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Research Article

Effects of Seasonal Dynamics on Cyanobacteria Proliferation in Aquaculture Fish Ponds

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Aquaculture production supports the United Nations Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), by enhancing food security and sustainable practices. This study investigated the seasonal dynamics of cyanobacterial (CB) blooms in aquaculture fishponds in South Africa (SA) and Nigeria (NGA). Water samples were collected twice per season for 1 year and analyzed for physicochemical (temperature, pH, and nutrients), biological (chlorophyl-a and cyanobacteria biomass), and meteorological parameters. FlowCAM analysis revealed *Microcystis* sp. as the dominant cyanobacterium across all seasons and locations. Cyanobacteria biomass peaked during dry and wet seasons in NGA, with strong positive correlations with nitrate $(r = 0.87)$ and phosphate $(r = 0.82)$. In contrast, SA fishponds showed lower cyanobacteria biomass, which was not significantly correlated with temperature or rainfall. Principal component analysis (PCA) revealed that chlorophyl-a and temperature were key drivers in SA, while nutrients were more influential in NGA. The study concludes that nutrient dynamics and aquaculture management practices, rather than seasonal temperature or precipitation, are the primary factors driving CB blooms in tropical fishponds. NGA fishponds experienced sustained dominance of *Microcystis* blooms, driven by elevated nutrient inputs from intensive fertilization and high stocking densities. Hydrological flushing and rainfall-induced dilution offer potential for CB bloom control, though their effectiveness is influenced by local management practices.

Keywords: CyanoHABs; fishpond management; *microcystis*; seasonal dynamics; sustainable aquaculture

1. Introduction

The worldwide proliferation of CyanoHABs poses a significant threat to the safety and sustainability of water resources utilized for human consumption, agricultural irrigation, inland fisheries (including aquaculture), and recreational purposes [1]. Aquaculture ecosystems are highly vulnerable to cyanobacterial (CB) blooms as cyanobacteria constitute the integral component of the food web as phytoplankton biomass [2, 3]. Additionally, cyanobacteria can easily adapt to environmental conditions usually encountered in fishponds, such as high temperature, reduced light conditions, nitrogen (N) depletion in the upper layer, a high degree of eutrophication, and a decrease in the number of large phytoplanktivorous filter-feeders [4, 5].

Fish ponds are often enriched with nutrients, particularly N and phosphorus (P), due to fish feed, waste, and runoff from surrounding agricultural or urban areas. These nutrients provide an essential food source for cyanobacteria, promoting rapid growth [2, 6]. Excessive nutrient loading can lead to eutrophication, a process that fosters the formation of harmful algal blooms (HABs) [7, 8]. High turbidity, resulting from suspended particles or fish activity that stirs up the pond substrate, can also influence CB growth. While cyanobacteria are generally phototrophic, some species have adaptations to thrive in low-light, turbid conditions due to buoyancy control mechanisms [9]. Turbidity can limit the growth of other phytoplankton, giving cyanobacteria a competitive advantage [10]. Cyanobacteria are considered harmful to aquaculture systems

as they affect water quality, leading to the loss of water clarity. They also produce secondary metabolites, which can cause a change in the taste and odors of the waters, resulting in negative effects on invertebrate and fish habitats [11–13].

In tropical regions, particularly in Africa, a pronounced gap exists in research on the temporal drivers of CB biomass in aquaculture fishponds, despite their critical role in the aquatic food web. Cyanobacteria not only contribute significantly to nutrient cycling but also influence fish growth and water quality. Cyanobacteria can pose risks through toxin production, which may escalate under certain seasonal conditions. Cyanotoxins are toxic secondary metabolites produced by cyanobacteria that pose significant risks to aquatic organisms, animals, and humans [14, 15]. They are typically classified based on their primary targets into three major groups: hepatotoxins (e.g., microcystin, cylindrospermopsin, nodularin) [16], neurotoxins (e.g., anatoxin-a, anatoxin-a(s), saxitoxins) [17], and dermatotoxins or irritant compounds (e.g., lipopolysaccharides, lyngbyatoxin, aplysiatoxins) [18]. In fish, exposure to these toxins can result in sublethal effects, including hepatic accumulation, hepatocellular damage, hepatocyte degeneration, and in severe cases, fatal liver hemorrhaging [19]. In both animals and humans, cyanotoxin exposure has been linked to numerous adverse health outcomes, such as carcinogenicity, gastroenteritis, dermal irritation, liver damage, vomiting, headaches, allergic reactions, and even death [20, 21]. Human exposure may occur through multiple routes, including ingestion of contaminated drinking water, fish, seafood, crops, vegetables, and dietary supplements, as well as accidental ingestion during recreational water activities [22].

FlowCAM has become a widely adopted technique for the enumeration of CB cells. The system identifies cyanobacteria by analyzing their morphological characteristics and image-based features, captured through an integrated optical microscope and high-resolution digital camera [23]. FlowCAM thus provides a rapid, semiautomated approach for monitoring CB composition and abundance [24, 25].

Meteorological conditions, alongside nutrient availability, play a critical role in the occurrence and proliferation of CB blooms [26–28]. Various weather variables including air temperature, rainfall, wind, sunshine duration, humidity, and solar radiation have been shown to influence CB dynamics significantly [29, 30]. Wind, in particular, can directly impact CB distribution by generating internal waves or seiches, which alter water column structure, influence light availability, and nutrient mixing [31]. These physical processes affect not only the spatial patterns but also the growth conditions of cyanobacteria, especially in stratified and deep lakes [32, 33]. Many bloom-forming CB species exhibit optimal growth at temperatures of 25°C or higher, with limited growth below 5°C or above 35°C [34]. The rising frequency of CB blooms has also been associated with global climate change, and increasing air temperatures [35]. As such, integrating meteorological variables into monitoring frameworks is essential for developing effective early warning systems for CB proliferation, particularly in drinking water sources [28].

