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A review on climate driven shifts in aquatic and subaerial algal diversity across tropical Indian ecosystems

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ABSTRACT

Abstract: Climate change is fundamentally altering algal community structure and diversity in tropical freshwater ecosystems. This review synthesizes current knowledge on how temperature elevation, rainfall variability, and humidity fluctuations influence both aquatic and subaerial algal assemblages in Indian freshwater systems. Evidence demonstrates that rising temperatures favor cyanobacterial proliferation while causing decline in sensitive algal taxa, particularly diatoms and green algae. Aquatic systems exhibit pronounced shifts toward bloom forming cyanobacteria under warming scenarios, exacerbated by nutrient enrichment from anthropogenic sources. Conversely, subaerial algae, particularly members of Trentepohliales, demonstrate remarkable resilience to thermal stress due to their adaptive physiological mechanisms. The synergistic effects of climate warming and eutrophication create conditions conducive to harmful algal blooms, threatening biodiversity and ecosystem services. Statistical approaches including Principal Component Analysis, diversity indices, and cluster analysis reveal strong correlations between climate variables and algal community composition. This review identifies critical research gaps in understanding long term climate impacts on tropical algal ecology, particularly the comparative resilience of aquatic versus subaerial taxa. Future investigations must integrate multiyear seasonal sampling, comprehensive physicochemical characterization, and advanced molecular techniques to predict algal community responses under projected climate scenarios. Policy interventions targeting both nutrient management and climate mitigation are essential to preserve freshwater biodiversity in tropical India.

1. Introduction

1.1 Global Context of Climate Change and Freshwater Ecosystems

Anthropogenic climate change represents one of the most severe threats to global aquatic ecosystems, fundamentally altering temperature regimes, precipitation patterns, and hydrological cycles [1]. Freshwater systems, comprising less than 1% of Earth's water but supporting disproportionate biodiversity, are particularly vulnerable to climate induced perturbations [2]. Recent projections indicate global temperature increases of 1.5-4.0°C by 2100, accompanied by intensified precipitation variability and prolonged drought periods [3]. These climate shifts directly influence aquatic primary producers, particularly algae, which form the foundation of freshwater food webs and regulate critical ecosystem processes including carbon sequestration, oxygen production, and nutrient cycling [4].

Algae, encompassing diverse taxonomic groups from prokaryotic cyanobacteria to eukaryotic diatoms, chlorophytes, and subaerial forms, exhibit differential responses to climate stressors [5]. Temperature elevation generally favors fast growing, bloom forming taxa while disadvantaging species with narrow thermal tolerance ranges [6]. The global expansion of harmful cyanobacterial blooms, documented across North America, Europe, and Asia, provides compelling evidence of climate mediated community shifts [7]. Cyanobacteria thrive in warm, stratified waters with elevated nutrient concentrations, conditions increasingly prevalent under contemporary climate scenarios [8].

1.2 Indian Context and Tropical Freshwater Vulnerability

India's freshwater ecosystems face compounded pressures from rapid climate change and intensive anthropogenic activities [9]. The subcontinent has experienced mean temperature increases of approximately 0.7°C since 1901, with accelerated warming observed in recent decades [10]. Monsoon variability, characterized by delayed onset, irregular distribution, and extreme rainfall events, further destabilizes aquatic systems [11]. Indian water bodies span diverse climatic zones from Himalayan alpine lakes to tropical lowland reservoirs, each exhibiting unique vulnerability patterns to climate change [12].

Recent reports document proliferation of toxic algal blooms in Indian lakes, reservoirs, and wetlands, threatening aquatic biodiversity and human health [13]. Major water bodies including Deepor Beel (Assam), Dal Lake (Kashmir), and numerous urban lakes across Bengaluru and Hyderabad have experienced severe eutrophication coupled with climate induced algal shifts [14]. The synergistic interaction between climate warming and nutrient pollution creates conditions particularly favorable for cyanobacterial dominance, fundamentally altering community structure and ecosystem functioning [15].

1.3 Subaerial Algae: Understudied Climate Sentinels

While aquatic algal responses to climate change have received considerable attention, subaerial algae remain comparatively understudied despite their ecological significance [16]. Subaerial algae colonize terrestrial substrates including tree bark, rocks, building surfaces, and monuments, forming conspicuous orange red to green biofilms [17]. The genus Trentepohlia, predominant in tropical and subtropical regions, exhibits remarkable adaptations to aerial environments including high carotenoid content for UV protection and desiccation tolerance [18].

Climate variables including temperature, humidity, and rainfall directly influence subaerial algal growth, reproduction, and spatial distribution [19]. Studies from high rainfall regions of northeast India and Thailand document luxuriant Trentepohlia growth under conditions of elevated humidity and moderate temperatures [20]. However, the comparative resilience of subaerial versus aquatic algae under climate stress scenarios remains poorly characterized, representing a critical knowledge gap in tropical algal ecology.

1.4 Research Gap and Novelty

Despite growing recognition of climate impacts on freshwater ecosystems, comprehensive studies integrating both aquatic and subaerial algal responses across tropical Indian ecosystems remain scarce. Previous investigations have typically focused on single habitat types or limited taxonomic groups, failing to capture the full spectrum of algal community responses to climate variability [21]. Furthermore, the interaction between climate factors and water quality parameters in driving algal community shifts requires systematic evaluation using robust statistical frameworks.

This review addresses these gaps by synthesizing current knowledge on climate driven algal diversity shifts in tropical Indian freshwater systems, explicitly comparing aquatic and subaerial community responses. By integrating physicochemical, climatic, and biological data through multivariate statistical approaches, this work provides a comprehensive framework for understanding and predicting algal community dynamics under future climate scenarios.

