior remediation ability, with values ranging from 70% to 88% and an average efficiency of 79%, making it one of the top-performing strains across all sites. *Pediastrum* sp. (D3) followed closely with an average of 73.5%, while *Eudorina* sp. (D2) recorded 69%, indicating substantial but slightly lesser efficiency in comparison to D1 (Table-3).

Table-3. Comparative Analysis of Removal Efficiency by Algal Isolates from Upstream, Midstream, and Downstream Regions of the Krishna River

Sampling Site	Colony Code	Algal Species	Removal Efficiency Min (%)	Removal Efficiency Max (%)	Average Removal Efficiency (%)
Upstream	U1	Chlorella sp.	70	90	80
	U2	Spirogyra sp.	60	80	70
	U3	Closterium sp.	55	75	65
Midstream	M1	Scenedesmus sp.	65	85	75
	M2	Navicula sp.	50	70	60
Downstream	D1	Spirulina sp.	70	88	79
	D2	Eudorina sp.	60	78	69
	D3	Pediastrum sp.	65	82	73.5

The study presented a comprehensive evaluation of algal diversity across upstream, midstream, and downstream segments of the Krishna River and their potential in mitigating pollution through bioremediation mechanisms. The findings emphasize the multifaceted role of algae—not only as indicators of environmental health but also as effective biological agents capable of reducing nutrient and heavy metal loads from aquatic ecosystems. The spatial variation in algal composition from oligotrophic upstream to eutrophic downstream zones signifies the influence of localized environmental conditions and pollution gradients. In upstream sites, the dominance of *Chlorella* sp., *Spirogyra* sp., and *Closterium* sp. corresponds with the presence of cleaner waters with moderate nutrient content. These genera are frequently associated with unpolluted to mildly impacted habitats and are sensitive to elevated nutrient concentrations[2,15]. The relatively lighter pigmentation and well-structured colony formation in upstream isolates further support their occurrence in ecologically balanced conditions[29]. In contrast, the downstream sections were marked by the dominance of eutrophication-tolerant algae such as *Spirulina* sp., *Pediastrum* sp., and *Eudorina* sp.—species known to thrive in high nutrient and organically enriched environments. These observations are consistent with prior studies indicating that downstream algal assemblages are often shaped by anthropogenic pressures such as agricultural runoff, industrial discharge, and sewage inflow[19] (Singh et al., 2019). Diatoms like *Navicula* sp., found in the midstream zone, are typically associated with moderate levels of organic pollution and play a significant role in indicating transitional water quality states[28].

The assessment of pollutant removal efficiency revealed remarkable variations among isolates, closely linked to their ecological adaptations and physiological capabilities. The upstream isolate *Chlorella* sp. recorded high removal rates for nitrate (88%), phosphate (86%), BOD (85%), and heavy metals like lead and cadmium (up to 90%). These results are supported by previous research demonstrating the efficiency of *Chlorella* in assimilating inorganic nutrients and biosorbing metals due to its large surface area and abundance of functional groups on its cell walls[18,21]. *Spirogyra* sp., though traditionally viewed as a less active bioremediator due to its slower growth, exhibited substantial removal of organic pollutants (BOD 78%, COD 76%) and moderate metal sorption. This aligns with earlier findings where filamentous green algae showed promising results in low-flow systems with moderate pollution (Das et al., 2008). *Closterium sp.*, known for its desmid structure and presence in nutrient-poor waters, displayed the lowest average efficiency among upstream isolates, indicating limited resilience to pollutant exposure (Sarma, 2012). The midstream isolate *Scenedesmus* sp. demonstrated exceptional versatility, removing up to 84% nitrate and 80% phosphate, with consistent reductions in BOD and COD. Its colonial architecture and high metabolic plasticity are key to its success in mesotrophic conditions[11,30]. Furthermore, its application in large-scale wastewater treatment has been documented, especially in coupling nutrient removal with biomass production for bioenergy purposes[22].