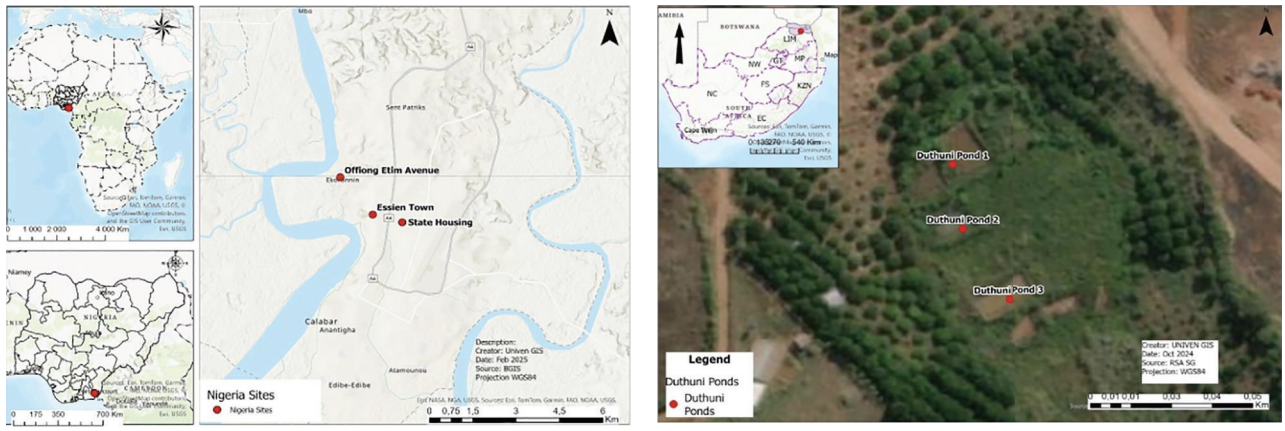
Current knowledge gaps pertain to how CB populations fluctuate across different seasons and the factors driving these variations, such as temperature, nutrient availability, and pond management practices. Understanding these patterns is critical for optimizing aquaculture productivity and mitigating risks associated with CB blooms. This highlights the need to understand the influence of seasonal variations on cyanobacteria in tropical regions. Therefore, the present study aims to investigate the effects of seasonal variations on cyanobacteria proliferation in aquaculture fish ponds found in SA and NGA. Addressing these gaps is crucial for optimizing aquaculture productivity, preventing harmful blooms, and ensuring the ecological sustainability of fishponds. This underscores the urgent need for comprehensive studies on seasonal variations in CB populations and their environmental drivers, particularly in tropical aquaculture systems.

2. Methodology

2.1. Study Area. The study was conducted in commercial aquaculture fishponds in Vhembe District, Limpopo Province, South Africa (SA), and Calabar Municipality, Cross River State, Nigeria (NGA). In NGA, the sampling sites in Figure 1A were located in Offiong Etim avenue (4°59′58.92” N and 8°19′03.97” E), Essien town (4°59′15.49” N and 8°19′40.21” E), and state housing (4°59′6.50” N and 8°20′13.29” E). The aquaculture fishponds in Vhembe District in Figure 1B were located in Duthuni (22°57′56.98” S and 30°23′43.96” E). A total of six fish ponds located in Vhembe District (3 fish ponds) and Calabar Municipality (3 fish ponds) were used for this study. Sampling sites were selected using the following criteria: commercial fishponds, accessibility, consent from the owners, and the presence of cultured fish.

2.2. Water Sampling. Water samples were seasonally collected from the fishponds in triplicate during the South African winter and summer and the Nigerian dry and wet seasons, respectively. Data collection involved four field trips conducted during specific seasonal periods: January and February (summer), June (winter), August and September (wet season), and November and December (dry season). Water samples were sampled at depths between 0 and 0.5 m from each fishpond using sterilized labeled bottles. Water samples were collected approximately 1–2 m away from the edge to avoid contamination from edge-related disturbances. Approved consent was obtained from the owners of the fishponds in NGA and SA before sampling.

2.3. Meteorological Data. Monthly climatic data (maximum and minimum temperatures and precipitation) from 1991 to 2022 were obtained from the archives of the Nigerian Meteorological Agency and South African Weather Services. The annual mean of each dataset was computed from the monthly datasets. A trend analysis was carried out to assess the air temperature and rainfall patterns for 32 years.



(A) (B)

FIGURE 1: Map of the sampling sites. (A) Calabar municipality, cross river state, Nigeria, and (B) Vhembe district, Limpopo province, South Africa.

2.4. Water Samples Analyses

2.4.1. Nutrient Analyses. Samples for dissolved nutrient concentration underwent filtration using membrane filters before analyses. The nutrient analyses, specifically for nitrates, nitrites, and phosphates, were conducted on the samples using Ion Chromatography (Dionex 1600), employing EPA method 300 [36]. These analyses took place at the Agricultural Research Council (ARC) Laboratory.

2.4.2. Chlorophyl-a Analysis. Water samples (250 mL) were filtered through a Whatman (Glass Fiber) filter paper. Then, the filter paper was cut into smaller pieces and immersed in 10 mL of ethanol, followed by ultrasonication for 30 min. The tube was labeled and stored in the dark for 24 h at room temperature. This was followed by 15 min of centrifugation at 3500 rpm to get a clear sample. The samples were transferred to a clean vessel and the volume was recorded. The supernatant was poured into a 1 cm cuvette, and a spectrophotometer was used to measure the amount of light absorbed by the sample in the cuvette placed in the spectrophotometer at a wavelength of 665 and 750 nm. This absorbance wavelength ratio (665 and 750 nm) was used because it fluoresces at 665 and 750 nm. Two batches at 665 and 750 nm were used.

1. 1 cm cuvette sample without hydrochloric acid (total absorb) (665a and 750a nm).
2. 1 cm cuvette sample with a 0.01 mL drop of hydrochloric acid (665b and 750b nm).

Adding HCl (0.01 mL) to the sample before measurement assists in dissolving the suspended particles scattered in the samples, so that light can pass through the cuvette without interference from scattered particles. After measuring, chlorophyl-a concentration was conducted using the equation shown below [37].

2.4.2.1. Calculation. Correct turbidity by subtracting absorbance 665a − 750a = corrected 665a,

665b − 750b = corrected 665b

The corrected 665a and 665b absorbance was used to calculate the chlorophyl-a concentration.

$$\text{Chl-a} = \frac{29.62\,(665a - 665b) \times Ve}{Vs \times 1},$$

where Vs = Volume of water samples in liters, Ve = Volume of ethanol extract (mL), 1 = Cuvette light-path length in centimeters

The final concentration was expressed in units mg m^{-3}.