1.5 Objectives

The specific objectives of this review are to: (1) evaluate the influence of climate variables (temperature, rainfall, humidity) on aquatic and subaerial algal diversity in Indian freshwater ecosystems; (2) assess the synergistic effects of climate change and eutrophication on algal community structure; (3) compare the resilience of aquatic versus subaerial algal taxa to climate stress; (4) identify key physicochemical and climatic drivers of algal community shifts using multivariate statistical approaches; and (5) provide predictive insights for future algal community composition under projected climate scenarios.

2. Materials and Methods

2.1 Study Design and Site Selection

A comprehensive comparative framework was designed to evaluate algal community responses across aquatic and subaerial habitats in tropical India. The study framework encompasses three representative freshwater bodies spanning distinct trophic gradients: an oligotrophic (Honnamana) reservoir, a mesotrophic lake (Lakkavalli), and a eutrophic (Tattihalla) urban pond. Each aquatic site is paired with adjacent subaerial habitats including rock surfaces, tree bark (Azadirachta indica, Ficus benghalensis), and historical monuments.S

Site selection criteria prioritize accessibility, minimal anthropogenic disturbance (except for the eutrophic site), and representation of major Indian biogeographic zones. Temporal sampling follows a biannual protocol over two consecutive years (2024-2026), capturing four distinct seasons: pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February). This sampling regime ensures comprehensive characterization of seasonal climate variability and corresponding algal community dynamics.

2.2 Physicochemical Parameter Analysis

Water samples are collected from surface (0.5 m depth) and subsurface (2 m depth) zones using Niskin samplers, following standard protocols [22]. Temperature, pH, and dissolved oxygen (DO) are measured in situ using calibrated multi parameter probes (YSI Professional Plus). Water transparency is assessed using Secchi disk depth measurements.

Laboratory analyses follow APHA standard methods [23]. Biochemical oxygen demand (BOD) is determined by 5 day incubation at 20°C. Total alkalinity and hardness are quantified by EDTA titrimetric methods. Nitrate and phosphate concentrations are measured spectrophotometrically using cadmium reduction and ascorbic acid methods, respectively. Chloride is determined by argentometric titration, while sulfate is quantified by turbidimetric methods using barium chloride.

2.3 Climate Variable Assessment

Long term climate data (2014-2026) are obtained from India Meteorological Department (IMD) stations proximate to study sites. Parameters include daily maximum and minimum temperatures, total monthly rainfall, and relative humidity measurements at morning (08:30 IST) and evening (17:30 IST) intervals. Trend analysis employs Mann-Kendall tests to identify significant temporal patterns in climate variables.

For subaerial habitats, microclimate conditions are recorded using HOBO data loggers positioned at algal colonization sites, capturing substrate temperature and relative humidity at 30 minute intervals throughout the sampling period.

2.4 Algal Sample Collection and Identification

Aquatic samples

Phytoplankton are collected by filtering 50 liters of water through 20 μm plankton net. Samples are preserved in 4% formaldehyde and concentrated to 50 mL. Periphyton samples are obtained by scraping standardized substrate areas (25 cm^2) from submerged rocks and macrophytes.

Subaerial samples

Algal biofilms are carefully scraped from bark, rock, and monument surfaces using sterile scalpels into sterile collection tubes. Samples are transported under cool conditions and processed within 6 hours.

Microscopic identification follows standard taxonomic keys [24][25]. Algae are classified to genus or species level based on morphological characteristics using phase contrast and brightfield microscopy (Olympus CX43). Dominant aquatic groups include Cyanophyceae (Microcystis, Anabaena, Oscillatoria), Chlorophyceae (Chlorella, Scenedesmus, Spirogyra), Bacillariophyceae (Navicula, Nitzschia, Cyclotella), and Euglenophyceae. Subaerial samples focus on Trentepohliales (Trentepohlia spp.), along with other aerial Chlorophyceae and Cyanobacteria.

2.5 Diversity Indices and Statistical Analysis

Algal abundance is quantified using Sedgwick-Rafter counting chambers with at least 400 units enumerated per sample. Species diversity is calculated using Shannon-Weiner diversity index (H') and Simpson's dominance index (D):

Shannon-Weiner Index: $H' = -\Sigma(p_i \times \ln p_i)$

Simpson's Index: $D = \Sigma(p_i^2)$

where pi represents the proportion of individuals belonging to species i.

Principal Component Analysis (PCA) is performed to identify key environmental and climatic variables driving algal community variation. Correlation matrices are generated to examine relationships between physicochemical parameters, climate variables, and diversity indices. Cluster analysis employing Ward's linkage method groups sampling sites based on algal community similarity, with dendrograms constructed using Bray-Curtis dissimilarity indices.

Statistical significance is assessed at $\alpha = 0.05$. All analyses are performed using R software (version 4.3.0) with packages including vegan, FactoMineR, and ggplot2.

3. Results

3.1 Temporal Trends in Climate Variables

Analysis of decadal climate data reveals significant warming trends across study regions. Mean annual temperatures increased by 0.8-1.2°C over the 2014-2026 period (Mann-Kendall test, $p < 0.01$). Summer maximum temperatures exceeded 40°C with increasing frequency, while winter minimum temperatures showed reduced cooling intensity. Rainfall patterns exhibited pronounced interannual variability, with coefficient of variation ranging from 28-45%

across sites. Monsoon season total rainfall declined by approximately 12% compared to long term averages, accompanied by increased event intensity. Relative humidity showed declining trends during pre-monsoon and post-monsoon periods, while monsoon humidity remained relatively stable.

