

Plankton Ecology in the Philippines: Diversity, Dynamics, and Ecological Significance Across Tropical Marine and Freshwater Ecosystems

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ABSTRACT: Plankton communities in the Philippines occupy a critical ecological position in one of the world's most biologically diverse marine regions. Situated within the Coral Triangle and traversed by the Western Pacific Warm Pool, Philippine waters support extraordinary phytoplankton and zooplankton assemblages that regulate primary production, mediate carbon fluxes, and sustain the productivity of pelagic and coastal fisheries. Yet these communities are shaped by complex interactions among the Southwest and Northeast Monsoons, seasonal upwelling, El Niño–Southern Oscillation (ENSO) events, eutrophication, and the proliferation of harmful algal blooms (HABs), particularly *Pyrodinium bahamense* var. *compressum* causing paralytic shellfish poisoning across coastal provinces. This review synthesizes published knowledge on phytoplankton diversity, zooplankton assemblage structure, HAB ecology, nutrient–plankton interactions, and the roles of plankton in biogeochemical cycles within Philippine marine and freshwater ecosystems. We further evaluate the impacts of eutrophication in enclosed bays such as Manila Bay and Laguna de Bay, coastal upwelling dynamics in the Visayas and Mindanao Seas, meroplankton contributions to larval connectivity, and emerging threats from climate change and land-based pollution. Knowledge gaps, monitoring priorities, and research directions including molecular approaches, autonomous sensing, and citizen science are identified. Integrative and long-term ecological research on Philippine plankton is urgently needed to support evidence-based marine spatial planning, fisheries management, and coastal conservation policy.

KEYWORDS: Plankton communities; critical ecological position; phytoplankton diversity; Philippine archipelago

1. Introduction

The Philippine archipelago, comprising 7,641 islands spread across approximately 300,000 km² of seas, constitutes one of the most species-rich marine environments on Earth. Positioned within the Coral Triangle, a region recognized as the global epicentre of marine biodiversity, Philippine waters harbor exceptional diversity across all trophic levels, from microscopic plankton to apex predators. Plankton, defined broadly as organisms whose horizontal motion

is overwhelmingly governed by water currents rather than self-propulsion, constitute the foundational tier of aquatic food webs and are central to virtually every major biogeochemical cycle operating in the ocean [1–4]. Phytoplankton account for approximately half of global net primary production, fixing dissolved inorganic carbon through photosynthesis and channelling organic matter into marine food webs. In Philippine coastal and oceanic waters, phytoplankton community composition and biomass fluctuate in response to seasonal shifts between the Northeast Monsoon (*amihan*) and Southwest Monsoon (*habagat*), typhoon passages, riverine nutrient inputs, and coastal upwelling driven by wind forcing and complex bathymetric topography [5–8]. These dynamics determine whether waters support productive fisheries or tip into conditions that favor harmful algal bloom formation [1, 6, 9].

The ecological and socioeconomic consequences of HABs in the Philippines have been severe. Recurrent blooms of the toxic dinoflagellate *Pyrodinium bahamense* var. *compressum* have caused mass mortalities of bivalves, fish kills, and hundreds of human fatalities from paralytic shellfish poisoning (PSP) since the 1980s, affecting both subsistence fishing communities and the commercial shellfish industry. Despite decades of monitoring by the Bureau of Fisheries and Aquatic Resources (BFAR) and the Philippine Coast Guard, ecological understanding of bloom initiation, persistence, and termination remains incomplete, partly due to limitations in spatiotemporal sampling resolution [8–11].

Zooplankton, encompassing copepods, chaetognaths, medusae, euphausiids, appendicularians, and meroplanktonic larvae, function as critical trophic intermediaries transferring energy from phytoplankton to fish stocks [3, 10, 11–18]. In Philippine waters, copepods typically dominate holoplankton biomass, with community composition varying strongly across shelf-to-offshore gradients, between enclosed bays and open seas, and seasonally with monsoon-driven mixing [11, 13, 15]. Meroplankton, the temporary zooplankton comprising larval stages of benthic invertebrates and reef fish, are ecological gatekeepers of community recruitment and population connectivity across the archipelago's mosaic of habitats [19–21].

