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PHYTOPLANKTON COMMUNITY STRUCTURE, SPECIES DIVERSITY, AND ENVIRONMENTAL INTERACTIONS IN THE ANYANUI CREEK.

BY

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DECLARATION

This dissertation is the result of research work undertaken by Comfort Opoku in the Department of Marine and Fisheries Sciences, University of Ghana, under the supervision of Prof. Edem Mahu and Dr. Benjamin Osei Botwe of the University of Ghana. I certify that this thesis is my work, and that any ideas taken from other sources have been properly acknowledged. This dissertation has not been submitted for any degree or examination to any other university or institution.

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DEDICATION

I dedicate this work to my dear parents, Mr. and Mrs. Opoku, and my lovely siblings, Marvin, Michael, Gabriel, and Seraphim Opoku. Thank you for your encouragement and motivation during this academic journey.

ABSTRACT

This study aimed to assess the structure and distribution of phytoplankton communities in the Anyanui Creek, focusing on species composition, diversity, and the relationships between environmental factors and phytoplankton populations. The Anyanui Creek was zoned into three Zones A (upstream), Zone B (midstream), and Zone C (downstream) based on salinity levels from a preliminary study. Phytoplankton samples were collected between April 2023 and March 2024. A total of 34 phytoplankton species were identified, which were dominated by diatoms, comprising 92.92% of the population. The most abundant species, *Chaetoceros sp.* (36.85%), thrives in silica-rich environments, facilitating bloom formation and affecting the ecosystem dynamics. The presence of bloom-forming species raises concerns regarding eutrophication risks, whereas toxin-producing species pose potential threats to ecological and human health. The diversity of phytoplankton was assessed using the Shannon-Wiener diversity index (H′), with values ranging from 1.38 to 3.04, indicating low pollution levels. The high Pielou's evenness of species distribution (0.995-0.999) suggests a stable phytoplankton community structure across zones. Cluster analysis based on phytoplankton species compositions across the sampling zones isolated upstream, likely due to its higher salinity and absence of cyanobacteria, whereas midstream and downstream exhibited high similarity. Cluster analysis based on phytoplankton species compositions across the sampling period indicated seasonal influences, with March 2024 and April 2023 forming a distinct group due to variations in environmental conditions. Correlation analysis highlighted the relationship between the physicochemical parameters and species abundance. Salinity and dissolved oxygen were negatively correlated ($r = -0.689$, $p < 0.01$). *Chaetoceros daniscus* preferred oxygen-rich waters, whereas *Nitzschia sp.* preferred ammonium-rich waters, low-oxygen conditions. This study provides insights into the factors shaping the phytoplankton community structure in the Anyanui Creek, which can inform future management and conservation strategies to preserve the creek’s ecological health.

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CHAPTER 1

1.0 INTRODUCTION

1.1 Background

Phytoplankton are microscopic organisms that drift with tides and currents, and include groups such as dinoflagellates, diatoms, blue-green algae (cyanobacteria), and coccolithophores. They contribute to approximately 95% of the ocean's primary production. These microscopic organisms are fundamental to the functioning of marine and estuarine food webs and serve as the base of food chains. Phytoplankton communities are therefore the primary energy sources for higher trophic levels, including zooplankton, fish, and shellfish (Cuici et al., 2006). Bivalves that filter feed, including oysters, mussels, and clams, are highly dependent on rich and varied phytoplankton communities. Additionally, phytoplankton are a crucial food source for the larvae of commercially valuable crustaceans and finfish during their early developmental stages (Hallegraeff et al., 2004).

Estuarine ecosystems are highly dynamic environments that are subjected to frequent and often unpredictable changes in salinity due to irregular inflows of freshwater from rivers and seawater from tidal currents. This variability creates unique ecological conditions influenced by both terrestrial and marine factors (Surge & Lohmann, 2008). The interaction between freshwater and saltwater in estuaries results in nutrient-rich waters that support diverse biological communities (Amri et al., 2019; Piranti et al., 2021). Nutrient availability in these environments can promote high primary productivity, making estuaries crucial for sustaining various life forms. However, nutrient enrichment can also lead to negative outcomes. Anthropogenic activities such as agriculture, urbanization, and industrial discharge often introduce excess nutrients into estuaries, exacerbating the risk of eutrophication. Eutrophication is characterised by rapid phytoplankton growth or blooms, which can destabilize ecosystems by reducing oxygen levels and causing the death of aquatic organisms

(Menezes et al., 2013; Piranti et al., 2021). The biological significance of estuaries extends beyond their primary production. Many estuarine systems support economically and ecologically important fisheries, particularly shellfish fisheries. Any substantial change in the phytoplankton population, whether in terms of species composition or abundance, can directly affect organisms higher in the food web, such as oysters and other bivalves (Surge & Lohmann, 2008). Therefore, a decrease in the availability or quality of phytoplankton due to environmental stressors can negatively impact the productivity and health of estuarine fisheries. Monitoring phytoplankton dynamics in estuarine ecosystems is crucial, particularly in light of ongoing climate change and increasing human impacts.

The dynamics of phytoplankton growth, distribution, and community composition in aquatic environments are influenced by the complex interplay between environmental factors (Winder & Sommer, 2012). These include nutrient availability, light conditions, water temperature, salinity, and hydrological factors such as water movement and stratification. Nutrient enrichment, particularly through anthropogenic inputs, has been increasingly recognised as a key driver of phytoplankton blooms in estuarine environments (Cabrerizo et al., 2017; Srichandan et al., 2019; Chen et al., 2019). The structure, diversity, distribution, and abundance of phytoplankton species in estuarine systems are also influenced by seasonal and temporal variabilities (Rojas-Herrera, 2012; Amri et al., 2019; Devlin et al., 2019). Seasonal shifts in temperature, precipitation, and light availability can lead to predictable patterns in phytoplankton productivity, whereas temporal variations, such as sudden changes in salinity or nutrient input due to extreme weather events or human activities, can result in more abrupt changes (Egerton, 2013). Furthermore, areas farther from direct human activities tend to exhibit greater phytoplankton diversity as they are less subject to disturbances such as pollution, nutrient loading, and habitat alteration (Piranti et al., 2021). In contrast, regions near human-impacted zones are more likely to experience reduced diversity and altered community structures because of environmental degradation.

1.2 Justification of the Study

Phytoplankton are fundamental components of aquatic ecosystems, serving as the primary producers that sustain food webs. They drive crucial ecological processes, including nutrient cycling and oxygen production (Hu et al., 2024), thereby supporting aquatic biodiversity. Beyond their ecological role, phytoplankton are highly responsive to environmental variability, which makes them effective bioindicators of ecosystem health (Chandel et al., 2024). The Anyanui Creek is subject to the mixing of freshwater and marine water inflows, which creates a dynamic and variable environment (Montagna et al., 2012). Such a dynamic system exposes phytoplankton to fluctuations in salinity, nutrient availability, temperature, and pH, which can lead to changes in diversity and composition. Shifts in phytoplankton community structure can have cascading impacts on higher trophic levels, including zooplankton, fish, and shellfish populations (Pershing et al., 2015).

The Anyanui Creek is an ecologically and socio-economically important ecosystem in Ghana. It supports biodiversity and sustains local fisheries, including oysters, which provide livelihoods for surrounding communities. The system is increasingly threatened by nutrient enrichment, land use change, pollution, and climate-related stressors (Mahu et al., 2023), yet it remains poorly studied. Understanding phytoplankton composition and diversity in this system is therefore crucial for assessing ecosystem stability and resilience, which can inform management.

This study aimed to characterise phytoplankton in the Anyanui Creek, assess spatial and temporal variations in their diversity, and investigate relationships between community structure and physicochemical parameters.