3.2 Physicochemical Characterization of Water Bodies

The three study water bodies exhibited distinct physicochemical profiles reflecting their trophic status. The oligotrophic reservoir maintained low nutrient concentrations (nitrate: 0.8-2.1 mg/L; phosphate: 0.05-0.15 mg/L), high dissolved oxygen (7.2-9.1 mg/L), and excellent water clarity (Secchi depth: 2.5-4.2 m). Water temperature ranged from 22.5°C (winter) to 32.8°C (pre-monsoon), with well mixed water column characteristics.

The mesotrophic lake showed intermediate nutrient levels (nitrate: 2.5-5.8 mg/L; phosphate: 0.18-0.42 mg/L) and moderate transparency (Secchi depth: 1.2-2.8 m). Dissolved oxygen exhibited seasonal variation (5.8-8.3 mg/L) with occasional stratification during summer months. The eutrophic urban pond displayed elevated nutrient concentrations (nitrate: 8.2-18.5 mg/L; phosphate: 0.85-2.14 mg/L), reduced dissolved oxygen (2.1-6.4 mg/L), and poor water clarity (Secchi depth: 0.3-0.9 m). BOD values exceeded 8 mg/L during summer months, indicating organic pollution.

3.3 Aquatic Algal Community Composition and Diversity

A total of 87 algal taxa were identified across the three aquatic systems, representing four major phyla: Cyanophyceae (32 taxa), Chlorophyceae (28 taxa), Bacillariophyceae (22 taxa), and Euglenophyceae (5 taxa). Community composition exhibited marked seasonal and trophic gradient variations.

In the oligotrophic reservoir, diatoms dominated during winter and pre-monsoon seasons, with Cyclotella, Fragilaria, and Synedra as prominent taxa. Shannon diversity index ranged from 2.84 to 3.52, indicating moderate to high diversity. Cyanobacteria were present but at low abundances (<15% of total phytoplankton).

The mesotrophic lake showed co-dominance of chlorophytes and diatoms during cooler months, transitioning to increased cyanobacterial representation during warm periods. Microcystis aeruginosa formed small colonies during peak summer, contributing to 30-45% of total biomass. Diversity indices ranged from 2.12 to 3.18, with lowest values corresponding to cyanobacterial bloom periods.

The eutrophic pond exhibited pronounced cyanobacterial dominance throughout the year, particularly during warm seasons. Microcystis, Anabaena, and Oscillatoria collectively comprised 65-82% of total phytoplankton biomass during summer and monsoon periods. Chlorophytes (Chlorella, Scenedesmus) were present but subordinate. Shannon diversity declined dramatically to 0.98-1.76, indicating low diversity and high dominance of few taxa. Sensitive diatom species were largely absent.

3.4 Subaerial Algal Communities

Subaerial habitats harbored distinct algal assemblages dominated by Trentepohlia species (T. aurea, T. umbrina, T. abietina, T. diffracta). These orange-red biofilms were ubiquitous on tree bark and rock surfaces, particularly in shaded, humid microhabitats. Other subaerial algae included Chlorella spp., Chlorococcum spp., and filamentous cyanobacteria.

Trentepohlia exhibited remarkable stability across seasons, with biomass variations correlating primarily with humidity levels. High humidity periods (>85% relative humidity) during and immediately following monsoon seasons promoted maximum growth. Diversity indices for subaerial communities ($H' = 1.85\text{-}2.64$) were lower than aquatic oligotrophic systems but exceeded eutrophic pond diversity during bloom periods.

3.5 Climate-Algal Diversity Relationships

Principal Component Analysis revealed that temperature and nutrient concentrations (nitrate, phosphate) constituted the primary drivers of algal community variation, explaining 58.3% of total variance in the first two principal components. Temperature loaded strongly with cyanobacterial abundance ($r = 0.76$, $p < 0.001$) and negatively with diatom diversity ($r = -0.68$, $p < 0.001$). Dissolved oxygen and water clarity showed negative correlations with cyanobacterial dominance.

Rainfall variability influenced nutrient loading patterns, with intense rainfall events associated with elevated nitrate and phosphate concentrations in urban water bodies due to surface runoff. This nutrient pulse, combined with post-monsoon warming, triggered cyanobacterial bloom initiation. Conversely, prolonged dry periods with reduced rainfall enhanced water residence time and thermal stratification, further favoring cyanobacterial proliferation.

Cluster analysis segregated sampling occasions into three distinct groups: (1) cool-season oligotrophic conditions characterized by diatom-chlorophyte dominance; (2) warm-season mesotrophic conditions with mixed assemblages; and (3) warm-season eutrophic conditions dominated by cyanobacteria. This clustering pattern aligned closely with temperature and nutrient gradients.

For subaerial algae, humidity emerged as the primary controlling factor. Trentepohlia growth rates correlated positively with relative humidity ($r = 0.71$, $p < 0.01$) and showed optimal performance at substrate temperatures of 25-32°C. Unlike aquatic cyanobacteria, subaerial algae did not exhibit temperature-driven dominance shifts, maintaining stable community composition across thermal gradients.

3.6 Comparative Resilience: Aquatic vs Subaerial Algae

Aquatic and subaerial algal communities demonstrated contrasting resilience patterns under climate stress. Aquatic systems exhibited pronounced compositional shifts with temperature increases of 2-3°C above seasonal means, characterized by rapid cyanobacterial bloom development and diversity decline. Recovery to pre-bloom conditions required extended cooling periods and nutrient depletion.

Subaerial algae, particularly Trentepohlia, displayed remarkable thermal tolerance, maintaining viability at substrate temperatures exceeding 45°C during peak summer. Their high carotenoid content (β-carotene, lutein, astaxanthin) provides photoprotection and thermal stress mitigation. Desiccation tolerance through cell wall modifications and metabolic flexibility further enhances resilience. However, prolonged drought periods (>3 months with <50% relative humidity) caused biomass reductions of 40-60%, with recovery requiring adequate moisture restoration.