Freshwater ecosystems are equally important. Laguna de Bay, the largest lake in the Philippines and Southeast Asia's third largest, provides an inland counterpart to marine plankton studies, with phytoplankton succession closely linked to nutrient loading from aquaculture, urban runoff, and seasonal water level changes [2, 22–27]. Shallow coastal lagoons, river mouths, and fishponds throughout the archipelago further extend the ecological relevance of plankton research to aquaculture productivity, water quality management, and public health [28–30].

Despite the ecological and economic importance of plankton in the Philippines, integrative reviews that connect taxonomic diversity, ecosystem type, environmental forcing, biogeochemical function, anthropogenic pressure, and monitoring remain limited. Existing Philippine syntheses have tended to concentrate on particular problems or settings, especially harmful algal blooms, selected coastal systems, or individual plankton groups, while evidence from freshwater ecosystems and cross-ecosystem comparisons remains comparatively fragmented. The present review addresses this gap by jointly examining phytoplankton, zooplankton, and meroplankton across marine, coastal, estuarine, reservoir, and lake environments and by linking their ecological patterns to monsoon variability, upwelling, nutrient enrichment, HAB development, trophic transfer, and climate-related change. This integrated perspective is intended to move beyond a catalogue of individual studies toward a

comparative understanding of how different Philippine aquatic environments regulate plankton dynamics and how that knowledge can inform monitoring, fisheries management, and conservation [31–33, 41–43]. Figure 1 provides the conceptual basis for the review. Environmental forcing and human pressures act simultaneously on plankton communities, altering composition, abundance, productivity, and bloom risk. These community-level responses subsequently influence food-web transfer, fisheries productivity, and carbon and nutrient cycling. The framework also emphasizes a management feedback: improved monitoring of plankton and environmental conditions can strengthen HAB early warning, ecosystem assessment, and adaptive fisheries and conservation decisions.

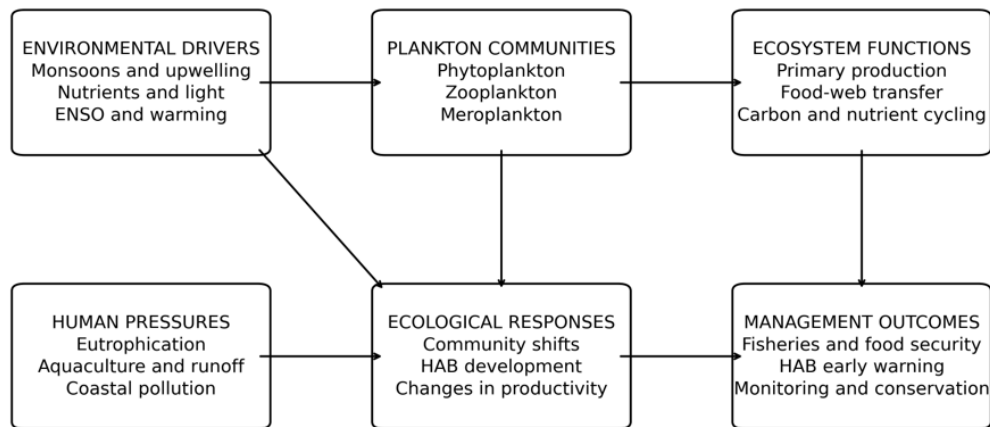


Figure 1. Conceptual Framework Linking Environmental Drivers and Human Pressures with Plankton Community Responses, Ecosystem Functions, and Management Outcomes in Philippine Aquatic Ecosystems.

2. Phytoplankton Diversity and Community Dynamics

2.1. Taxonomic Composition and Species Richness.

Philippine phytoplankton communities are dominated by diatoms (Bacillariophyta) and dinoflagellates (Dinoflagellata), with cyanobacteria, haptophytes, and chlorophytes contributing substantially in estuarine and freshwater environments [5, 7]. The relative dominance of these groups reflects differences in nutrient availability, water-column stability, salinity, light conditions, and hydrodynamic processes. Diatoms generally benefit from nutrient-rich and well-mixed conditions because their relatively rapid growth enables them to respond quickly to pulses of nitrogen and other nutrients. Dinoflagellates, in contrast, can become increasingly important under more stratified conditions, where their motility provides an advantage in accessing vertically separated light and nutrient resources. Consequently, changes in the relative abundance of these major groups can provide useful indications of shifts in environmental conditions and ecosystem productivity.