1.3 Aim and Objectives

1.3.1 Aim

This study aimed to characterize the distribution and community structure of phytoplankton in Anyanui Creek, providing data for monitoring ecosystem health, fisheries management, and conservation.

1.3.2 Objectives

The objectives were to:

1. Characterize the phytoplankton species in Anyanui Creek
2. Assess variations in phytoplankton diversity in Anyanui Creek
3. Investigate the relationships between physicochemical parameters and phytoplankton species in the Anyanui Creek.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

Like terrestrial plants, phytoplankton rely on nutrients such as nitrate, phosphate, silicate, and ammonium, with the required quantities varying by species. Some phytoplankton thrive even under low-nitrate conditions (Lindsey et al., 2010). They also need trace amounts of iron, and their growth can be restricted to extensive ocean regions where iron is scarce. Other factors influencing their growth include water temperature, salinity, depth, wind, and the variety of predators that feed on them. Approximately 95% of the primary production in the seas is carried out by marine phytoplankton, which includes diatoms, dinoflagellates, blue-green algae, silicoflagellates, and coccolithophores. Both secondary (zooplankton) and tertiary (fish, shellfish, mammals, etc.) production rely on this. Large populations of phytoplankton may indicate the richness of fish and shellfish populations that are significant to the marine economy since they provide a fundamental food supply for marine creatures (Verlecar and Desai 2004).

2.2 Importance of Phytoplankton in Aquatic Ecosystems

Although phytoplankton make up only 1% of the Earth's photosynthetic biomass, they contribute nearly 50% to global net primary production, serving as a crucial energy source in aquatic ecosystems (Field et al., 1998). They play a significant role in climate regulation and biogeochemical cycles globally (Winder & Sommer, 2012). As primary producers at the base of aquatic food webs, phytoplankton support a wide range of organisms, from tiny zooplankton to large whales. Small fish and invertebrates consume these plant-like organisms, which in turn sustain larger predators (Lindsey et al., 2010). However, some phytoplankton species also produce potent biotoxins, leading to "red tides" or harmful algal blooms, which can harm marine life and pose risks to humans consuming contaminated seafood (Lindsey et al., 2010). Thus, phytoplankton are essential contributors to the health and productivity of aquatic ecosystems (Barbosa, 2009). Their abundance and activity are influenced by various factors, including climate change and the chemical and biological components of the water. (Hosmani, 2014). Phytoplankton are efficient accumulators of reactive elements, and their interaction with toxic compounds can impact their transport through the ecosystem (Sanders & Riedel, 1998). In addition, their extracellular production is an important source of nutrients for bacteria, contributing to the overall productivity of the ecosystem (Boulion, 2021).

2.2.1 Significance of Seasonal Studies

Seasonal studies of phytoplankton are significant as they provide critical insights into the dynamics of these organisms in varying environments over time. Forsström et al. (2005) showed that factors such as thermal stability, water temperature, and the duration of the ice-free season are essential for controlling phytoplankton dynamics in subarctic lakes. These elements influence nutrient and light availability, which are critical for phytoplankton growth and productivity. Similarly, Muñiz et al. (2018) studied the phytoplankton communities in temperate estuaries and found that nutrients and temperature were key factors influencing the seasonal variations in these communities. They noted that temperature fluctuations and nutrient availability affected phytoplankton abundance and species composition, with different species responding to these factors in various ways. Both studies underscore the importance of understanding seasonal patterns in phytoplankton populations. Seasonal shifts in environmental factors can significantly impact primary production and the broader aquatic food webs. Monitoring these patterns is essential for predicting how ecosystems respond to changing climatic conditions or human-induced pressures, such as nutrient pollution. Seasonal patterns in phytoplankton diversity vary across regions and are influenced by several factors. In saline-alkaline ponds, diatoms dominate year-round, with euglenophytes and blue-green algae appearing in summer and *Chrysophyta* in spring and winter (Wen et al., 2000). In the southern Mid-Atlantic Bight, phytoplankton blooms occur in January, February, and early autumn, with diatom diversity peaking in winter (Makinen et al., 2012). The Bohai Sea and North Yellow Sea experience a shift in phytoplankton community structure, with diatoms dominating throughout the year and the highest diversity in autumn (Fu et al., 2021). Diatoms and pico-nanoplankton are dominant in the lower Chesapeake Bay, with maximum development in winter, spring, and fall (Marshall, 1986). Seasonal changes in phytoplankton diversity are caused by several factors. Kivrak (2006) showed that phytoplankton density is influenced by the interplay of nutrients, temperature, pH, light availability, and water circulation. Nutrients provide the essential materials for growth, while temperature and pH regulate metabolic and physiological processes. Light availability, determined by water transparency, affects photosynthesis, and circulation patterns redistribute both nutrients and cells. Together, these factors interact with controlling phytoplankton abundance and distribution in aquatic systems. Jiang et al. (2012) highlighted that phytoplankton distribution is strongly shaped by temperature, chlorophyll *a*, and nutrient availability. Temperature regulates metabolic activity and seasonal succession, favoring different taxa under varying thermal conditions, while chlorophyll *a* serves as a reliable proxy for biomass, indicating areas and periods of high phytoplankton abundance. Nutrient levels, particularly nitrogen, phosphorus, and silica, directly control growth and community structure, with nutrient-rich waters supporting greater diversity and density. Together, these factors interact with both the spatial and temporal patterns of phytoplankton distribution. Schabhüttl et al., (2013) found that temperature and species richness can affect phytoplankton growth, with higher temperatures leading to higher fractions of cyanobacteria in the communities. Therefore, a comprehensive understanding of phytoplankton seasonality is vital for conserving and managing aquatic ecosystems as it aids in maintaining biodiversity, ecosystem stability, and water quality.

2.3 Potential Climate Change Influences on Phytoplankton Communities

Climate change is expected to alter tropical phytoplankton communities through multiple, interacting physical, chemical, and biological pathways. Rising atmospheric CO_2 can elevate dissolved inorganic carbon and alter seawater chemistry, while some taxa (e.g., coccolithophores) may show stimulated growth under higher CO_2, most phytoplankton display only limited direct photosynthetic responses to CO_2 enrichment (Beardall et al., 2009). Thus, direct carbon fertilization is likely to be species-specific and insufficient on its own to predict community shifts. Warming-driven increases in water temperature strengthen stratification in tropical oceans, which tends to reduce vertical nutrient flux into the euphotic zone and exacerbate nutrient limitation. This favors small, nutrient-efficient taxa (e.g., some picophytoplankton) over larger, fast-growing diatoms, and can alter size structure and productivity of the community (Beardall et al., 2009). At the same time, climate variability and warming drive biogeographic shifts, warm-adapted species expand their ranges while cold-water taxa retreat poleward, producing regional turnover in community composition and potential novel species assemblages (Hallegraeff, 2010).

In tropical systems, the effect of climate change on phytoplankton is modulated strongly by local abiotic context and micronutrient availability. Micronutrients (iron, trace metals) and macronutrient ratios influence which taxa can capitalize on changing conditions, so climate impacts are expressed differently across tropical environments (Oliveira et al., 2017). For example, semi-arid tropical regions may experience stronger synergistic effects between climate drivers (e.g., changed precipitation, runoff) and local physicochemical factors, producing more pronounced shifts in community structure compared with wetter regions (Oliveira et al., 2017).

Collectively, these changes have cascading consequences for primary productivity, biogeochemical cycling, and higher trophic levels. Altered community composition and size structure affect carbon export efficiency, nutrient recycling, and food-web transfer to zooplankton and fish, with implications for fisheries and ecosystem services. Importantly, responses are spatially heterogeneous and taxon-specific; therefore, predicting outcomes requires integrating species traits, nutrient dynamics, and physical forcing in observational and modeling frameworks

(Beardall et al., 2009; Hallegraeff, 2010; Oliveira et al., 2017).