2.4.3. Dry Weight Biomass. Measures the total dry weight of phytoplankton collected from a sample. The samples (1L) were filtered through a preweighed filter. The filter paper was oven-dried at 60°C until constant weight was reached. The weight difference was measured to calculate biomass. The unit was expressed in mg/L.

2.5. Microscopic Identification. A benchtop FlowCAM (Model VS IV) was used for the morphological identification of cyanobacteria species. This involved capturing images and employing comparative analysis with existing literature for identification purposes. A filtered water sample (2 mL) was poured into the flow chamber via a pipette after rinsing the pump with deionized water to execute this experiment. The computer's digital signal processor and the trigger circuitry collaborated to initiate, retrieve, and process these images saved on the visual spreadsheet. Each pixel grouping representing individual particles was isolated from the raw images and stored as distinct collage images.

2.6. Statistical Analysis. The statistical analyses were conducted to establish the correlation between variables using the Statistical Package for the Social Sciences (SPSS). The obtained data were input into Microsoft Excel before performing statistical analyses. Principal component analysis (PCA) was employed to explore patterns and relationships among environmental variables across different seasons and regions. PCA was performed separately for South African (summer and winter) and Nigerian (dry and wet season) fishpond datasets to

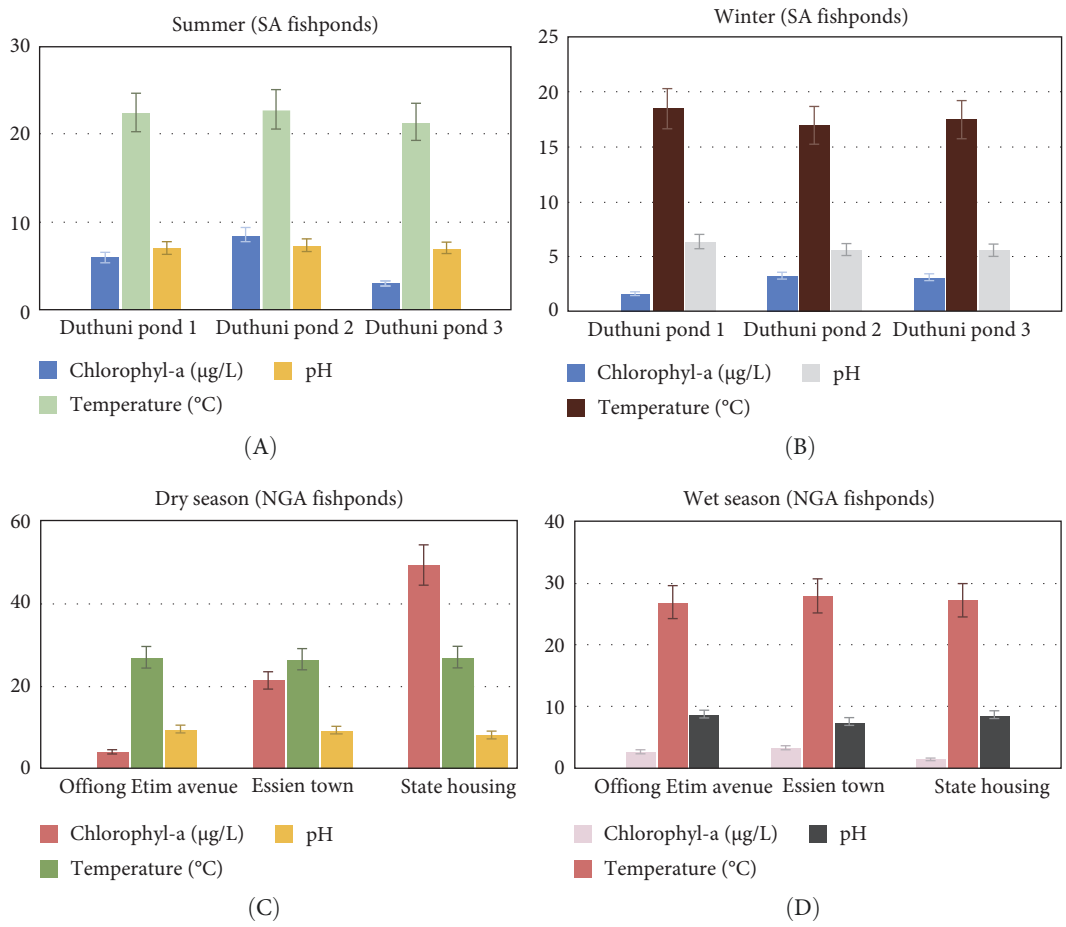


FIGURE 2: (A–D) Graphical representation of environmental factors including temperature, pH, and chlorophyl-a during summer, winter, dry, and wet seasons in SA and NGA fishponds.

assess seasonal variation in environmental parameters. Pattern analysis was applied to the meteorological data, followed by fitting the data with linear models.

3. Results

3.1. Environmental Factors. Figure 2A–D illustrates environmental variation in SA and NGA fishponds, showing generally higher temperatures during the dry, wet, and summer seasons. Seasonal fluctuations in water temperature, pH, chlorophyl-a, phytoplankton biomass, and nutrients were found in Nigerian and South African fishponds. All the sampling sites showed elevated temperatures >20°C in dry, wet, and summer seasons, with NGA generally warmer than SA.

However, the temperature dropped notably during winter to 16.5°C, specifically at the Duthuni (SA) sampling sites. High concentration of nitrite and nitrate was observed during the wet season, followed by the dry season in NGA fishponds, corresponding to 10.42 and 6.45 mg/L, respectively. Meanwhile, in SA, the fishponds exhibit lower concentrations of nutrients (NO_3^-, NO_2^-, and PO_2^3; 1.9, 1.4, and 2.1 mg/L, respectively) in both summer and winter. Phosphate levels were the same in winter and summer in SA for all fishponds and higher in the wet season for Nigerian fishponds. The water samples in Nigerian fishponds showed neutral to alkaline pH in rainy seasons, while South African fishponds maintained a slightly acidic to neutral pH of 5.59–7.22.

3.2. Phytoplankton Biomass. Figure 3A,B displays phytoplankton biomass peaks during dry and wet seasons, especially in NGA, suggesting a response to warmer temperatures and increased nutrient input. Chlorophyl-a displays strong variations during warmer months of summer and dry seasons compared to the winter and rainy seasons. Phytoplankton biomass in Nigerian fishponds was higher in both seasons. There were no significant variations in phytoplankton biomass across all fishponds during the dry and wet seasons. However, increased phytoplankton biomass was noted in summer in Duthuni ponds 1 and 2, with relatively lower values in winter.