Coastal waters generally support greater phytoplankton richness than offshore oligotrophic waters because they receive nutrients from river discharge, terrestrial runoff, sediment resuspension, and coastal circulation. At the same time, the physical heterogeneity of bays, estuaries, reefs, and nearshore waters creates a wide range of ecological niches. Across the Zamboanga Peninsula, more than 80 phytoplankton genera have been recorded, with *Chaetoceros*, *Coscinodiscus*, *Rhizosolenia*, and *Ceratium* among the most frequently encountered [7]. This taxonomic diversity is ecologically important because different phytoplankton groups vary in cell size, nutrient requirements, sinking characteristics, and food quality for zooplankton. Community composition therefore influences not only primary

productivity but also the efficiency with which phytoplankton production is transferred to zooplankton, fish larvae, and higher trophic levels.

As summarized in Table 1, phytoplankton diversity in the Philippines is consequently regulated by interacting processes operating across multiple temporal and spatial scales. Monsoon circulation, typhoons, nutrient enrichment, ENSO variability, and regional oceanographic circulation influence not only species composition but also productivity, bloom development, and trophic transfer. Considering these drivers together provides a stronger basis for interpreting differences among Philippine coastal, oceanic, estuarine, and freshwater environments.

Table 1. Key Patterns of Phytoplankton Diversity and Environmental Regulation in Philippine Waters.

Theme	Key Findings	Ecological Significance	References
Taxonomic Composition and Diversity	Diatoms and dinoflagellates dominate Philippine waters, while cyanobacteria and other groups contribute in estuarine and freshwater habitats. Coastal regions exhibit the highest species richness, with over 80 genera recorded in Zamboanga waters.	Supports primary productivity, biodiversity, and food-web stability.	[5, 7, 25]
Monsoon-Driven Variability	Northeast Monsoon enhances mixing and diatom abundance, whereas Southwest Monsoon upwelling supplies nutrients that stimulate phytoplankton blooms.	Regulates seasonal productivity and fisheries resources.	[8, 15, 34–39]
Typhoon Effects	Typhoons disrupt stratification and increase nutrient availability, causing short-term bloom events.	Creates episodic productivity pulses and ecosystem fluctuations.	[15, 39]
Nutrient Enrichment and Eutrophication	Nutrient availability and N:P ratios strongly influence community composition. Urban and riverine inputs promote eutrophication-adapted taxa in coastal bays.	Alters species dominance and increases bloom potential.	[28, 29]
ENSO and Climate Variability	El Niño suppresses upwelling and reduces productivity, whereas La Niña enhances runoff, productivity, and harmful algal bloom risk.	Controls interannual ecosystem productivity and bloom occurrence.	[8, 19, 25, 28]
Oceanographic Influence	Indonesian Throughflow and regional circulation shape distinct phytoplankton assemblages in the Sulu and Celebes Seas.	Determines species distribution and regional biogeographic patterns.	[25]

2.2. Seasonal and Monsoon-Driven Variability.

Monsoon seasonality is the primary structuring force of phytoplankton biomass and composition across Philippine coastal seas [8, 15, 34–39]. During the Northeast Monsoon (November–February), enhanced mixing and cooler sea surface temperatures promote diatom dominance and elevated chlorophyll-*a* concentrations in upwelling-influenced regions off Mindanao and western Visayas. The Southwest Monsoon (June–October) drives upwelling along Zamboanga Peninsula, delivering deep nutrient-rich water that temporarily sustains phytoplankton blooms before stratification redevelops. Typhoon passages disrupt thermal stratification episodically, injecting nutrients and triggering short-lived bloom events with significant but poorly quantified biogeochemical impacts [15, 39].