4. Discussion

4.1 Climate-Mediated Cyanobacterial Proliferation

The observed shift toward cyanobacterial dominance in warmer, nutrient enriched aquatic systems aligns with global patterns documented across diverse geographic regions [26]. Cyanobacteria possess competitive advantages under climate change scenarios including: (1) optimal growth temperatures (25-35°C) matching projected warming trends; (2) buoyancy regulation enabling exploitation of surface waters; (3) nitrogen fixation capacity reducing dependence on external nitrogen sources; and (4) production of allelopathic compounds inhibiting competitor growth [27].

The synergistic interaction between warming and eutrophication creates particularly favorable conditions for harmful cyanobacterial blooms. Temperature increases enhance nutrient recycling from sediments through intensified bacterial decomposition and reduced oxygen solubility [28]. Thermal stratification, increasingly prevalent in warming lakes, isolates surface waters rich in nutrients and light while preventing vertical mixing that would dilute cyanobacterial populations [29]. This positive feedback loop explains the dramatic cyanobacterial expansion observed in eutrophic systems despite similar temperature increases across all study sites.

4.2 Decline of Sensitive Algal Taxa

The progressive decline of diatoms and sensitive chlorophytes under warming conditions represents a critical biodiversity loss with cascading ecosystem consequences. Diatoms, characterized by siliceous frustules and high nutritional quality, constitute preferred food sources for zooplankton grazers [30]. Their replacement by cyanobacteria, many of which produce toxins and have poor nutritional value, disrupts energy transfer to higher trophic levels and can compromise entire food webs.

Several mechanisms underlie diatom decline. Elevated temperatures exceed optimal growth ranges for many temperate diatom species (typically 15-25°C). Increased stratification reduces silica availability in surface waters, as this essential nutrient becomes trapped in deeper layers. Additionally, cyanobacterial allelopathy directly inhibits diatom growth through production of bioactive compounds. The combined effect produces community simplification, with Shannon diversity indices declining from >3.0 in diatom-dominated assemblages to <2.0 in cyanobacteria dominated systems.

4.3 Subaerial Algae: Climate-Resilient Primary Producers

The remarkable stability of subaerial algal communities, particularly Trentepohlia, under climate stress contrasts sharply with aquatic system vulnerability. This resilience derives from evolutionary adaptations to terrestrial environments characterized by extreme temperature fluctuations, desiccation stress, and high irradiance [31]. High carotenoid:chlorophyll ratios (often >10:1) provide dual functions of photoprotection and thermal stress mitigation through non-photochemical energy dissipation.

Trentepohlia exhibits metabolic flexibility, capable of heterotrophic nutrition during unfavorable photosynthetic conditions. Thick mucilaginous sheaths and specialized cell wall structures minimize water loss during drought periods. Rapid rehydration and metabolic activation following rainfall enable efficient exploitation of transient favorable conditions typical of monsoon climates.

However, subaerial algae face distinct climate threats. Prolonged droughts combined with temperature increases may exceed tolerance thresholds even for adapted species. Altered rainfall patterns disrupting seasonal humidity regimes could shift competitive balances among subaerial algal taxa. Furthermore, extreme weather events including intense storms and heat waves may cause catastrophic biomass loss from substrate surfaces.

4.4 Eutrophication-Climate Change Interactions

The compounding effects of nutrient pollution and climate change represent a critical management challenge for tropical Indian freshwater systems [32]. Anthropogenic nutrient loading from agricultural runoff, domestic sewage, and industrial effluents has progressively eutrophied water bodies across India. Climate change amplifies these impacts through multiple pathways.

Altered precipitation patterns, characterized by intense rainfall events separated by prolonged dry periods, enhance nutrient mobilization from watersheds during storm events while concentrating nutrients in water bodies during dry phases. Warming temperatures accelerate organic matter decomposition, releasing nutrients previously sequestered in sediments. Reduced river flows during droughts decrease dilution capacity, elevating nutrient concentrations. Simultaneously, warming directly stimulates primary production and nutrient uptake rates, creating ideal conditions for algal bloom formation.

Breaking this synergy requires integrated management approaches targeting both nutrient source control and climate adaptation strategies. Conventional wastewater treatment focusing solely on nutrient removal proves insufficient if climate-enhanced internal loading and altered hydrological regimes continue driving eutrophication.

4.5 Predictive Insights and Future Trajectories

Statistical relationships identified through PCA and correlation analyses enable preliminary predictions of algal community responses under projected climate scenarios. Regional climate models project temperature increases of 1.5-2.5°C and rainfall reductions of 8-15% across tropical India by 2050 under moderate emission scenarios [33]. Applying these projections to empirical relationships suggests:

Aquatic systems:

Cyanobacterial bloom frequency and duration will increase by 40-60% in eutrophic systems, with bloom seasons extending from 3-4 months to 6-8 months annually. Oligotrophic systems may transition toward mesotrophic status through climate-enhanced nutrient recycling, even without increased external loading. Diatom diversity will decline by 25-40% as thermal optima are exceeded. Emergence of tropical cyanobacterial species currently restricted to warmer regions may occur through range expansion.

Subaerial systems:

Trentepohlia distributions may contract in regions experiencing severe drought intensification, particularly Western Ghats rain shadow areas. Conversely, range expansion into currently cooler Himalayan regions may occur as temperatures rise. Community composition may shift toward more drought-tolerant taxa including certain Chlorococcales and xerophytic cyanobacteria.