3.3. Seasonal Dynamics of Air Temperature and Precipitation. Figure 4A,B highlights long-term temperature trends (1991–2022) in NGA, revealing a gradual warming pattern, particularly in the wet season. Similarly, Figure 5A,B depicts SA's temperature trends, showing consistent seasonal fluctuations with a slight warming trend in winter months over the years. Figure 6A,B presents rainfall patterns in SA, where winter seasons exhibit significantly lower precipitation than summer. In contrast, Figure 7A,B reveals higher rainfall during the

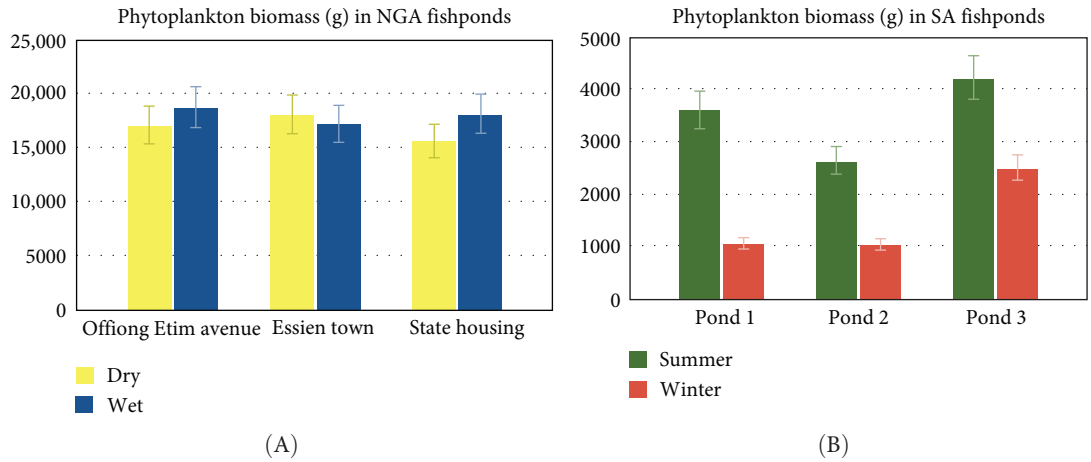


FIGURE 3: (A, B) Graphical representation of phytoplankton biomass during summer, winter, dry, and wet seasons in SA and NGA fishponds.

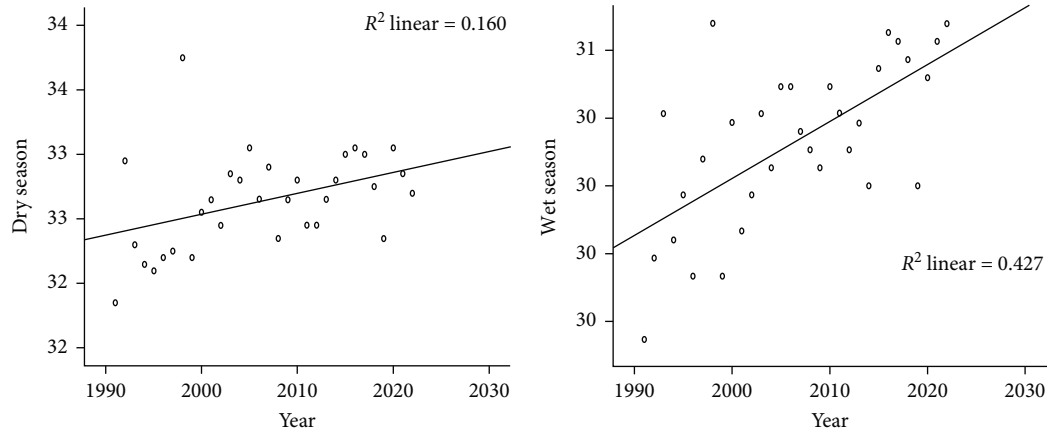


FIGURE 4: Temperature trends (1991–2022) during (A) dry and (B) wet seasons in the NGA sampling location.

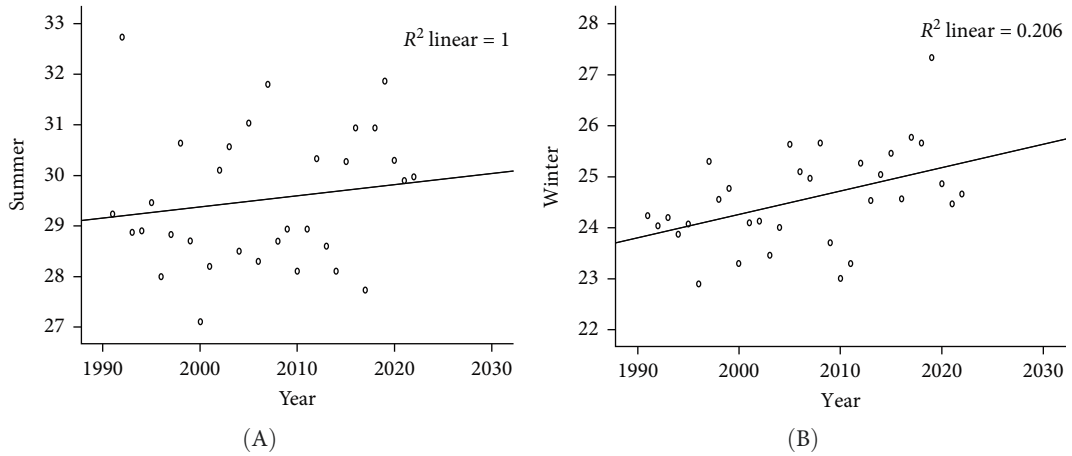


FIGURE 5: Temperature trends (1991–2022) during the (A) summer and (B) winter seasons in the SA sampling location.