2.3. Environmental Drivers: Nutrients, Light, and El Niño.

Nutrient stoichiometry, especially the ratio of dissolved inorganic nitrogen to phosphorus, shapes phytoplankton community structure in enclosed Philippine bays [28, 29]. Manila Bay receives substantial anthropogenic nitrogen loading from the Pasig River and direct urban discharge, shifting phytoplankton toward eutrophication-adapted taxa during wet season peaks. ENSO warm events suppress upwelling and deepen the thermocline, reducing phytoplankton

productivity across much of the archipelago and diminishing fishery yields. Conversely, La Niña periods are associated with enhanced rainfall, river discharge, and coastal productivity, but also with increased HAB risk in susceptible embayments [8, 19, 25, 28]. Recent Philippine freshwater evidence reinforces the importance of ecosystem-specific physical controls. In Pantabangan Reservoir, littoral phytoplankton and zooplankton communities varied horizontally and vertically, with trophic interactions and light availability contributing to community patterns [42]. In Lake Yambo, seasonal stratification during the Southwest Monsoon and mixing during the Northeast Monsoon reorganized vertical nutrient availability and phytoplankton functional groups, demonstrating that monsoon effects in inland waters can operate through water-column structure rather than coastal upwelling [43]. These findings illustrate why marine and freshwater plankton responses should not be treated as ecologically interchangeable.

3. Zooplankton Assemblage Structure and Trophic Roles

3.1. Copepod diversity and spatial distribution.

Copepods represent the most numerically dominant and functionally significant zooplankton group in Philippine waters, typically comprising 60–85% of total mesozooplankton abundance [10, 11, 38]. Calanoida, Cyclopoida, and Harpacticoida are all represented, with calanoids dominating shelf assemblages. Copepod species richness increases from enclosed bays to open shelf and oceanic environments, correlating with water mass characteristics and prey availability. Panguil Bay, a semi-enclosed coastal inlet in Mindanao, exhibits high temporal variability in copepod dominance linked to freshwater influx and organic enrichment from surrounding aquaculture [10–15].

3.2. Vertical migration, diel patterns, and grazing.

Diel vertical migration (DVM) is a widespread behavioral strategy among Philippine zooplankton, with copepods, euphausiids, and chaetognaths descending to mesopelagic depths during daylight and ascending to surface layers at night to feed [18, 33]. This migration has profound implications for the biological carbon pump, as organisms feed in surface waters and respire or defecate at depth, effectively transferring fixed carbon to the deep ocean [18]. Microzooplankton grazing, primarily by ciliates and heterotrophic dinoflagellates, accounts for a major fraction of phytoplankton mortality in tropical oligotrophic waters typical of Philippine oceanic environments, often exceeding the contribution of mesozooplankton [13].

3.3. Meroplankton and larval connectivity.

Meroplanktonic larvae of reef fish, bivalves, gastropods, echinoderms, and polychaetes constitute a numerically important and ecologically significant component of Philippine zooplankton communities [31]. Their abundance and diversity reflect the health of adjacent benthic communities, particularly coral reefs, seagrass beds, and mangroves, and govern recruitment dynamics [16, 17]. In the Visayas Sea, meroplankton abundance peaks during the Northeast Monsoon, coinciding with reduced turbulence and enhanced larval survival [31]. Connectivity patterns inferred from oceanographic modelling suggest that the Philippine Sea and Sibuyan Sea serve as critical nursery grounds for reef fish populations distributed across the archipelago [3, 31]. Summary of the diversity, distribution, behavioral ecology, and trophic

roles of zooplankton communities in Philippine waters is shown in Table 2. The table highlights dominant copepod assemblages, diel vertical migration patterns, grazing processes, meroplankton dynamics, and larval connectivity, emphasizing their importance in marine food webs, carbon cycling, ecosystem productivity, and population recruitment across the Philippine archipelago.

Table 2. Zooplankton Assemblage Structure and Trophic Roles in Philippine Waters.