4.6 Ecological and Societal Implications

Climate-driven algal shifts carry profound implications for ecosystem services and human welfare. Cyanobacterial bloom proliferation threatens drinking water safety through toxin production (microcystin, anatoxin, cylindrospermopsin), requiring expensive treatment interventions [34]. Recreational water use becomes hazardous during bloom periods, with health risks including dermatotoxicity, hepatotoxicity, and neurotoxicity. Aquaculture operations suffer fish kills and product contamination, causing economic losses.

Biodiversity consequences extend beyond algae themselves. Altered algal community structure affects entire food webs, potentially leading to shifts in zooplankton, fish, and waterbird communities. Loss of clear-water, diatom-dominated states may represent regime shifts difficult to reverse even if climate or nutrient conditions improve. Cultural ecosystem services including aesthetic values and spiritual significance of clear lakes and historically significant monuments degraded by algal biofilms suffer impairment.

4.7 Research Gaps and Future Directions

Despite growing knowledge, critical gaps remain in understanding climate-algal diversity relationships in tropical Indian ecosystems. Long-term monitoring programs (>10 years) integrating climate, water quality, and biological data across representative water body types are urgently needed. Molecular approaches including metabarcoding and metagenomics would reveal cryptic diversity and functional gene responses invisible to morphological surveys.

Experimental research examining threshold responses, tipping points, and recovery dynamics under simulated climate scenarios remains limited. Mechanistic understanding of cyanobacterial toxin production responses to climate drivers requires expansion. The role of biotic interactions including allelopathy, grazing, and viral lysis in mediating climate effects deserves greater attention.

Comparative studies of subaerial versus aquatic algae remain remarkably scarce. Given their contrasting resilience patterns, subaerial algae may serve as climate refugia and diversity reservoirs during aquatic system degradation. Their potential roles in ecosystem recovery following climate disturbances warrant investigation.

Conclusion

Climate change is fundamentally restructuring algal communities across tropical Indian freshwater ecosystems, with cascading consequences for biodiversity and ecosystem functioning. Rising temperatures, combined with altered precipitation patterns and humidity fluctuations, drive pronounced shifts toward cyanobacterial dominance in aquatic systems while threatening subaerial algal communities through drought intensification. The synergistic interaction between climate warming and anthropogenic eutrophication creates particularly severe impacts, accelerating harmful algal bloom proliferation beyond historical patterns.

Aquatic algal communities demonstrate high vulnerability to climate stress, characterized by rapid compositional shifts, diversity decline, and regime changes toward simplified, cyanobacteria-dominated states. Sensitive taxa including diatoms and temperate chlorophytes face progressive elimination as thermal optima are exceeded and competitive conditions favor thermophilic cyanobacteria. Subaerial algae exhibit greater resilience through physiological adaptations to terrestrial environments, yet face distinct threats from altered humidity regimes and extreme weather events.

Statistical analyses reveal temperature and nutrients as primary drivers of community variation, with humidity controlling subaerial algal dynamics. Principal Component Analysis and cluster approaches successfully segregate community states along climate-trophic gradients, enabling predictive modeling of future trajectories. Projections suggest substantial expansion of cyanobacterial bloom conditions and contraction of clear-water, diverse algal assemblages under continuing climate change.

Addressing these challenges requires integrated management combining climate mitigation, nutrient pollution control, and ecosystem-based adaptation strategies. Policy interventions must recognize the compounding nature of climate-eutrophication interactions, targeting both anthropogenic nutrient loading and climate resilience enhancement. Long-term monitoring, experimental research on climate thresholds, and comparative resilience assessments across aquatic and subaerial systems constitute critical research priorities.

The integration of both aquatic and subaerial algal responses represents a novel contribution advancing understanding of climate impacts across habitat types within tropical freshwater landscapes. This holistic perspective reveals differential vulnerability patterns essential for conservation prioritization and climate adaptation planning. As climate change intensifies, preserving algal diversity and ecosystem integrity in tropical Indian freshwater systems demands urgent, coordinated action spanning research, policy, and on-ground management interventions.

References

1. IPCC. (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
2. Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., Naiman, R. J.,
3. Prieur-Richard, A. H., Soto, D., Stiassny, M. L., & Sullivan, C. A. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews, 81(2), 163-182.
4. O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., Schneider, P., Lenters, J. D., McIntyre, P. B., Kraemer, B. M., Weyhenmeyer, G. A., Straile, D., Dong, B., Adrian, R., Allan, M. G., Anneville, O., Arvola, L., Austin, J., Bailey, J. L., Baron, J. S., Brookes, J. D., de Eyto, E., Dokulil, M. T., Hamilton, D. P., Havens, K., Hetherington, A. L., Higgins, S. N., Hook, S., Izmest'eva, L. R., Joehnk, K. D., Kangur, K., Kasprzak, P., Kumagai, M., Kuusisto, E., Leshkevich, G., Livingstone, D. M., MacIntyre, S., May, L., Melack, J. M., Mueller-Navarra, D. C., Naumenko, M., Noges, P., Noges, T., North, R. P., Plisnier, P. D., Rigosi, A., Rimmer, A., Rogora, M., Rudstam, L. G., Rusak, J. A., Salmaso, N., Samal, N. R., Schindler, D. E., Schladow, S. G., Schmid, M., Schmidt, S. R., Silow, E., Soylu, M. E., Teubner, K., Verburg, P., Voutilainen, A., Watkinson, A., Williamson, C. E., & Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. Geophysical Research Letters, 42(24), 10773-10781.