2.4 Phytoplankton Diversity in Estuaries

Phytoplankton, a highly diverse group of microorganisms, are essential for global processes such as oxygen generation and nutrient cycling (Not et al., 2012). The composition and biomass of phytoplankton assemblages can vary significantly, with dominant species influencing their overall diversity (Burchardt et al., 2006). The Liguro-Provençal Basin in the northwestern Mediterranean Sea is particularly rich in phytoplankton species, with 168 taxa identified during the spring bloom (Percopo et al., 2011; Boudjenah et al., 2019). Collectively, these studies highlight the vast diversity of phytoplankton and the need for further research to understand and protect these vital organisms. The diversity index is an effective tool for assessing ecosystem health as it reflects ecosystem stability, which tends to improve with greater biodiversity. Studies have explored the Shannon-Wiener diversity index (H) in phytoplankton. Dagaonkar (2011) found a range of 2.6298 to 3.2112 in Munj Sagar Talab, indicating a high level of diversity. Ikhsan et al., (2015) reported a lower range of 1.30 to 1.71 in Diatas Lake. Zhang (2021) found a range of 1.34 to 2.24 in M River, indicating moderate diversity. These studies highlight the variability in phytoplankton diversity, which is influenced by location and water quality factors. Mason (1981) stated that a Shannon-Wiener diversity index above 3 indicates clean water, values between 1 and 3 reflect moderately polluted conditions, and values below 1 indicate heavy pollution. Generally, greater species diversity is linked to better ecological quality (Magurran, 1996).

Research on phytoplankton diversity in West African freshwater systems reveals remarkable taxonomic richness, functional variability, and strong seasonal dynamics influenced by hydrology and nutrient availability. In Ghana’s Bui Dam area, for instance, Alhassan (2015) identified 35 phytoplankton species spanning four major classes: Cyanophyceae (48.6%), Chlorophyceae (43%), Bacillariophyceae, and Euglenophyceae, with Cyanophyceae and

Chlorophyceae dominating across sampling stations. Similarly, Awortwi et al. (2015) examined Lake Bosomtwe, Ghana's only natural lake, and found persistent dominance of Cyanophyceae throughout its seasonal mixing and stratification cycles. The study highlighted strong temporal variability in phytoplankton biomass (CV > 28%), primarily controlled by changes in the mixed layer depth and euphotic zone, which regulate nutrient regeneration and light availability. These results emphasize how hydrodynamic processes influence both diversity and productivity in tropical deep lakes.

Investigations in Nigeria's Great Kwa River by Eyo et al. (2013) documented 89 species from six taxonomic groups, with Bacillariophyceae (55.06%) being the most dominant. The study attributed this dominance to the silica-rich conditions and dynamic riverine flow regimes that favor diatom proliferation.

Regional estuarine studies further highlight this variability. A study of the Eastern Obolo River Estuary, Nigeria, conducted between June - November 2015 (wet season) and December - May 2016 (dry season), examined phytoplankton diversity, distribution, and water quality. Species were more evenly distributed across three stations in the dry season, but less evenly distributed in the wet season. Shannon-Wiener indices (H) varied by station and season, while Simpson's diversity index (D) recorded the lowest values at station 2 in both seasons. Overall, 5,109 individuals representing 85 taxa, 16 orders, 8 classes, and 5 divisions were recorded in the wet season, compared to 6,906 individuals, 84 taxa, 18 orders, 6 classes, and 4 divisions in the dry season (Effiong et al., 2018).

Similarly, in the Nyong River Estuary, Cameroon, monitored over two seasonal cycles (2014–2015), 208 phytoplankton species were recorded, representing five algal groups. The Shannon-Wiener index showed qualitative seasonal differences in community composition, while dissolved nutrients (nitrogen and phosphorus) varied seasonally. Nutrient ratios were high during the rainy season (42.78) and low in the dry season (5.89), patterns that aligned with changes in species richness. Water quality assessments, using both biological indices (abundance, Shannon-Wiener, richness) and the Water Quality Index (WQI), indicated fluctuations between good and poor conditions (Mama et. al., 2018).

Phytoplankton diversity in estuarine environments is highly influenced by environmental factors, particularly by nutrient concentrations and their ratios. Research conducted in estuaries has demonstrated that phytoplankton species diversity, often assessed using indices such as Shannon's diversity and Pielou's evenness, tends to decrease from the upper to the middle reaches of estuaries but increases again toward the lower reaches (Deeley & Paling, 1998; Effiong et al., 2018; Ge et al., 2022). This pattern highlights the role of nutrient availability and hydrological dynamics in shaping the phytoplankton communities. Nutrient enrichment in estuaries often leads to lower diversity and higher phytoplankton abundance, with certain groups, particularly diatoms, dominating the community structure (Deeley & Paling, 1998; Badsi et al., 2012). This shift is typically associated with eutrophic conditions, where an overabundance of nutrients, such as nitrogen and phosphorus, can lead to phytoplankton blooms and reduce overall species richness. In these scenarios, dominant species thrive at the expense of a more diverse community, which can disrupt the ecosystem's balance and impact higher trophic levels. Salinity gradients also play a crucial role in influencing phytoplankton distribution and composition within estuaries. Variations in salinity, ranging from freshwater to brackish and marine zones, result in distinct phytoplankton communities that adapt to different salinity conditions (Badsi et al., 2012; Ge et al., 2022). These studies underscore the importance of phytoplankton diversity as a key indicator of estuarine health, highlighting the need for effective nutrient and salinity management strategies to maintain the ecosystem balance and prevent biodiversity loss (Deeley & Paling, 1998; Ge et al., 2022).

2.4.1 Ecological Importance of Phytoplankton Diversity

Cardinale et al. (2011) demonstrated that greater producer diversity enhances ecosystem functioning by improving resource-use efficiency and biomass production. This occurs because different species exploit resources such as light, nutrients, and space in complementary ways, leading to more complete utilization of available resources. As a result, species-rich communities often produce higher total biomass compared to less diverse systems. Ptáčník et al. (2008) showed that phytoplankton diversity has a direct relationship with resource use efficiency and carbon fixation, with diversity requirements increasing with nutrient levels. Reynolds (2006) provided a broad synthesis of phytoplankton ecology by examining how their adaptations, physiology, and population dynamics interact with environmental conditions across aquatic systems. He described how phytoplankton adapt morphologically (e.g., size, shape, buoyancy regulation) and physiologically (e.g., nutrient uptake strategies, light-harvesting pigments) to exploit variable conditions of light, nutrients, and turbulence. He also discussed how these adaptations drive population dynamics, including succession, bloom formation, and seasonal cycles, within lakes, rivers, and estuaries. Striebel et al. (2009) proposed that biodiversity–ecosystem functioning relationships in phytoplankton are strongly mediated by pigment diversity, as different taxa possess distinct pigments that absorb varying parts of the light spectrum. In species-rich communities, this diversity of pigments enables more complete utilization of available light, resulting in higher primary production and biomass accumulation compared to less diverse communities. The study further highlights the value of trait-based approaches, showing that understanding phytoplankton not only through taxonomy but also through functional traits such as pigment composition provides deeper insight into how diversity underpins ecosystem functioning and the ecological roles of different phytoplankton groups. Collectively, these studies highlight the crucial role of phytoplankton diversity in maintaining ecosystem stability, resource-use efficiency, and primary production in aquatic systems, with potential implications for global carbon cycling and ecosystem management (Reynolds, 2006; Ptáčník et al., 2008; Striebel et al., 2009; Cardinale et al., 2011).