Aspect	Key Findings	Ecological Significance	References
Copepod diversity and spatial distribution	Copepods constitute approximately 60–85% of total mesozooplankton abundance in Philippine waters. Calanoida, Cyclopoida, and Harpacticoida are present, with calanoids dominating shelf ecosystems. Species richness generally increases from enclosed bays to open shelf and oceanic waters.	Copepods are the principal link between phytoplankton production and higher trophic levels, supporting fish larvae and pelagic food webs. Spatial variability reflects environmental gradients, water mass characteristics, and prey availability.	[10, 11, 38]
Copepod dynamics in Panguil Bay	High temporal variability in copepod community composition and dominance is observed in Panguil Bay, influenced by freshwater inputs and organic enrichment from aquaculture activities.	Indicates strong sensitivity of zooplankton communities to anthropogenic influences and environmental fluctuations in semi-enclosed coastal systems.	[10–15]
Diel vertical migration (DVM)	Copepods, euphausiids, and chaetognaths migrate to deeper waters during daylight and return to surface waters at night for feeding.	Enhances predator avoidance and contributes significantly to the biological carbon pump through vertical transport of organic carbon.	[18, 33]
Microzooplankton grazing	Ciliates and heterotrophic dinoflagellates account for a substantial proportion of phytoplankton consumption in oligotrophic tropical waters, often exceeding mesozooplankton grazing.	Regulates phytoplankton biomass, nutrient recycling, and energy transfer within microbial food webs.	[13]
Meroplankton abundance and diversity	Larvae of reef fishes, bivalves, gastropods, echinoderms, and polychaetes form an important component of zooplankton assemblages.	Reflects the condition of adjacent coral reefs, seagrass meadows, and mangrove ecosystems while supporting recruitment processes.	[16, 17, 31]
Seasonal variation in meroplankton	Meroplankton abundance in the Visayas Sea peaks during the Northeast Monsoon when reduced turbulence enhances larval survival.	Seasonal recruitment pulses influence population replenishment and fisheries productivity.	[31]
Larval connectivity and dispersal	Oceanographic modelling identifies the Philippine Sea and Sibuyan Sea as important nursery and dispersal areas for reef fish larvae.	Supports population connectivity among marine ecosystems and informs marine conservation and fisheries management strategies.	[3, 31]

4. Harmful Algal Blooms: Ecology, Toxicology, and Impacts

4.1. Paralytic Shellfish Poisoning.

A toxin-producing dinoflagellate is the primary causative agent of paralytic shellfish poisoning (PSP) events in the Philippines and is regarded as one of the most socioeconomically damaging harmful algal bloom (HAB) organisms in Southeast Asia [23, 35]. Blooms preferentially develop in sheltered, semi-enclosed bays with restricted water exchange, warm temperatures ($>28^{\circ}\text{C}$), moderate salinities, and elevated phosphorus concentrations [8, 35]. Toxin accumulation in filter-feeding shellfish, particularly mussels and oysters, creates public health hazards that have resulted in government-mandated fishing bans affecting thousands of fishing households [6, 23]. The saxitoxins produced during these bloom events are among the most potent natural toxins known, with lethal doses estimated at less than $1\text{ }\mu\text{g}$ STX equivalents per kg body weight [37].

4.2. Diversity of HAB Species and Bloom Conditions.

Beyond the primary PSP-causing organism, Philippine waters are affected by a wide range of harmful algal bloom species, including toxin-producing dinoflagellates, cyanobacteria, and harmful diatoms [1, 5, 37]. Eutrophication in Bolinao, Pangasinan, associated with intensive fish-pen aquaculture, triggered a series of cyanobacterial and dinoflagellate blooms that caused mass mortality of juvenile cultured fish and substantial economic losses during the early 2000s [36]. Environmental factors such as light availability and temperature strongly regulate algal growth and toxin production, with higher toxicity often observed under nitrogen-limited but phosphorus-rich conditions [37]. More recent synthesis indicates that toxic algal blooms have expanded geographically in Philippine coastal waters and that PSP-causing taxa have been reported across a growing number of sites, with climate variability and warming increasingly considered alongside local eutrophication and hydrodynamic controls [41]. This evidence shifts the management question from documenting isolated bloom events toward understanding how chronic nutrient pressure and climate-related forcing may interact to alter bloom frequency, duration, and spatial extent.