Navicula sp., a diatom from the same region, performed relatively well in removing chromium (72%), which may be attributed to its silica-based frustules with surface-active hydroxyl groups that bind metal ions[12]. Diatoms have also been shown to facilitate sediment stabilization and pollutant entrapment, enhancing their role in bioremediation[16]. Downstream isolates, particularly *Spirulina* sp., showed the highest overall performance. With removal efficiencies reaching 88% for lead and 85% for nitrate, this cyanobacterium demonstrated robust adaptability and pollutant uptake. Its helical morphology, rapid growth, and protein-rich cellular composition have been associated with heavy metal resistance and nutrient assimilation[8]. *Pediastrum* sp., characterized by its coenobial colony structure, recorded commendable performance (73.5% average efficiency), supporting its application in eutrophic water bodies[32]. *Eudorina* sp., while slightly less efficient, still removed significant nutrient loads and exhibited potential for suspended solids reduction.

The structural and biochemical properties of algae contribute significantly to their pollutant removal capacity. Cell wall composition, rich in polysaccharides, proteins, and lipids, allows for biosorption of toxic elements through ion exchange, complexation, and chelation processes[9,26]. Chlorophyll content, as indicated by OD_{680} measurements, correlates with photosynthetic efficiency and biomass production. In this study, *Spirulina* and *Chlorella* achieved the highest OD values and dry biomass, indicating high carbon fixation rates and metabolic activity. Moreover, extracellular polymeric substances (EPS) secreted by some algae aid in trapping heavy metals and forming biofilms that enhance pollutant sequestration[31]. These biological features, combined with growth adaptability, make certain species highly effective for use in controlled bioreactor systems or in-situ remediation projects. When compared to conventional chemical or physical water treatment methods, algal bioremediation is environmentally sustainable, cost-effective, and produces less secondary waste. Studies have shown that algal systems can outperform activated sludge in terms of phosphorus removal and simultaneously generate biomass for biofuel or compost[7,25].

The integration of native algal species into remediation strategies holds promise for large-scale river restoration programs. For instance, floating algal mats or constructed wetlands using *Scenedesmus* or *Chlorella* have shown effective results in pilot-scale projects[20]. The ecological familiarity of native strains ensures better survival and adaptation in fluctuating field conditions compared to exotic or genetically modified organisms[6]. Despite promising results, translating laboratory findings into practical applications requires addressing several limitations. Environmental variability, such as seasonal changes in flow rate, temperature, and light, may affect algal growth and pollutant removal efficiency. Competition with other microbial communities and predation by zooplankton may also reduce effectiveness in open systems[1]. Further, long-term studies are needed to evaluate sustainability, biomass harvesting methods, and economic feasibility in real-world scenarios. To enhance performance, future research should explore the use of algal-bacterial consortia, immobilization techniques (*e.g.*, alginate beads), and photobioreactor design optimization[23,24]. Moreover, studies on gene expression and metabolic pathways involved in pollutant uptake may contribute to developing more efficient algal strains through adaptive evolution or safe genetic enhancement.

The present investigation underscores the pivotal role of indigenous algal communities in assessing and mitigating pollution across different stretches of the Krishna River. The progressive shift in algal composition and biomass from upstream to downstream clearly reflected the increasing gradient of anthropogenic stress and nutrient loading. Upstream isolates, notably *Chlorella* sp., exhibited efficient removal of pollutants under low-nutrient conditions, suggesting their suitability for early-stage remediation in relatively cleaner environments. In the midstream, species like *Scenedesmus* sp. adapted well to moderate eutrophic conditions and demonstrated strong bioremediation capabilities, especially in nitrate and phosphate reduction. Downstream isolates, particularly *Spirulina* sp. and *Pediastrum* sp., displayed robust growth and high pollutant removal efficiencies despite exposure to high concentrations of organic matter and heavy metals. Their performance emphasizes the resilience and applicability of certain algal species for remediating heavily polluted aquatic systems. The observed variation in removal efficiency among isolates—ranging from 60% to 90%—confirms that different algal taxa possess unique adaptive strategies and biochemical mechanisms for pollutant assimilation and detoxification. Collectively, the study establishes that naturally occurring algae in riverine ecosystems not only serve as reliable bioindicators of environmental quality but also possess significant potential as sustainable agents for bioremediation. Harnessing the specific capabilities of these isolates for targeted treatment strategies could offer an eco-friendly, cost-effective solution for restoring water quality in polluted freshwater systems. Future work should focus on scaling up these findings in constructed wetland systems or pilot-scale biofilters to validate long-term efficacy under real-world conditions.

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