2.4.2 Laboratory Analysis Methods for Diversity

Recent advancements in phytoplankton diversity analysis have expanded beyond traditional microscopic techniques. High-throughput sequencing and molecular tools such as fingerprinting and fluorescence in situ hybridization have revealed exceptional phylogenetic and genomic diversity (Johnson & Martiny, 2015). Pigment analysis via CHEMTAX and spectral fluorometry using instruments such as the Algae Lab Analyser offers indirect methods for assessing community composition, although their accuracy may vary depending on the lake trophic state (Ilić et al., 2023). While newer technologies, such as flow cytometry and visible spectrophotometry, can analyze phytoplankton biomass, classical light microscopy remains irreplaceable for species identification and community structure analysis. Methodological considerations in transitional waters, including sampling, conservation, sedimentation, and counting, are crucial for obtaining accurate results using inverted microscopy (Mazziotti & Vadrucci, 2007). Interlaboratory comparison tests are emphasized to minimize discrepancies in identification and counting among analysts.

2.5 Environmental Factors Affecting Phytoplankton

Studies have examined the impact of environmental factors on phytoplankton composition in various aquatic ecosystems. Abubakar et al. (2012) demonstrated that phytoplankton composition in Nguru Lake is determined by the combined influence of physical and chemical conditions, with temperature, conductivity, alkalinity, and nutrients shaping which species can thrive and dominate under given environmental settings. Adesalu et al. (2010) observed that rainfall, temperature, salinity, and nutrient levels influenced the phytoplankton abundance in two tidal creeks. Adesalu and Kunrunmi (2012) reported that rainfall, phosphate-phosphorus, nitrate-nitrogen, and salinity affect phytoplankton abundance in a Lagos tidal creek. Adesalu and Nwankwo (2008) noted variations in physico-chemical parameters between wet and dry months, with a higher phytoplankton biomass recorded in dry months. In all studies, diatoms were the dominant phytoplankton group. This study highlights the importance of monitoring water quality parameters and their effects on phytoplankton communities, which can serve as indicators of ecosystem health and anthropogenic impacts on aquatic environments.

2.5.1 Temperature Effects on Phytoplankton

Research on the effects of temperature on phytoplankton has revealed significant impacts on growth rate, community structure, and global distribution. Thomas et al. (2012) found that phytoplankton temperature optima correlated with local ocean temperatures, predicting poleward shifts and reducing tropical diversity with warming. Edwards et al. (2016) demonstrated that light limitation reduces temperature optima and diminishes the temperature sensitivity of bulk growth. Eppley (1971) proposed an equation to estimate maximum growth rates based on temperature, noting low assimilation numbers in Antarctic seas due to cold temperatures. Agawin et al. (2000) observed that picophytoplankton dominate in warm, nutrient-poor waters but contribute less in cold, nutrient-rich environments. They also found a strong inverse correlation between temperature and nutrient concentration. These studies collectively highlight the complex interplay between temperature, light, and nutrients in shaping phytoplankton communities and emphasizing the importance of considering these factors in predicting future changes in marine ecosystems under global warming scenarios.

2.5.2 Salinity changes in estuaries and the effects on phytoplankton

Estuarine phytoplankton communities were significantly influenced by changes in salinity and river discharge. Rapid salinity fluctuations can affect phytoplankton survival and growth, with species-specific responses potentially driving short-term succession (Shikata et al., 2008). Salinity gradients and nutrient composition govern phytoplankton community structure, with higher biomass observed in upper estuarine regions due to lower salinity and higher nutrient concentrations (Bharathi et al., 2022). Sluice construction can alter salinity distributions, potentially restricting phytoplankton growth and causing sharp decreases in certain species

(Yuan et al., 2020). Diatoms generally dominate in higher salinity areas, whereas blue-green algae thrive under low salinity and high N:P ratio conditions. These factors collectively shape the estuarine phytoplankton communities and their temporal variations.

2.5.3 Nutrient Availability and Limitation

The distribution and abundance of phytoplankton are influenced by numerous environmental factors, with nutrient availability serving as a primary determinant (Philips et al., 1997). In particular, nitrogen and phosphorus are often found to be limiting factors for phytoplankton growth (Crane & Sommerfeld, 1976). However, the incidence of phosphorus and silicon limitation is increasing due to higher nitrogen loading, which may alter phytoplankton community composition (Turner et al., 2003). Nutrient inputs and sedimentary loss have been shown to significantly affect phytoplankton community structures, with nutrient availability being the predominant factor (Pannard et al., 2007). These studies collectively highlight the importance

of nutrient availability and limitation as an environmental factor in shaping phytoplankton distribution.

2.5.4 Light Availability and Limitation to Phytoplankton Growth

Light availability plays a crucial role in the regulation of phytoplankton growth and production in marine ecosystems. In the Southern Ocean, light limitation significantly constrains phytoplankton growth throughout most of the year, even during the summer (Venables & Moore, 2010). Similarly, in the Labrador Sea, light is the primary limiting factor for phytoplankton growth, with nutrients becoming limited only in the summer and autumn (Harrison & Li, 2007). The western Antarctic Peninsula also experiences light-limited phytoplankton growth during spring, with dissolved iron availability playing a secondary role (Joy-Warren et al., 2019). Light limitation can modify the size-scaling of phytoplankton growth rates by reducing the size-scaling exponent from 3/4 under abundant resource conditions to approximately 2/3 when light is restricted (Mei et al., 2009). This emphasizes the critical role of light availability in influencing phytoplankton communities and productivity in diverse marine ecosystems, with significant implications for carbon sequestration and food web dynamics in changing climates. Light availability frequently emerges as a primary limiting factor for phytoplankton growth in tropical and subtropical aquatic systems, often surpassing the influence of nutrient availability or grazing pressure (Loiselle et al., 2007). In turbid environments, low light penetration directly restricts phytoplankton standing crops, preventing them from reaching levels that available nutrients could potentially support (Philips et al., 1997). The critical photic depth to mixed depth ratio governs this limitation, as phytoplankton growth rates can be robust in optimal conditions but become negative when this ratio is small, forcing cells into light-deprived waters (Cloern & Alpine, 1988). This dynamic is not uniform across a water body; spatial variations reveal that light limitation typically decreases from the more turbid riverine zones to the clearer dam regions, where nutrient limitation, such as by phosphorus, may become more pronounced (Cunha & Calijuri, 2011). While tropical phytoplankton communities show similar energetic requirements to theoretical models, their lower efficiency compared to benthic algal communities underscores the fundamental role of light-mixing dynamics in controlling primary productivity across these diverse ecosystems (Loiselle et al., 2007).

2.5.5 Effects of turbidity on phytoplankton

Turbidity is a critical factor influencing light availability and primary productivity in estuarine ecosystems. Several studies have established a strong inverse relationship between turbidity and light penetration, where increased suspended particles in the water column significantly reduce the depth and intensity of photosynthetically active radiation (PAR) (Cloern, 1996; May et al., 2003). Estuaries are naturally dynamic environments characterized by strong interactions between freshwater inflows and tidal mixing, which frequently resuspend sediments and organic matter, leading to fluctuating turbidity levels (Loiselle et al., 2007). High turbidity itself reduces the sunlight needed for photosynthesis, thereby limiting phytoplankton growth. The very factors that cause high turbidity, such as rainfall runoff or the stirring of bottom sediments, can simultaneously introduce significant amounts of nutrients like nitrogen and silica. These newly available nutrients can then fuel algal growth. Therefore, the overall effect on the phytoplankton community depends on which factor is dominant: the light-limiting effect of the cloudy water or the growth-enhancing effect of the nutrient pulse. A study in Lake Batata investigated the complex relationship between inorganic turbidity and phytoplankton chlorophyll a (chl-a) concentrations. Contrary to a simple inverse relationship, the researchers found that inorganic turbidity did not consistently reduce chl-a levels. Instead, the effect depended on the initial chl-a concentration. In experiments with high initial chl-a, high turbidity was associated with a decrease in chl-a concentrations. Conversely, in low-chl-a treatments, high turbidity was linked to an increase in chl-a. This suggests that the impact of inorganic turbidity on phytoplankton is not solely due to light limitation, but is also mediated by other factors, potentially nutrient releases from the sediment itself, which have a more pronounced positive effect in systems with initially low algal biomass (Nunes et al., 2022). Spatial and temporal variations in turbidity, which are influenced by factors such as wind, tides, and fetch, play crucial roles in phytoplankton bloom development (May et al., 2003). Turbulence, a key component of water movement, generally inhibits phytoplankton growth but can improve nutrient uptake at low concentrations (Zhao et al., 2020). The interplay between turbidity, nutrients, and phytoplankton is intricate, with turbidity often being the dominant factor affecting phytoplankton dynamics. Understanding these relationships is crucial for the effective management of aquatic ecosystems, especially shallow lakes and reservoirs vulnerable to human-induced disturbances.