4.3. Monitoring, Early Warning, and Regulatory Frameworks.

The Bureau of Fisheries and Aquatic Resources (BFAR) operates a national harmful algal bloom (HAB) monitoring network involving the weekly collection of shellfish tissue and seawater samples from more than 50 monitoring stations during the annual bloom season (April–November) [6]. This surveillance system plays an important role in protecting public health because HAB events can lead to rapid toxin accumulation in commercially important shellfish even when visible changes in water colour are absent. Routine monitoring therefore provides the evidence needed to issue shellfish advisories, impose temporary harvesting restrictions, and determine when affected areas can safely be reopened. Such measures are particularly important in coastal communities where shellfish harvesting and aquaculture contribute substantially to local food security and household income.

Conventional HAB surveillance relies on the identification and enumeration of potentially harmful phytoplankton together with direct measurements of toxins in seafood. Mouse bioassays and, increasingly, high-performance liquid chromatography (HPLC) coupled with tandem mass spectrometry are employed for toxin analysis [23]. These approaches provide complementary information: phytoplankton observations indicate changes in potentially harmful organisms in the water column, whereas toxin measurements provide a more direct assessment of seafood-safety risk. Combining biological observations with toxin measurements is important because the abundance of a harmful species does not always correspond directly to toxin concentration. Toxicity can vary among species or strains and may also change according to environmental conditions and bloom development.

Environmental observations provide an opportunity to complement direct biological and toxin monitoring. Predictive models integrating satellite-derived chlorophyll-*a*, sea surface temperature, sea-level anomalies, and nutrient-related indicators show considerable potential for regional-scale HAB forecasting and early warning [8,24,25]. Satellite observations are particularly useful for detecting broad spatial patterns that cannot be captured efficiently through field sampling alone. However, chlorophyll-*a* represents overall phytoplankton biomass rather than the abundance of a particular harmful species, meaning that elevated

satellite-derived chlorophyll does not necessarily indicate a toxic bloom. Remote sensing should therefore be used as a screening and early-warning component that identifies areas requiring targeted field verification rather than as a replacement for species identification and toxin testing.

Recent technological advances also indicate a transition from predominantly periodic microscopy and toxin testing toward integrated HAB surveillance combining automated sensors, molecular detection, imaging systems, and remote sensing [41–43]. Molecular approaches, including quantitative PCR, metabarcoding, and environmental DNA-based methods, can improve the detection of harmful taxa that are difficult to distinguish using conventional microscopy and may identify target organisms when they occur at relatively low abundance. Automated imaging and in situ sensors can provide much higher temporal resolution than periodic field sampling, while satellite observations extend surveillance over much larger geographical areas. Together, these technologies could substantially improve the detection of bloom initiation and provide earlier indications of changing environmental conditions.

As summarized in Table 3, effective HAB management therefore requires integration of bloom ecology, toxin detection, environmental forecasting, and community participation. Strengthening these connections could shift Philippine HAB management from predominantly reactive responses after bloom development toward a more anticipatory system capable of detecting emerging risks, supporting timely seafood-safety decisions, and reducing ecological and socioeconomic impacts on vulnerable coastal communities.

Table 3. Major Characteristics, Impacts, and Monitoring Approaches of Harmful Algal Blooms in Philippine Waters.

Aspect	Key Findings	Ecological and Socioeconomic Significance	References
Paralytic Shellfish Poisoning (PSP)	Toxic dinoflagellate blooms develop mainly in sheltered bays with restricted water exchange, warm temperatures, moderate salinity, and elevated phosphorus concentrations. Toxins accumulate in filter-feeding shellfish.	Causes serious public health risks and fisheries closures, affecting coastal livelihoods and seafood safety.	[6, 8, 23, 35, 37]
Bloom diversity and environmental drivers	Philippine waters experience HABs caused by dinoflagellates, cyanobacteria, and harmful diatoms. Bloom development is promoted by eutrophication, aquaculture-derived nutrient inputs, temperature, and light availability.	Leads to fish mortality, ecosystem disruption, and economic losses in aquaculture and fisheries sectors.	[1, 5, 36, 37]
Monitoring and toxin detection	National monitoring programs collect shellfish and seawater samples from multiple stations, while toxin analyses employ bioassays and advanced chromatographic techniques.	Supports seafood safety management, public health protection, and timely implementation of harvesting restrictions.	[6, 23, 25]
Early warning and community-based surveillance	Satellite-derived environmental indicators, predictive modelling, mobile reporting systems, and fisherfolk networks are increasingly used for HAB forecasting and detection.	Improves early warning capability, enhances monitoring coverage, and supports cost-effective HAB management.	[6, 8, 24, 25]