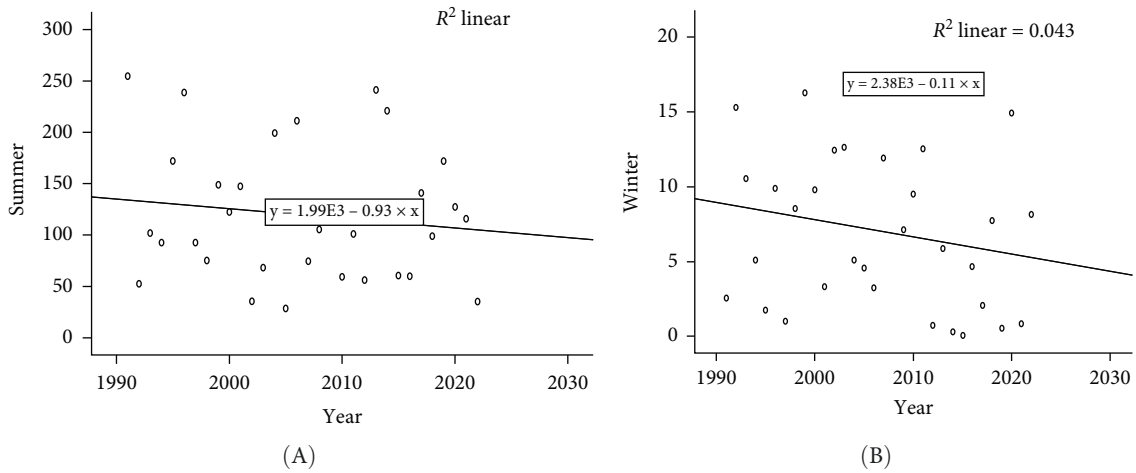


FIGURE 6: Rainfall trends (1991–2022) during (A) summer and (B) winter seasons in the South Africa sampling location.

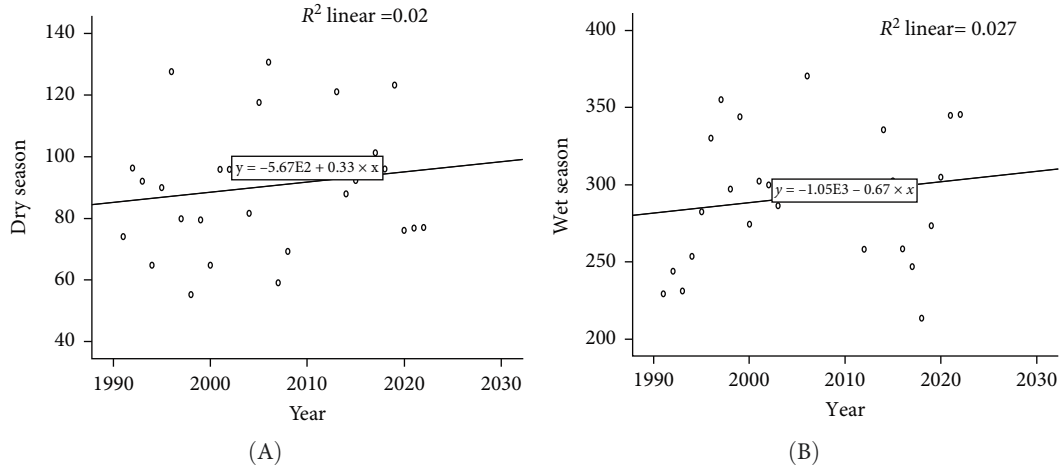


FIGURE 7: Rainfall trends (1991–2022) during (A) dry and (B) wet seasons in the Nigeria sampling location.

wet season in NGA, showing increasing rainfall variability over time.

3.4. Management Practices. Field observations revealed a notable dominance of algal blooms in Nigerian fishponds, predominantly characterized by CB scums and greenish-colored water, with visible accumulations of blue-green algae on the water surface displayed in Figure 8A–D. During the dry season, these ponds exhibited a pronounced layer of CB blooms over the water surface. Figure 8E shows raindrops disrupting the algal bloom, while Figure 8F depicts a diluted algal bloom caused by rainfall.

In contrast, during the rainy season, the CB blooms were diluted by rainwater, resulting in the absence of thick surface layers of CB scums in Figure 8E,F. In South African fishponds, no CB blooms were observed during either winter or summer, as presented in Figure 9A,B. The water samples from the SA fishponds maintained a consistent coloration (muddy brown color) across all seasons in Figure 9.

The SA fishponds were constantly receiving freshwater from the Duthuni Dam in Figure 10B. Conversely, the NGA fishponds relied exclusively on borehole water released into the fishponds, as periodically displayed in Figure 10B.

3.5. Phytoplankton Species Composition. Microcystis sp. cells were dominant across all sampling sites and seasons, as displayed in Figures 11 and 12. Notably, no other CB genus was identified in the morphological results from the FlowCam and microscopic analysis.

3.6. Correlation Between Water Quality Parameters. The PCA biplots illustrate the clustering and correlation patterns of environmental parameters across seasons in the two studied regions. The PCA results in Figure 13A (SA—Summer) show that temperature and chlorophyl-a are positively correlated and align closely with PC1. suggesting that higher temperatures in summer are associated with increased algal productivity in South African fishponds. Figure 13B (SA—Winter) reveals a more even distribution of variables, with pH contributing more

FIGURE 8: Visible presence of blue-green algae bloom in (A) Essien town, (B and D) spring road, (C) state housing fishponds during the dry season, while (E) spring road and (F) state housing fishponds during the wet (rainy) season.

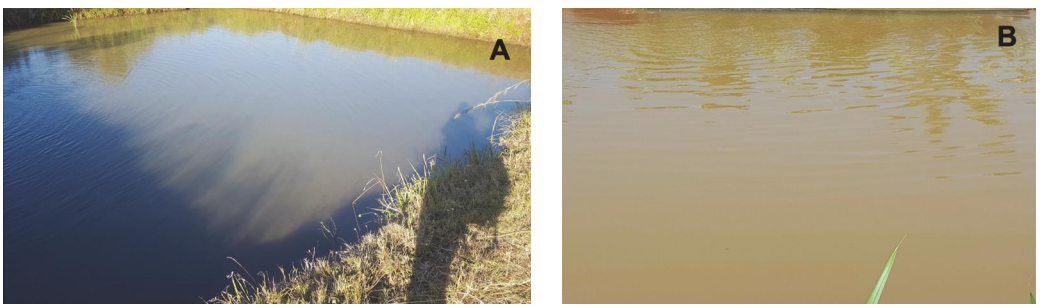


FIGURE 9: Duthuni fishpond during (A) summer and (B) winter.