2.5.6 Effects of pH changes in estuaries on phytoplankton

Estuarine pH in Ghana and other tropical regions is influenced by various factors, including seasonal changes, anthropogenic activities, and natural processes. Studies in Ghanaian estuaries have shown that pH levels can vary significantly between 6.10 and 7.59, with higher values observed in some estuaries than in others (Dzakpasu & Yankson, 2015). Phytoplankton communities in tropical estuaries are strongly affected by pH and salinity gradients, with lower pH being associated with reduced taxonomic diversity (Majewska et al., 2017). Environmental degradation, such as increased turbidity from illegal mining activities, can negatively affect estuarine water quality and potentially affect fish recruitment (Okyere, 2019). Long-term studies in large estuaries have revealed that local processes, including changes in phytoplankton biomass and river alkalinity, can significantly influence pH trends, often overshadowing the effects of ocean acidification (Hall et al., 2023). These findings highlight the complex interplay between factors affecting estuarine pH and emphasize the need for comprehensive management strategies to protect these vital ecosystems.

2.6 Sampling Techniques in Phytoplankton Research

Kraberg et al. (2017) provided an overview of sampling methods, emphasizing the importance of consistency in time series studies and highlighting the potential of molecular techniques. Majaneva et al. (2009) compared five sampling methods, noting no significant differences when used properly, although samples collected from ships of opportunity may underestimate the biomass during cyanobacterial blooms. McAlice (1971) proposed a two-stage sampling approach using the Sedgwick-Rafter cell designed for larger phytoplankton species with high densities. Irish and Clarke (1984) introduced a stratified random sampling method with two-stage sub-sampling to estimate chlorophyll a and algae species concentrations in limnetic environments and found that stratification could reduce the estimator variance by up to 50% for certain species and sampling dates. These studies emphasize the importance of selecting appropriate sampling methods based on research objectives, environmental conditions, and target species to ensure accurate and reliable phytoplankton abundance estimates.

2.6.1 Challenges and Limitations of Existing Methods of Phytoplankton Analysis

The enumeration and taxonomic identification of phytoplankton face several challenges and limitations of the existing methods. Traditional microscopy methods, such as the Utermöhl technique, are labor-intensive and may fail to accurately capture smaller cells (Utermöhl, 1958). The proposed sampling frequency of the Water Framework Directive may be insufficient to detect algal blooms and assess phytoplankton succession (Domingues et al., 2008). Inverted microscopy, commonly used worldwide, cannot distinguish between autotrophic and heterotrophic cells or observe smaller-sized organisms (Domingues et al., 2008). Imaging flow cytometry has become a promising technology by merging the rapid analysis of flow cytometry with detailed imaging of microscopy, although it still has certain limitations (Dashkova et al., 2017). For pigment analysis, spectrophotometric methods are practical and cost-effective for routine chlorophyll estimation, whereas HPLC is more suitable for determining various pigment concentrations in phytoplankton communities (Hasani, 2023). Each method has its advantages and drawbacks, necessitating careful consideration when selecting an approach for phytoplankton analysis.

2.7 Taxonomy and Classification of Phytoplankton

The taxonomy and classification of phytoplankton have been explored in various studies. Soylu (2010) identified 112 taxa in Liman Lake, categorizing them into R- and C-strategists. Chrétiennot-Dinet (1993) presented a comprehensive classification of marine phytoplankton, organized by class, family, and genus. (Yamada et al.,1980) proposed a classification system for eutrophic levels in marine regions based on dominant phytoplankton species. Gopinathan (2007) provided an overview of phytoplankton and highlighted the importance of various classes and their characteristic pigments. These studies collectively contribute to our understanding of phytoplankton taxonomy and classification.

Phytoplankton classification encompasses various taxonomic groups, including diatoms, dinoflagellates, and cyanobacteria (Gopinathan et al., 2007). Chrétiennot-Dinet et al. (1993) provided an updated classification of marine phytoplankton from class to genus, following botanical nomenclature. Johnsen et al. (1994) examined the light absorption characteristics of ten phytoplankton classes and demonstrated that spectral analysis can distinguish between groups based on their accessory chlorophylls. They achieved 97-99% accuracy in classifying low- and high-light-adapted cells using discriminant analysis. Diatom classification has evolved. Williams and Kociolek (2007) emphasized the importance of recognizing monophyletic groups based on evidence, rather than relying on paraphyletic taxa. They suggested that the natural classification of diatoms may require significant restructuring, impacting future research and training in the field.

Phytoplankton taxonomic groups are vital to marine ecosystems and the global carbon cycle. Six primary groups dominate the global phytoplankton populations: chlorophytes, diatoms, haptophytes, cryptophytes, cyanobacteria, and dinoflagellates (Li et al., 2023). These groups have distinct spatial distributions, with diatoms common in high-latitude and coastal regions, whereas chlorophytes and haptophytes are more dominant in open ocean areas (Li et al., 2023). Phytoplankton communities can be classified using functional taxonomic or size-based criteria, with species-richness-cell-size relationships following similar patterns across groups (Ignatiades, 2017). Absorption spectra can be used to estimate phytoplankton taxonomic group concentrations, potentially enabling satellite-based monitoring (Zhang et al., 2018). In specific ecosystems such as the Mesopotamian Marshlands, Bacillariophyceae, Chlorophyta, and Cyanophyta are the dominant groups, with species richness and diversity varying seasonally due to environmental factors such as nutrients, salinity, temperature, and light intensity (Al-Obaidi et al., 2009).

2.7.1 Diatoms

Diatoms are a highly diverse group of phytoplankton that are essential for global carbon fixation and the functioning of marine ecosystems (Falciatore et al., 2019). They exhibit complex size scaling patterns and functional group relationships, which are important for understanding phytoplankton community structure (Ignatiades, 2017). Accurate taxonomic identification, often requiring electron microscopy, is essential for correctly associating diatom species with functional groups, particularly in karst lakes (Gligora Udovič et al., 2017). Recent molecular phylogenetic analyses of organelle genomes have revealed discrepancies between morphological characteristics and evolutionary relationships in some diatom genera, suggesting the need for taxonomic reinvestigation (Jeong & Lee, 2024). Model species such as *Thalassiosira pseudonana* and *Phaeodactylum tricornutum* have become essential for diatom molecular research, enhancing our understanding of their biology, evolutionary processes, and metabolic adaptations. (Falciatore et al., 2019). These findings highlight the complexity of diatom taxonomy and the importance of integrating morphological and molecular approaches into phytoplankton research.