5. Biogeochemical Roles, Anthropogenic Threats, and Conservation Priorities

5.1 Carbon, Nitrogen, and Phosphorus Cycling

Plankton mediate the bulk of marine biogeochemical cycling in Philippine waters through primary production, grazing, excretion, fecal pellet production, and microbial degradation [12, 13, 18, 21]. The microbial loop, encompassing dissolved organic matter, heterotrophic bacteria,

and protist grazers, is particularly important in the oligotrophic open-ocean regions of the Philippine Sea, where phytoplankton biomass is dominated by picoeukaryotes and *Prochlorococcus* [20]. Sinking fecal pellets and marine snow generated by zooplankton represent the primary conduit for biological carbon export, and their flux is tightly linked to surface phytoplankton community size structure and bloom intensity [18]. Philippine estuaries and mangrove margins serve as hot spots for dissolved inorganic nitrogen and phosphorus release, fuelling coastal phytoplankton production [29].

5.2 Eutrophication, Land Use Change, and Climate Change Impacts

Coastal eutrophication driven by agricultural runoff, urban wastewater, and aquaculture effluents represents one of the most acute stressors on Philippine plankton communities [28, 36]. Nutrient enrichment promotes dominance by filamentous cyanobacteria and small-celled phytoplankton, reducing the size-structured transfer efficiency of energy to mesozooplankton and fish [22]. Ocean warming associated with climate change is projected to intensify thermal stratification, suppress upwelling-driven nutrient supply, and shift phytoplankton community composition toward smaller, less nutritious taxa across the Philippines [12, 19]. Tropical cyclone intensification, sea level rise, and changes in monsoon precipitation patterns will further alter freshwater–marine gradients, sediment inputs, and the seasonality of plankton blooms [15, 24].

5.3 Cross-Ecosystem Synthesis: Marine, Coastal, and Freshwater Patterns.

Across Philippine aquatic ecosystems, plankton dynamics are governed by a common set of controls, nutrient supply, light, temperature, hydrodynamics, and trophic interactions, but the relative importance and expression of these controls differ markedly among ecosystem types. Open-ocean and upwelling-influenced marine systems are strongly regulated by monsoon winds, water-mass exchange, and episodic nutrient injection, whereas semi-enclosed bays are more directly exposed to river discharge, wastewater, aquaculture effluents, and restricted flushing. These coastal conditions can favour eutrophication-adapted phytoplankton and increase HAB risk. Freshwater lakes and reservoirs show a different pathway: monsoon seasonality alters stratification, mixing depth, oxygen conditions, and vertical nutrient redistribution, which then structures phytoplankton functional groups and zooplankton distributions [42, 43]. Thus, similar seasonal forcing can generate contrasting ecological responses depending on basin morphology, salinity, residence time, and anthropogenic nutrient loading. This comparison also reveals an important monitoring implication. Coastal HAB surveillance requires high temporal resolution and toxin-focused early warning, while inland systems require vertically resolved measurements of stratification, nutrients, and plankton succession. A national plankton-monitoring strategy should therefore use shared core indicators but retain ecosystem-specific sampling designs and management thresholds.

5.4 Research Gaps and Conservation-Relevant Priorities.

Major knowledge gaps constraining evidence-based management of Philippine plankton include: (1) insufficient long-term time-series datasets for detecting decadal and climate-driven trends; (2) limited taxonomic resolution for nano- and picoplankton because molecular surveys are not yet routine; (3) poor documentation of deep-sea, mesopelagic, remote-island, and many

inland-water plankton communities; (4) limited experimental evidence on trophic responses under future warming, acidification, and altered nutrient regimes; and (5) weak integration among biological observations, water-quality data, remote sensing, and fisheries information [9, 20, 32, 41–43]. Priority actions should include establishing representative long-term coastal and freshwater observatories equipped with automated temperature, oxygen, fluorescence, and nutrient sensors; expanding eDNA/metabarcoding and imaging-based identification alongside microscopy; integrating satellite observations with field sampling for bloom detection; and developing standardized, interoperable datasets that permit comparison among regions and ecosystem types. Climate adaptation should be incorporated explicitly through experiments and scenario-based assessments of warming, altered monsoon rainfall, stratification, and extreme events. Participatory monitoring involving coastal communities can further expand spatial coverage, while integration of plankton indicators into marine spatial planning and fisheries management would increase the direct conservation value of these observations [16, 17, 22, 25, 32, 41–43]. Major Biogeochemical Roles, Anthropogenic Threats, and Conservation Priorities Related to Plankton Communities in Philippine Waters is shown in Table 4.