5. Paerl, H. W., & Paul, V. J. (2012). Climate change: Links to global expansion of harmful cyanobacteria. Water Research, 46(5), 1349-1363.
6. Litchman, E., & Klausmeier, C. A. (2008). Trait-based community ecology of phytoplankton. Annual Review of Ecology, Evolution, and Systematics, 39, 615-639.
7. Yvon-Durocher, G., Montoya, J. M., Trimmer, M., & Woodward, G. (2011). Warming alters the size spectrum and shifts the distribution of biomass in freshwater ecosystems. Global Change Biology, 17(4), 1681-1694.
8. Huisman, J., Codd, G. A., Paerl, H. W., Ibelings, B. W., Verspagen, J. M., & Visser, P. M. (2018). Cyanobacterial blooms. Nature Reviews Microbiology, 16(8), 471-483.
9. Visser, P. M., Verspagen, J. M., Sandrini, G., Stal, L. J., Matthijs, H. C., Davis, T. W., Paerl, H. W., & Huisman, J. (2016). How rising CO_2 and global warming may stimulate harmful cyanobacterial blooms. Harmful Algae, 54, 145-159.
10. Nimma, D., Rao, D. S., Radhakrishna, I., & Kumar, J. A. (2025). Implications of climate change on freshwater ecosystems and aquatic biodiversity. Aquatic Ecology, 59(1), 85-102.
11. Kothawale, D. R., & Rupa Kumar, K. (2005). On the recent changes in surface temperature trends over India. Geophysical Research Letters, 32(18), L18714.
12. Guhathakurta, P., Sreejith, O. P., & Menon, P. A. (2011). Impact of climate change on extreme rainfall events and flood risk in India. Journal of Earth System Science, 120(3), 359-373.
13. Sharma, R. C., Singh, N., & Chauhan, A. (2016). The influence of physico-chemical parameters on phytoplankton distribution in a head water stream of Garhwal Himalayas: A case study. Egyptian Journal of Aquatic Research, 42(1), 11-21.
14. Kumar, M., & Singh, R. (2025). Algal blooms threaten India's freshwater ecosystems under climate stress. Environmental Science and Pollution Research, 32(5), 7234-7248.
15. Bhat, S. U., Pandit, A. K., & Mushtaq, B. (2014). Influence of anthropogenic activity on the trophic status of Anchar lake in Kashmir Himalayas. Limnological Review, 14(3), 127-135.
16. Marin, V., Castro, L. R., Oerder, V., & Miranda, M. (2025). Relative effects of eutrophication and warming on freshwater ecosystems: A multi-level experimental approach. Environmental Research Letters, 20(2), 024018.
17. Rindi, F. (2007). Diversity, distribution and ecology of green algae and cyanobacteria in urban habitats. In J. Seckbach (Ed.), Algae and Cyanobacteria in Extreme Environments (pp. 619-638). Springer.
18. López-Bautista, J. M., Rindi, F., & Guiry, M. D. (2006). Molecular systematics of the subaerial green algal order Trentepohliales: An assessment based on morphological and molecular data. International Journal of Systematic and Evolutionary Microbiology, 56(7), 1709-1715.
19. Rindi, F., Lam, D. W., & López-Bautista, J. M. (2009). Phylogenetic relationships and species circumscription in Trentepohlia and Printzina (Trentepohliales, Chlorophyta). Molecular Phylogenetics and Evolution, 52(2), 329-339.
20. Thajuddin, N., & Subramanian, G. (2005). Cyanobacterial biodiversity and potential applications in biotechnology. Current Science, 89(1), 47-57.
21. Norris, A., & Chantanachat, S. (2020). Environmental factors affecting the diversity and photosynthetic pigments of Trentepohlia species in Northern Thailand's Chiang Dao Wildlife Sanctuary. Acta Societatis Botanicorum Poloniae, 89(1), Article 8912.
22. Paerl, H. W., Hall, N. S., & Calandrino, E. S. (2011). Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. Science of the Total Environment, 409(10), 1739-1745.
23. Wetzel, R. G., & Likens, G. E. (2000). Limnological Analyses (3rd ed.). Springer-Verlag.
24. APHA. (2017). Standard Methods for the Examination of Water and Wastewater (23rd ed.). American Public Health Association.
25. Bellinger, E. G., & Sigee, D. C. (2015). Freshwater Algae: Identification, Enumeration and Use as Bioindicators (2nd ed.). Wiley-Blackwell.
26. Guiry, M. D., & Guiry, G. M. (2024). AlgaeBase. World-wide electronic publication, National University of Ireland, Galway. https://www.algaebase.org
27. Qi, L., Hu, C., Mikelsons, K., Wang, M., Lance, V., Sun, S., Barnes, B. B., Zhao, J., & Van der Zande, D. (2025). Global floating algae blooms are expanding. Nature Communications, 16, Article 1247.
28. O'Neil, J. M., Davis, T. W., Burford, M. A., & Gobler, C. J. (2012). The rise of harmful cyanobacteria blooms: The potential roles of eutrophication and climate change. Harmful Algae, 14, 313-334.
29. Vasilakou, K., Stylianou, K. S., & Hauschild, M. Z. (2025). Global spatiotemporal characterization factors for freshwater eutrophication under climate change scenarios. Science of the Total Environment, 918, 170156.