2.7.2 Dinoflagellate

Dinoflagellates are a diverse group of phytoplankton classified within the division Pyrrhophyta (Steidinger et al., 2001). They comprise over 2,300 species across 238 genera, including both armored and unarmored species (Gómez, 2012). Classification is based on the morphological features of motile stages and cysts, as well as molecular data. Key taxonomic characteristics include thecal plate patterns, cingular plate numbers, and chloroplast presence (Hallegraeff & Lucas, 1988). For example, the genus *Dinophysis* includes both photosynthetic neritic and non-photosynthetic oceanic species (Hallegraeff & Lucas, 1988). Some dinoflagellates, such as Pfiesteria, are thinly armored and characterized by distinct plate formulae (Steidinger et al., 2001). Despite advances in molecular techniques, dinoflagellate classification remains a challenge, particularly at the order level (Gómez, 2012). Ongoing research combines morphological and genetic approaches to refine the taxonomic relationships within this important phytoplankton group (Steidinger et al., 2001).

2.7.3 Cyanobacteria

Cyanobacteria, a diverse group of phytoplankton, play crucial roles in global biogeochemical cycles and form symbiotic relationships with various organisms (Foster & Zehr, 2019). Their taxonomy has evolved from traditional morphological classifications to modern genomic approaches (Komárek, 2003; Palińska & Surosz, 2014). Recent ecogenomic studies have identified 57 genera and 87 species of cyanobacteria, categorizing them into three major ecological groups based on their temperature and nutrient preferences (Walter et al., 2017). However, the concept of cyanobacterial species remains challenging due to their morphological variability and genetic diversity (Komárek, 2003). Taxonomic classification incorporates morphological, physiological, ecological, and molecular data to better define cyanobacterial species (Palińska & Surosz, 2014). Despite their ecological importance, cyanobacterium-phytoplankton symbioses, particularly those involving nitrogen-fixing cyanobacteria, remain understudied, but are potentially more widespread and significant in global nitrogen cycling than previously thought (Foster & Zehr, 2019).

2.7.4 Green Algae

Green algae have become valuable model organisms for investigating biological fluid dynamics such as flagellar movement, nutrient absorption, and collective behaviours (Goldstein, 2015). Green algae, particularly *Chlamydomonas reinhardtii*, show promise for biofuel production by utilizing their photosynthetic capacity to generate renewable energy sources such as hydrogen and biodiesel (Dubini, 2011). The cell walls of green algae exhibit remarkable diversity and complexity, with some taxa possessing polymers like those found in land plants, including cellulose, pectins, and lignin (Domozych et al., 2012). This diversity in cell wall composition varies across different green algal groups and life cycle phases, highlighting the need for further research to fully understand the evolutionary trends and potential industrial applications of these organisms (Domozych et al., 2012).

2.7.5 Cocolithophores

Coccolithophores are unicellular algae that produce intricate calcite plates, called coccoliths (Young & Henriksen, 2003). These organisms play crucial roles in marine primary production, carbon fixation, and the global carbon cycle (Charalampopoulou, 2011). Coccolithophores belong to the algal division Haptophyta and are characterized by golden-brown chloroplasts and a unique organelle called haptonema (Young & Henriksen, 2003). Recent studies have revealed complex life cycle strategies and novel metabolic pathways that contribute to the ecological success of species that are being reintroduced or are part of restoration efforts (Taylor et al., 2017). Research has also uncovered evidence of pseudocryptic speciation in coccolithophores, suggesting strong stabilizing selection of their phenotypes (Sáez et al., 2003). Environmental factors, such as temperature, nutrient concentrations, and mixed layer irradiance, influence coccolithophore distribution and calcification rates (Charalampopoulou, 2011). Understanding these organisms is crucial for improving biostratigraphic resolution, paleoceanographic data retrieval, and predicting their responses to future ocean changes (Sáez et al., 2003; Charalampopoulou, 2011).

2.8 Phytoplankton Blooms

Phytoplankton blooms are significant events in coastal ecosystems and are characterized by the rapid production and accumulation of phytoplankton biomass. These blooms can be triggered by various physical forcings, including tides, wind, and river runoff, and they play crucial roles in biogeochemical cycles (Cloern, 1996). Blooming species often escape microzooplankton grazing control through mechanisms such as increased size, colony formation, and toxin production (Irigoien et al., 2005). Nutrient enrichment from continental sources frequently leads to high-biomass blooms in coastal waters, as has been observed in the Belgian Coastal

Zone (Rousseau et al., 2006). However, anthropogenic nutrient loading can have long-term consequences for estuarine systems, potentially causing disruptions in food webs and reductions in invertebrate and fish populations (Livingston, 2007). The impact of these blooms can be exacerbated by factors such as drought conditions and hypoxia caused by salinity stratification (Livingston, 2007).

2.8.1 Toxin-Producing Phytoplankton

Toxin-producing phytoplankton pose significant health risks and economic challenges globally, causing various shellfish poisoning syndromes (Pradhan et al., 2022; Hernández-Becerril et al., 2007). However, these toxins also have potential therapeutic applications in conditions such as cancer, diabetes, and Alzheimer's disease (Pradhan et al., 2022). In Mexico, harmful algal blooms have led to human fatalities and economic losses, with dinoflagellates being the primary toxin producers (Hernández-Becerril et al., 2007). The dynamics of toxin-producing phytoplankton populations are influenced by nutrient concentrations and toxin liberation rates, which can affect the persistence of plankton populations and potentially terminate harmful algal blooms (Jang & Allen, 2015). Although the harmful effects of these toxins are well-established, their mechanisms of action and molecular pathways, especially concerning reactive oxygen species, still require further study (Pradhan et al., 2022). Ongoing research focuses on monitoring, mitigating, and exploring the pharmacological potential of these toxins (Pradhan et al., 2022; Hernández-Becerril et al., 2007).

2.8.2 Shellfish Poisoning

Shellfish poisoning results from the consumption of seafood contaminated with marine biotoxins produced by algae (Çetinkaya & Mus, 2012; Kumar et al., 2021). The five main types of shellfish poisoning are paralytic (PSP), neurotoxic (NSP), diarrhetic (DSP), amnesic (ASP), and azaspiric acid (AZP), which are associated with various gastrointestinal and neurological symptoms (Çetinkaya & Mus, 2012; Chegini & Metcalfe, 2005). PSP is the most dangerous form, potentially leading to respiratory paralysis and fatality within 2-12 hours after consumption (Lehane, 2000). Mouse bioassays are commonly used to detect PSP toxins, but there is pressure to develop alternative chemical methods (Lehane, 2000). Shellfish poisoning can often be mistaken for allergic reactions, making diagnosis challenging (Chegini & Metcalfe, 2005). The prevalence of harmful algal blooms (HABs) has significant economic and health impacts, highlighting the need for improved detection and monitoring techniques (Kumar et al., 2021).

2.9 Community Structure

The phytoplankton community structure in estuaries is shaped by a combination of salinity gradients, nutrient compositions, and hydrological features, which interact to influence distribution and abundance (Bharathi et al., 2022). Salinity variations are particularly important, as they dictate which species thrive in different zones. For instance, green algae and diatoms are more prevalent in low-salinity areas, whereas diatoms tend to dominate high-salinity regions (Bharathi et al., 2022). Nutrient availability, particularly dissolved nitrogen, phosphorus, and silicate levels, further influences phytoplankton composition, with different nutrient regimes favoring certain species over others. Seasonal changes and anthropogenic activities can significantly alter nutrient concentrations and affect phytoplankton dynamics over time (Nunes et al., 2018). Nutrient inputs from agricultural runoff, urbanization, and industrial discharge often lead to shifts in phytoplankton communities, sometimes resulting in harmful algal blooms or reduced species diversity. Hydrological factors, including rainfall and riverine inputs, play a key role in shaping water flow, nutrient distribution, and salinity, which in turn affect phytoplankton community structure (Nunes et al., 2018). Beyond salinity and nutrients, environmental variables such as light availability, water depth, and suspended particulate matter also influence phytoplankton abundance and diversity. Fluctuations in these conditions can either limit or enhance phytoplankton growth by affecting photosynthesis and nutrient absorption (Bharathi et al., 2022; Nunes et al., 2018). A thorough understanding of these complex interactions is crucial for evaluating estuarine ecosystem health and for creating management strategies to reduce human impacts on phytoplankton communities.