FIGURE 10: (A) NGA fishpond and (B) SA fishponds receiving freshwater from the Duthuni Dam.

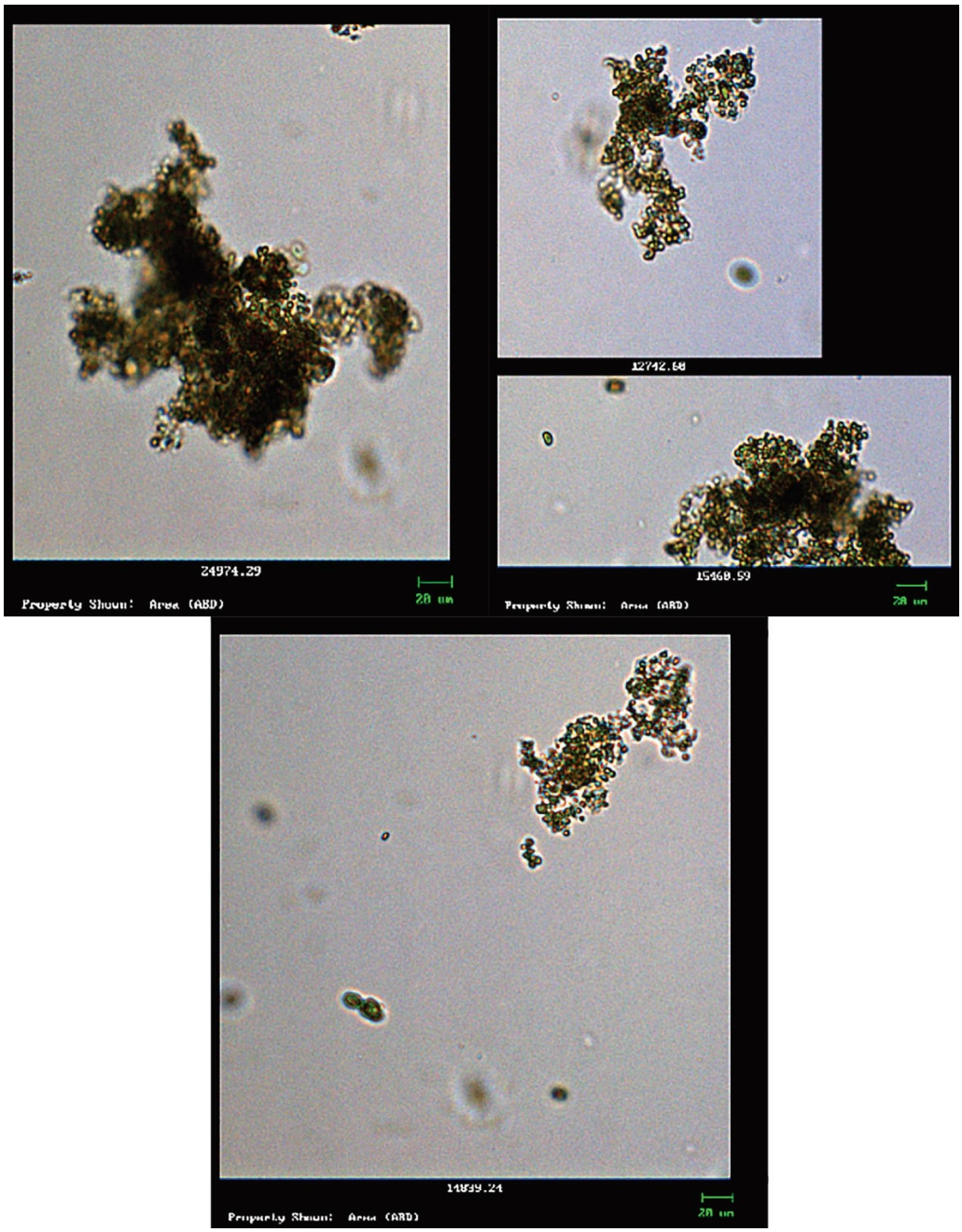


FIGURE 11: FlowCam chart of cyanobacteria in the water samples.

prominently to PC2, indicating seasonal pH shifts with lower biological activity.

In Figure 13C (NGA—Dry season), temperature and phytoplankton biomass (dry weight) are closely aligned along PC1, indicating a stronger temperature influence on biomass production under dry conditions. Figure 13D (NGA—Wet season) shows chlorophyl-a and biomass (wet weight) contributing significantly to PC2, likely reflecting increased nutrient input and algal growth due to runoff during wet periods. Overall, PCA separated seasonal effects distinctly for both regions, with temperature and chlorophyl-a being the main drivers in SA, while rainfall-influenced nutrient loading appeared more influential in NGA during the wet season.

4. Discussion

The influence of environmental variables on CB biomass is considered an important factor in regulating CB blooms. CB blooms are strongly correlated with climatic conditions, especially in temperate regions. Increased air temperature during warmer seasons serves as a strong predictor of biotic processes, notably influencing the behavior of cyanobacteria in the