30. Woolway, R. I., & Merchant, C. J. (2019). Worldwide alteration of lake mixing regimes in response to climate change. Nature Geoscience, 12(4), 271-276.
31. Sommer, U., Adrian, R., De Senerpont Domis, L., Elser, J. J., Gaedke, U., Ibelings, B., Jeppesen, E., Lürling, M., Molinero, J. C., Mooij, W. M., van Donk, E., & Winder, M. (2012). Beyond the Plankton Ecology Group (PEG) Model: Mechanisms driving plankton succession. Annual Review of Ecology, Evolution, and Systematics, 43, 429-448.
32. Holzinger, A., & Karsten, U. (2013). Desiccation stress and tolerance in green algae: Consequences for ultrastructure, physiological and molecular mechanisms. Frontiers in Plant Science, 4, Article 327.
33. Sharabian, M. N., Taheriyoun, M., & Akhavan, M. (2018). Climate change and eutrophication: A short review. Engineering, Technology & Applied Science Research, 8(6), 3668-3672.
34. Krishnan, R., Sanjay, J., Gnanaseelan, C., Mujumdar, M., Kulkarni, A., & Chakraborty, S. (2020). Assessment of Climate Change over the Indian Region: A Report of the Ministry of Earth Sciences (MoES), Government of India. Springer Nature.
35. Ibelings, B. W., & Chorus, I. (2007). Accumulation of cyanobacterial toxins in freshwater "seafood" and its consequences for public health: A review. Environmental Pollution, 150(1), 177-192.

36. Ali S., Li Y., Haq I. U., Abbas W., Shabbir M. Z., Khan M. M., Mamay M., Niaz Y., Farooq T., Skalicky M. and Zuan A. T. K. (2021). The impact of different plant extracts on population suppression of Helicoverpa armigera (Hub.) and tomato (Lycopersicon esculentum Mill) yield under field conditions. PloS One. 16(12):0260470.
37. Arumugam E., Muthusamy B., Dhamodaran K., Thangarasu M., Kaliyamoorthy K. and Kuppusamy E. (2015). Pesticidal activity of Rivina humilis L. (Phytolaccaceae) against important agricultural polyphagous field pest, Spodoptera litura (Fab.) (Lepidoptera: Noctuidae). Journal of Coastal Life Medicine. 3(5):389-394.
38. Baidoo P. K., Adu E. and Peprah S. (2017). The role of ethanolic extracts of leaves and roots of Lantana camara (L.) in the management of pests of okra Abelmoschus esculentus (L.) Moench. Advances in Entomology. 5:99-108.
39. Bilal T., Sofi P. A., Gangoo S. A., Ahad I., Mir S. A., Zaffar S. N. and Gulzar H. (2024). Phytochemical analysis and insecticidal potential of pyrethrum (Chrysanthemum cinerariaefolium) extracts: A sustainable approach to pest management.International Journal of Advanced Biochemistry Research. 8(5): 407-410.
40. Chakraborty N., Mitra R., Pal S., Ganguly R., Acharya K., Minkina T., Sarkar A. and Keswani C. (2023). Biopesticide consumption in India: Insights into the current trends. Agriculture. 13:557.
41. Dash L., Rout S., Mishra U., Sahoo G. and Prusty A. (2022). Insecticidal genes in pest management. Annals of the Romanian Society for Cell Biology. 25(6):5601 – 5608.
42. Dhale D. A. (2013). Plants Used for insect and pest control in North Maharashtra, India. The Journal of Ethnobiology and Traditional Medicine. 118: 379-388.
43. Duraipandiyan L. V., Ignacimuthu G. and Paulraj G. M. (2011). Antifeedant and larvicidal activities of Rhein isolated from the flowers of Cassia fistula. Saudi Journal of Biological Sciences.18:129–133.
44. Fowsiya J. and Madhumitha G. (2020). A review of bioinsecticidal activity and mode of action of plant derived alkaloids. Research Journal of Pharmacy and Technology. 13(12):963-973.
45. Gorawade V. B., Attar U. A. and Shiragave P. D. (2021). Insecticidal potential and thin layer chromatographic profiling of Chromolaena odorata L. and Leonotis nepetifolia (L) R. Br. leaf extracts against Helicoverpa armigera (Hubner). International Journal of Entomology Research. 6(2):46-5.
46. Gorawade V., Attar U. and Shiragave P. (2022). Bioefficacy and GC -MS analysis of Chromolaena odorata and Leonotis nepetifolia leaf extracts against Spodoptera litura. Journal of Crop Protection. 11 (3): 361 – 375.
47. Jeyasankar A., T. Chinnamani, V. Chennaiyan, G. Ramar and Arignar A., (2014). Antifeedant activity of Barleria buxifolia (Linn.) (Acanthaceae) against Spodoptera litura Fabricius And Helicoverpa armigera Hübner (Lepidotera:Noctuidae). International Journal of Natural Sciences Research. 2(5): 78-84.
48. Jose S. and Sujatha K. (2017). Antifeedant activity of different solvent extracts of Gliricidia sepium against third instar larvae of Helicoverpa armigera (Hubner) (Lepidoptera: Noctuidae). International Journal of Advanced Research in Biological Sciences. 4(4): 201-204.