CHAPTER 3

3.0 METHODOLOGY

3.1 Study Area

The Anyanui Creek is situated in the Volta region of Ghana, with coordinates ranging from 05°45’N - 000°42’E and 05°49’N - 000°50’E. The creek extends approximately 26 km, originates in the town of Atorkor, and flows through Dzita and Anyanui before ending at Fuveme, a town that has been eroded by coastal processes (Darpaah, 2013; Lamptey & Ofori-Danson, 2014). The Anyanui Creek has an average depth of 8 m, with some depressions reaching depths greater than 21 m. Tidal actions, along with continual erosion and deposition, have significant effects on the creek's morphology.

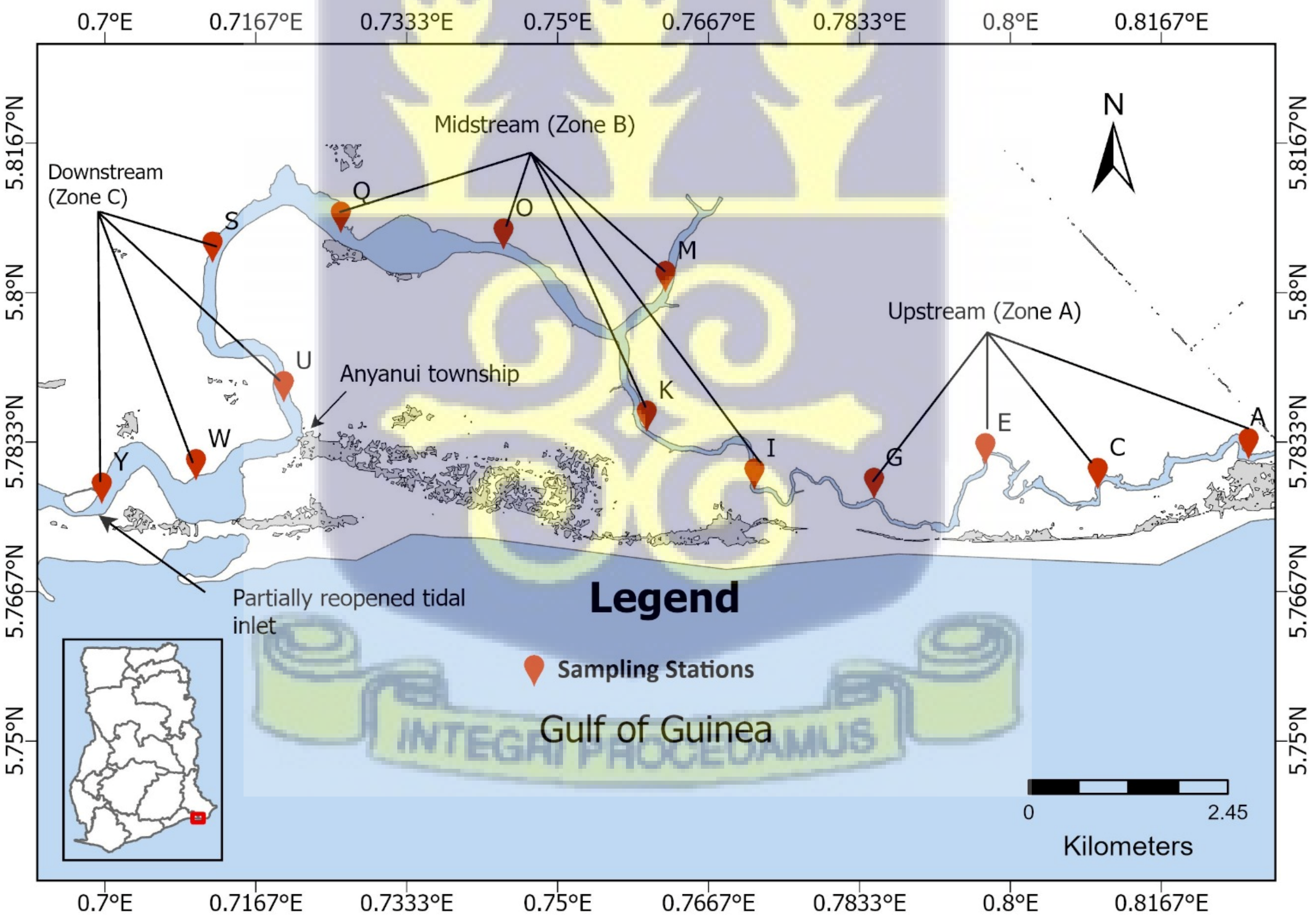

Fig. 1: Map of Anyanui Creek showing sampling points and zones.

The Anyanui Creek supports numerous local communities, including Anyanui, Atiteti, Dzita, and Glikpe, playing a crucial role beyond its geographical presence by integrating deeply into local society. It serves as a vibrant source of livelihood, facilitating various activities such as farming, mangrove plantation and harvesting, fishing, and the growing ecotourism sector, all of which contribute to the region's development. However, the health of the overall ecosystem has been severely impacted by nutrient overload due to urbanization and daily human activities. Besides its importance to human livelihoods, the Anyanui Creek is vital to the area's biodiversity. It offers essential nursery grounds for various fish species, including the black chin tilapia. The surrounding mangrove forests provide invaluable ecological services, serving as substrate for diverse shellfish species and underscoring the interconnected dependencies within these ecosystems.

3.2 Field Sampling

The coastline of Ghana stretches about 560 km, constituting the Western, Central, and Eastern coasts. There are two defined rainy seasons, from April to June and September to October, and two dry seasons, from November to March and July to August (Ntow and Botwe, 2011). Phytoplankton and water samples were collected monthly at low tide from approximately 0.8 meters below the surface in the Anyanui Creeks over ten months (April 2023, May 2023, July 2023, September 2023, October 2023, November 2023, December 2023, January 2024, February 2024, and March 2024). Phytoplankton samples were collected from thirteen (13) sampling locations using a phytoplankton net, following established methodologies (Piranti et al., 2021).

Approximately 100 L of water was collected at each station by filling a 10 L bucket ten times. The pooled water was then filtered through a 30-µm mesh phytoplankton net to concentrate the phytoplankton, and the resulting sample was transferred into labeled bottles for preservation and subsequent analysis. Each bottle was preserved with 2-3 drops of 5% formalin and covered with the lid to prevent any leakage. Replicates were not taken because the bulk sampling method already incorporated multiple sub-samples (10 × 10 L buckets) into a single composite, thereby reducing small-scale variability and ensuring that the final concentrate was representative of the sampling location (Piranti et al., 2021). Temperature, salinity, dissolved oxygen, and pH were recorded using a multi-parameter probe (Horiba AU-50 series).

3.3 Nutrient Analysis

3.3.1 Nitrate

For the analysis of nitrate, 0.5 mL of each sample was combined with 0.05 mL of amidosulfuric acid. 3.5 mL of a sulfuric acid-phosphoric acid mixture (1:1) was then added, followed by the addition of 0.5 mL 2.6-dimethylphenol and mixed thoroughly. The mixture was allowed to stand for 10 min to develop an amber color, after which the absorbance was measured at 360 nm using a UV-spectrophotometer (Angstrom-advance UV-1800 PC).

3.3.2 Phosphate

Phosphate (PO_4^{3-}) concentrations in the water samples were analyzed using the Ascorbic Acid Method. A combined reagent was prepared by mixing 50 mL of 2.5 M sulfuric acid, 5 mL of potassium antimonyl tartrate, 15 mL of ammonium molybdate, and 30 mL of ascorbic acid, which remained stable for up to 4 h. For phosphate analysis, 10 mL of each water sample was mixed with 5 mL of the combined reagent, which resulted in the formation of a blue color within 10-30 min. The absorbance was then measured at 880 nm using the UV-spectrophotometer. Standard calibration curves were generated using serial dilutions of a 1000 ppm phosphate stock solution with concentrations ranging from 0.1 ppm to 5 ppm. Distilled water was used as the blank for the spectrophotometric measurements.