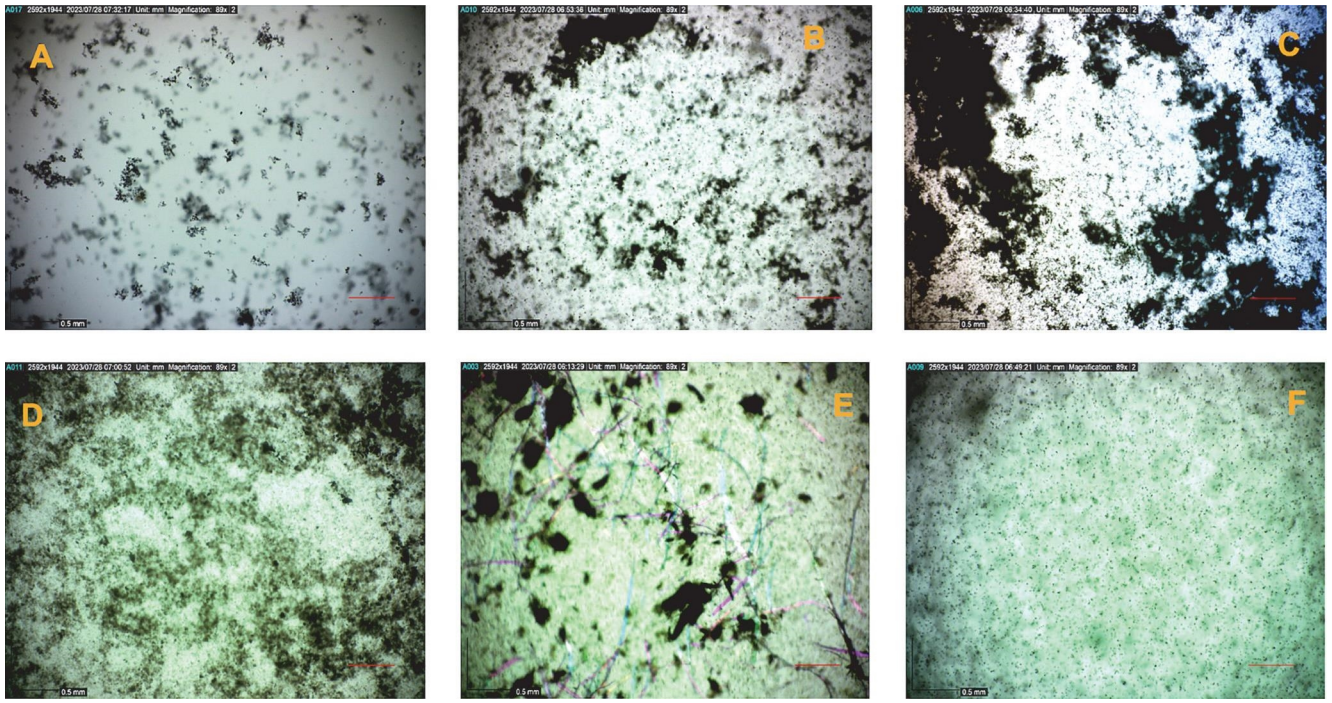


FIGURE 12: Microscopic identification of cyanobacteria cells in the water samples (A) Duthuni Pond 1, (B) Duthuni Pond 2, (C) Essien town, (D) Spring Road, (E) state housing, and (F) Duthuni Pond 3.

epilimnion [38, 39]. Air temperature plays a pivotal role in shaping the ecological and hydrological dynamics of aquatic ecosystems, acting as a direct link between atmospheric conditions and aquatic ecology [38, 40]. However, the increased air temperature pattern over the past three decades cannot be linked as the primary mechanism driving phytoplankton biomass growth in the fishponds during warmer seasons (dry, wet, and summer). CB proliferation in fishponds is influenced by multiple factors, not just temperature. Although, increased temperatures generally promote CB growth by enhancing metabolic rates and competitive advantages over other phytoplankton. Other environmental conditions, such as nutrient and light availability, must align to trigger a bloom [41].

While meteorological factors, such as warmer temperatures typically support CB growth, their impact in fishponds is context-dependent and often overshadowed by other environmental and management factors. The SA and NGA fishponds were typically less influenced by seasonal factors due to shallow depths. This limits the formation of thermoclines (temperature gradients within the water), which typically drive seasonal stratification in deeper water bodies [42, 43]. Without significant stratification, water temperature remains relatively consistent throughout the year, reducing seasonal temperature effects. In addition, fishponds in tropical regions are often subject to anthropogenic management, such as controlled feeding, water replenishment, stock density, and aeration. These practices ensure that water quality and temperature remain stable, regardless of external seasonal variations. Similar reports have been documented by Shchapov et al. [44], indicating that water quality conditions, especially in nutrient-rich and poststorm environments, were found to be stronger drivers of CB density and biomass than meteorological factors. In NGA and SA, rainfall patterns, land use, and agricultural runoff are often more impactful on water quality and fishpond conditions than temperature changes tied to seasons. This is why fishponds are more influenced by weather and human activities.

In tropical aquaculture systems, particularly fishponds, the rainy season introduces significant hydrological flushing that may serve as a natural mechanism to control CB blooms. This process can physically remove or dilute suspended particles, including cyanobacteria, thereby mitigating bloom intensity [27, 45]. Recent findings by Zhou et al. [28] provide compelling evidence for this mechanism, showing that short-term rainfall events can disrupt the surface aggregation of *Microcystis* colonies. Their study demonstrated that rainfall significantly reduces surface *Microcystis* biomass by breaking apart small-to-medium-sized colonies ($0-100\,\mu m$), causing larger colonies to migrate deeper into the water column. This suggests that intense rainfall events not only dilute surface CB populations but also interrupt their vertical positioning, thereby diminishing their competitive advantage for light and surface nutrients.

These findings complement observations from this study, where rainfall-induced dilution increases water transparency by lowering algal biomass [46, 47]. In systems where bloom formation is closely linked to nutrient enrichment, such as the Nigerian fishponds, dilution from heavy rain may offer temporary relief from eutrophic conditions, although this effect is often overshadowed by intense anthropogenic inputs (e.g., fertilization and high stocking densities).

Rainfall also affects CB blooms through nutrient enrichment. For instance, Xin et al. [48] found that while rainfall initially disrupted algal communities, it was followed by a delayed increase in bloom formation driven by postrainfall nutrient influxes from nonpoint sources. Liu et al. [49] reported