49. Kamaraj C., Rahuman A. A. and Bagavan A. (2008). Antifeedant and larvicidal effects of plant extracts against Spodoptera litura (F.), Aedes aegypti L. and Culex quinquefasciatus Say. Parasitology Research. 103(2):325-331. DOI: 10.1007/s00436-008-0974-8.
50. Khan S., Taning C., Bonneure E., Mangelinckx S., Smagghe G. and Shah M. (2017). Insecticidal activity of plant-derived extracts against different economically important pest insects. Phytoparasitica. 45:113–124.
51. Kulshreshtha A. and Saxena J. (2019). Alkaloids and non alkaloids of Tabernaemontana divaricata. International Journal of Research & Review. 6(8):517-524.
52. Mohan B., Prabha D. and Bhuvaneshwari C. (2024). Phytochemical characteristics and insecticidal activity of Sida acuta (Burm. f.) against Sitophilus oryzae (L.). Russian Agricultural Sciences. 50(1): 53-58.
53. Mwangi R. W. and Rembold H. (1987). Growth regulating activity of Melia volkensii extracts against the larvae of Aedes aegypti. In: Proceedings of third International Neem Conference. 1986:669–681.
54. Okwute S. K. (2012). Plants as potential sources of pesticidal agents: a review. Pesticides–Advances in chemical and botanical pesticides. 10: 208-232.
55. Pavunraj M., Rajeshkumar S. and Ignacimuthu S. (2024). Antifeedant activity of crude extract and fractiolns isolated from Cymodocea serrulate (R.Br.) leaf against tobacco caterpillar Spodoptera litura (Fab.) Lepidoptera: Noctuidae. Uttar Pradesh Journal of Zoology. 45(12):25-30.
56. Periyanayagam K., Dhanalakshmi Karthikeyan V. and Jagadeesan M. (2013). Phytochemical studies and GC/MS analysis on the isolated essential oil from the leaves of Citrus aurantium Linn. Journal of Natural Products and Plant Resources. 3 (6):19-23.
57. Reddy A. A., Reddy M. and Mathur V. (2024). Pesticide use, regulation, and policies in Indian agriculture. Sustainability. 16(17):7839.
58. Sedek M. M. (2003). Antifeedant and toxic activity of Adhatoda vasica leaf extract against Spodoptera littoralis (Lepidoptera: Noctuidae). Journal of Applied Entomology. 27: 396-404.
59. Senthil-Nathan S. (2013). Physiological and biochemical effect of neem and other Meliaceae plants secondary metabolites against Lepidopteran insects. Frontiers in Physiology. 4:359.
60. Sharma C., Jawalkar N., Patil G. and Jaiswal D. (2023). Bioefficacy of Nerium oleander leaf extract on the growth of Heliothis armigera H. (Lepidoptera: Noctuidae). Journal of Entomology and Zoology Studies. 11(6): 95-98.
61. Shiragave P. D. (2020). Phytochemical characterization, ovicidal and larvicidal potential of Pentanema indica against Spodoptera litura. International Journal of Entomology Research. 5(6):239-243.
62. Singh A. D. (2021). Bio-Efficacy of phyto-pesticides against major insect- pest of organically grown tomato. International Journal of Current Microbiology and Applied Sciences. 10 (05): 524-537.
63. Singh L. and Kumar V. (2021). Need of biopesticides triumph over chemical pesticides. International Journal of Current Microbiology and Applied Sciences. 10(01):93-101.
64. Sinha N. and Ray S. (2024). The potential of ginger (Zingiber officinale Rosc.) extracts as a bio-pesticide. Journal of Entomology and Zoology Studies. 12(3): 38-45.
65. Sivakumar R., Jebanesan A., Govindarajan M. and Rajasekar P. (2011). Larvicidal and repellent activity of tetradecanoic acid against Aedes aegypti (Linn.) and Culex quinquefasciatus (Say.) (Diptera: Culicidae). Asian Pacific journal of tropical medicine. 4(9):706-710.
66. Sjam S., Rosmana A., Vien S. D., Sulaeha T., Agung F. and Adhyaksa H. (2023). Insecticidal activity of fermented Calatropis gigantea L and Crescentea cujete L. extract combination against rice pests and natural enemies. Earth and Environmental Science. 1208(1):012026.
67. Tembo Y., Mkindi A. G., Mkenda P. A., Mpumi N., Mwanauta R., Stevenson P. C., Ndakidemi P. A. and Belmain S. R. (2018). Pesticidal plant extracts improve yield and reduce insect pests on egume crops without harming beneficial arthropods. Frontiers in Plant Science. 9:1425.
68. Thushimenan S., Baskaran J., Baranitharan M. and Jeyasankar A. (2016). Laboratory Investigation of Terminalia arjuna and Trachyspermum roxburghianum against Groundnut Pest, Helicoverpa armigera. Asian Journal of Pharmaceutical and Clinical Research. 9(1):232-236.
69. Tridiptasari A., Leksono A. S. and Siswanto D. (2019) Antifeedant effect of Moringa oleifera (L.) leaf and seed extract on growthand feeding activity of Spodoptera litura (Fab.) (Lepidoptera: Noctuidae).Journal of Experimental Life Science. 9(1): 2019.
70. Tura A. M., Belay H. K. & Merga H. (2015). Physiochemical characterization and evaluation of insecticidal activities of Delonix regia seed oil against termite (Odontotermes obesus), ticks (Ixodes scapularis) and cockroach (Blattella germanica). Journal of Natural Sciences Research. 5(15): 40-46.

71. Ugwu J. A., Bobadoye B. C. and Aluko O. J. (2022). Bioassay of aqueous extracts from six tropical plants against Tribolium castaneum (Coleoptera: Tenebrionidae). Nigerian Agricultural Journal. 53(3).
72. Ullah S., Gul J., Farzana G., Khan S., Khattak M., Sher J. and bibi H., (2018). Antifungal and phytochemical screening of selected medicinal plants of Malamjaba, Swat, Pakistan. The Pharma Innovation Journal. 7(5): 176-182.
73. Ushie O. A., Aikhoje E. F., Aasegh T. J., Ibrahim A. I., Bako B. and Ettah A. O. (2022). Estimation of total alkaloids, saponins flavonoid, tannins and phenols in Thaumatococcus Danielli leaves. World journal of pharmaceautical and medical research. 8(4):242-246.
74. Vetal D. S. and Pardeshi A. B. (2019). Larvicidal potential of Argemone mexicana L. Plant extracts against Spodoptera litura fab. The Pharma Innovation Journal. 8(6): 698-702
75. Yankanchi S. R. and Patil S. R. (2010). Field efficacy of plant extracts on larval populations of Plutella xylostella L. and Helicoverpa armigera Hub. and their impact on cabbage infestation. Journal of Biopesticides. 2(1):32-36.