Table 4. Major Biogeochemical Roles, Anthropogenic Threats, and Conservation Priorities Related to Plankton Communities in Philippine Waters.

Aspect	Key Findings	Ecological Significance	References
Biogeochemical cycling	Plankton drive carbon, nitrogen, and phosphorus cycling through primary production, grazing, nutrient regeneration, and microbial processes. Zooplankton fecal pellets and marine snow facilitate carbon export to deeper waters.	Supports marine productivity, nutrient recycling, and the biological carbon pump.	[12, 13, 18, 21, 29]
Anthropogenic and climate-related threats	Coastal eutrophication from agriculture, wastewater, and aquaculture promotes harmful shifts in plankton composition. Climate change may increase thermal stratification, reduce nutrient supply, and alter bloom dynamics.	Can reduce food-web efficiency, affect fisheries productivity, and increase ecosystem vulnerability.	[12, 15, 19, 22, 24, 28, 36]
Research gaps	Limited long-term monitoring, insufficient molecular characterization of plankton diversity, poor understanding of deep-sea communities, and few climate-change impact studies.	Restricts accurate assessment of ecosystem change and limits evidence-based management.	[9, 20, 32]
Conservation priorities	Establish long-term monitoring stations, expand eDNA/metabarcoding surveys, strengthen community-based monitoring, and integrate plankton assessments into marine spatial planning.	Improves ecosystem management, biodiversity conservation, and climate adaptation strategies.	[16, 17, 22, 25, 32]

6. Conclusions

Plankton ecology in the Philippines is characterized by high biological diversity and strong environmental variability across marine, coastal, estuarine, reservoir, and lake ecosystems. Across these settings, monsoon forcing, nutrient availability, hydrodynamics, and human pressures interact to regulate community composition, productivity, trophic transfer, and HAB risk. A central finding of this review is that these drivers do not operate uniformly: coastal and semi-enclosed systems are particularly sensitive to eutrophication and restricted flushing, open marine systems respond strongly to circulation and upwelling, and freshwater systems are structured by seasonal stratification and mixing. Plankton therefore provide both a mechanistic link between environmental change and fisheries productivity and a sensitive indicator of deteriorating water quality. For management, the evidence supports integrated observation systems combining conventional sampling with automated sensors, molecular tools, imaging, and remote sensing, together with stronger HAB early warning and incorporation of plankton

indicators into fisheries and spatial-planning frameworks. Major gaps remain in long-term time series, nano- and picoplankton diversity, deep and remote waters, cross-ecosystem standardization, and experimental understanding of climate responses. Future research should prioritize sustained observatories, eDNA/metabarcoding, high-frequency monitoring, climate-vulnerability experiments, and community-based surveillance. Addressing these gaps will be essential for protecting biodiversity, seafood safety, fisheries productivity, and the resilience of Philippine aquatic ecosystems under accelerating environmental change.

Author Contributions

Conceptualization, M.K.L.R. and E.B.M.; methodology, M.K.L.R. and E.B.M.; formal analysis, M.K.L.R. and E.B.M.; investigation, M.K.L.R. and E.B.M.; resources, M.K.L.R. and E.B.M.; data curation, M.K.L.R. and E.B.M.; writing—original draft preparation, M.K.L.R. and E.B.M.; writing—review and editing, M.K.L.R. and E.B.M.; visualization, M.K.L.R. and E.B.M.; supervision, E.B.M.; project administration, M.K.L.R. All authors have read and agreed to the published version of the manuscript.

Competing Interests

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Data Availability Statement

This review article does not report original data. Data supporting the ecological syntheses presented herein are available in the cited peer-reviewed literature.

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