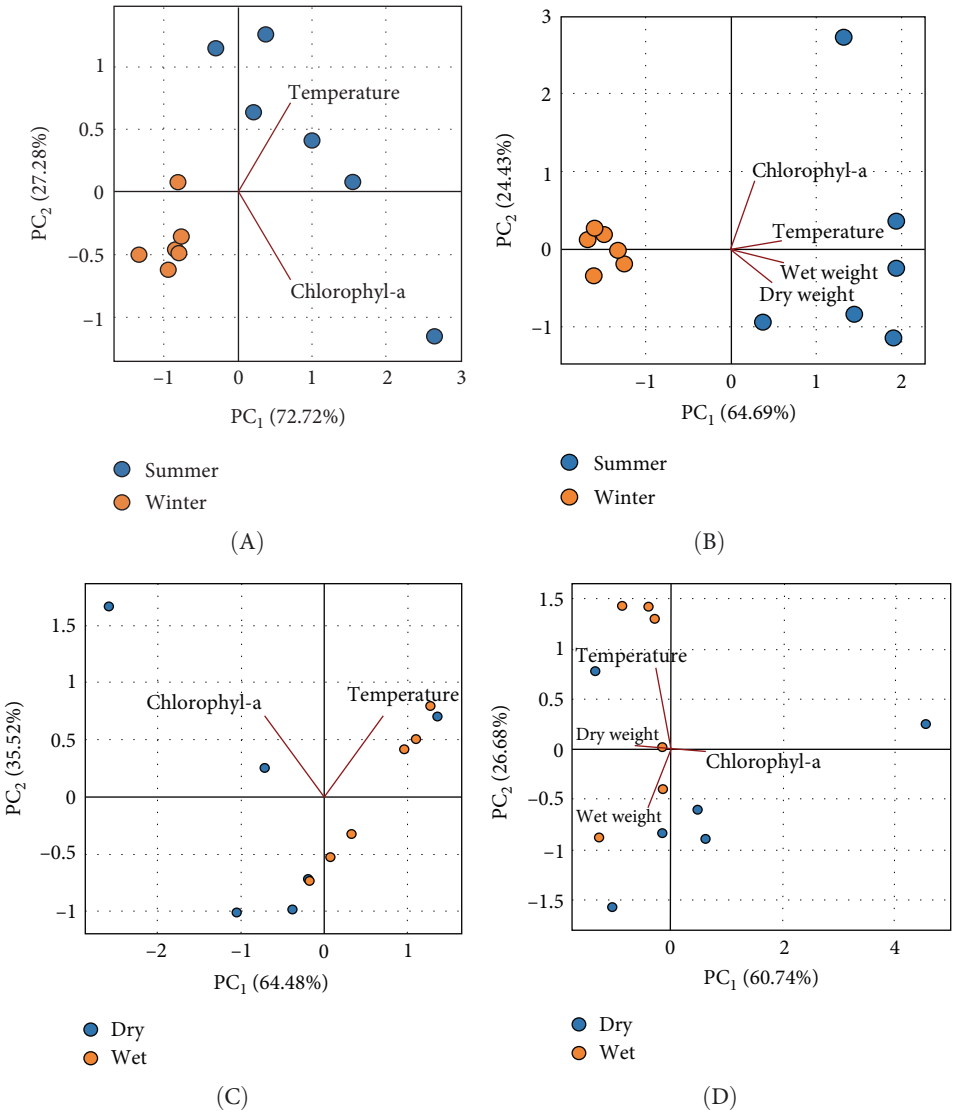


FIGURE 13: (A–D): Principal component analysis (PCA) of environmental variables during (A) summer, (B) winter, (C) dry, and (D) wet season (NGA).

that peak algal growth occurred 20–30 days after rainfall events, triggered by shifts in total N/total P ratios and cumulative precipitation. Tao et al. [50] further highlighted that sustained water level increases promote nutrient influx, leading to large-scale CB blooms. This supports the observed increase in nutrient concentrations in Nigerian fishponds during the rainy season, driven by increased runoff and external inputs. These findings provide strong evidence that meteorological variables, such as temperature and rainfall interact with nutrient dynamics to shape CB bloom patterns.

Nutrient enrichment in fishponds is considered a major stimulant for eutrophication and the occurrence of toxic CB blooms [51]. The presence of CB blooms in Nigerian fishponds during both dry and wet seasons could be linked to farming practices, such as fertilization of the ponds. Conversely, the low nutrient levels and absence of blooms in SA fishponds may be due to controlled feeding and frequent water exchanges, which dilute nutrient concentrations and disrupt bloom-forming conditions. The SA fishponds received constant freshwater inflows from a nearby dam, promoting intrusion, reducing retention time, and enhancing aeration.

Management practices in Nigerian fishponds, such as high stocking densities, directly influence cyanobacterial growth. Cyanobacteria dominate in fishponds with high stocking densities [42]. Increased fish stock density introduces elevated nutrient loads, primarily through uneaten feed, excretion, and waste accumulation, which accelerates the trophic status of the water body. Over time, this progression can lead to a state of hypertrophy, characterized by excessive nutrient enrichment [52, 53]. The brownish-muddy coloration in the SA fishponds could indicate turbidity, suggesting the presence of suspended sediments, such as silt, clay, or organic matter.

Microcystis species are the most abundant taxa encountered in fishponds and other surface waters globally. Most cyanobacteria species, such as *Microcystis* sp., tend to have a more competitive advantage over other phytoplankton [54]. *Microcystis* is

highly tolerant to varying temperatures, light intensities, and pH levels often experienced in fishponds [55]. This makes them better equipped to survive and thrive under such stresses compared to other cyanobacteria in the SA and NGA fishponds. Moreover, *Microcystis* sp. can regulate its buoyancy using gas vesicles, allowing it to move vertically in the water column [56]. This gives it access to optimal light conditions near the surface for photosynthesis while avoiding competition and predation at different depths [57]. This cyanobacteria species reproduces rapidly under favorable conditions, forming dense surface blooms that outcompete other species by shading them out and monopolizing light resources. Fishponds are often nutrient-rich due to feed inputs, fish excreta, and organic matter accumulation. *Microcystis* sp. thrives in high-nutrient environments, particularly those with elevated N and P levels [58, 59]. Its ability to efficiently uptake and store these nutrients gives it a competitive edge over other cyanobacteria [60]. This explains the dominant presence of *Microcystis* sp. during CB bloom in NGA fishponds.

5. Conclusion

This study demonstrates that CB blooms in Nigerian and South African fishponds are primarily driven by nutrient availability rather than temperature. In South African ponds, chlorophyl-a levels and phytoplankton biomass remained low despite seasonal warming, largely due to low nutrient concentrations, frequent water exchange, and aeration. In contrast, Nigerian fishponds exhibited persistent *Microcystis* bloom dominance, associated with high nutrient loads from fertilization and dense fish stocking. In tropical aquaculture systems, especially fishponds, hydrological flushing and rainfall dilution are valuable tools for managing CB blooms, but their effectiveness is highly influenced by the management practices. To fully harness these natural processes, they must be integrated with sound aquaculture practices that limit nutrient enrichment. The contrast between Nigerian and South African ponds illustrates that anthropogenic nutrient inputs can nullify natural controls, while effective water management (as seen in SA) can substantially reduce bloom risks even under similar climatic conditions. This underscores the need to consider both climate-induced hydrological changes and nutrient management in bloom mitigation strategies.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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