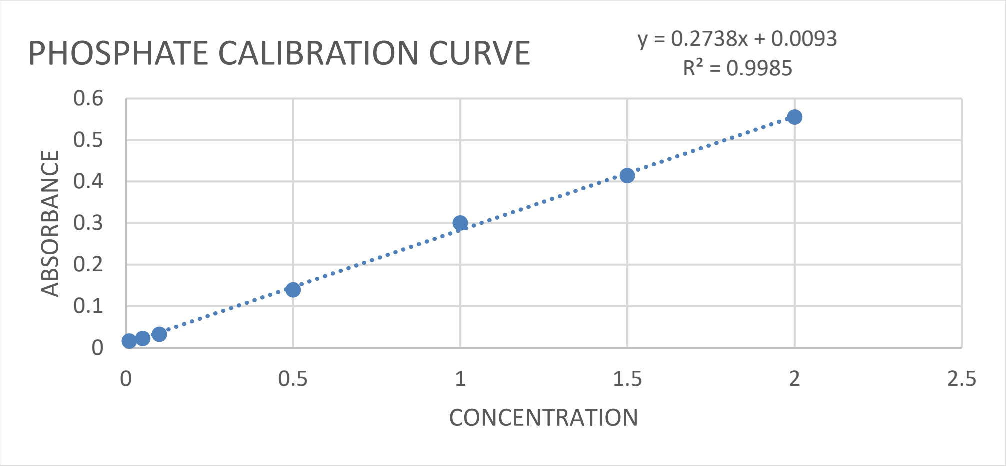

Fig. 2: Standard Calibration Curve for Phosphate (mg/L)

3.3.3 Silicate

The spectrophotometric determination of silicate in the water samples involved forming ά-molybdosilicic acid and reducing it with a Tin (IV)-Ascorbic-Oxalic acid mixture. 25 mL of each sample was mixed with an acetate buffer and a molybdate reagent, followed by the addition of a reductant solution after 15 min. 20 min after color development, the absorbance was measured at 740 nm using the UV-spectrophotometer. Due to high silicate concentrations, the samples were diluted to a 1:1 ratio with distilled water, and a conversion factor of 2 was applied.

3.3.4 Ammonium

To determine ammonium concentration, 5 mL of each sample was taken and 0.5 mL of Rochelle/Seignet salt solution was added, followed by the addition of 0.5 mL of Nessler reagent solution and mixing thoroughly. The mixture was left to stand for 10 min to allow the development of a yellow color. A 1000 ppm ammonium chloride stock solution was prepared by dissolving 3.8190 g of dried NH_4Cl in 1000 ml of distilled water. Serial dilutions of 0.1-5 ppm were made from a 100 ppm intermediate solution, and distilled water was used as blank. The absorbance of the final solution was measured at a wavelength of 425 nm using the UV-spectrophotometer.

3.4 Phytoplankton Analysis

In the laboratory, the water samples were analyzed under Optika B-383MET Microscope at 10x magnification to identify and count phytoplankton. The use of a microscope is crucial for accurately identifying and enumerating phytoplankton species (Piranti et al., 2021). A small amount of the preserved sample was placed on a Sedgewick Rafter for scanning and identification purposes.

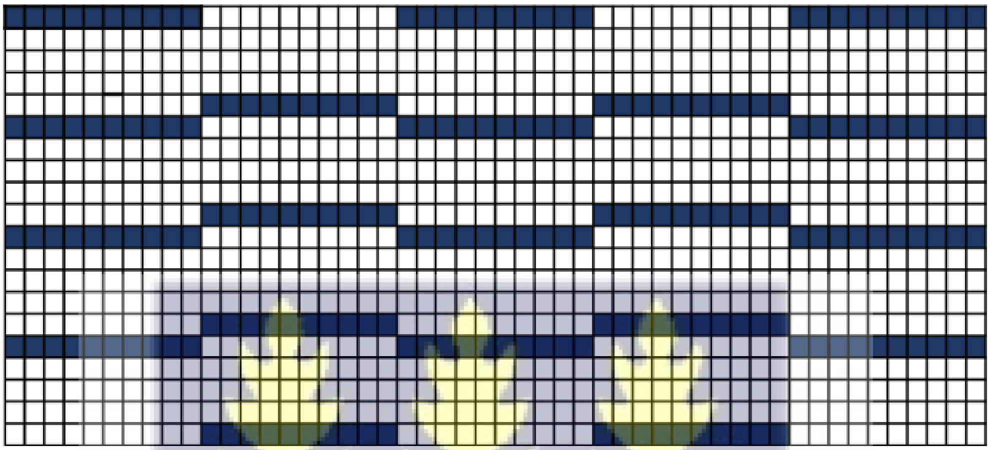

Fig. 3: Phytoplankton species counting pattern using the Sedgewick Rafter

Phytoplankton species were enumerated using counting chambers designed to hold 1000 mm³ of liquid, with a depth of 1 mm across an area measuring 50 mm x 20 mm. The base of the chamber was marked with 1 mm grid squares and covered with glass to ensure that the liquid reached the correct depth. A 10x magnification was used to observe, identify, and count the phytoplankton species present in 1 mm³ of the water sample. Identification of phytoplankton species was aided by a taxonomist expert, keys, and reference guides (Verlecar & Desai, 2004) to offer detailed descriptions and illustrations.

3.5 Data Analysis

3.5.1 Phytoplankton species abundance

Phytoplankton species density in the water samples was determined using Eqn. 1:

$$N = \frac{(Ax1000)}{L}$$

(Deswati, 2018) ....Eqn. 1

Where:

N = abundance of phytoplankton species (number of individuals in 1 L of water sample) A = number of individuals of a species in 1 ml of water sample

C = volume of water sample analysed

L = volume of water sampled (L).

3.5.2 Species diversity of Phytoplankton

Phytoplankton species diversity was calculated across the different sampling months and zones using the Shannon-Wiener diversity index (Shannon & Wiener, 1949) and Pielou's evenness (Pielou, 1966; Sun et al., 2004; Cuici et al., 2006).

3.5.2.1 Shannon-Wiener diversity index (H')

Calculation of the Shannon-Wiener Diversity Index (H′) assumes that individuals are randomly sampled from a sufficiently large population and that the sample includes all species present in the population. The Shannon-Wiener Diversity Index, though originally designed for benthic communities, is widely used for plankton studies because it captures both species richness and evenness (Lehtinen et al., 2017). To maintain consistency and enable meaningful comparisons with other studies and different habitats (Clarke and Warwick, 2001), this diversity index is commonly calculated using a logarithmic base (Log2 transformation). The Shannon-Wiener diversity index (H) is calculated from Eqn. 2:

$H = -\sum Pi \ In \ Pi$...Eqn. 2

Where:

Pi = S/N

S = number of individuals of a species

N = total number of all individuals in the sample;

In = the natural logarithm.

3.5.2.2 Pielou's evenness (J)

Pielou's evenness index is another measure of species diversity, which indicates how uniformly the individuals of the different species in a population are distributed.

$J = H/\ln S$ ....Eqn. 3

Where:

H = Shannon–Wiener Diversity Index

S = the total number of species in the sample

3.5.2.3 Margalef Species Richness (d)

Margalef's Species Richness Index (d) was calculated to estimate species richness while accounting for sample size. The index was computed using the formula:

$d=S-1/\ln N$ …………………………………..Eqn 4

Where:

S = total number of species observed (species richness)

N = total number of individuals in the sample

ln = natural logarithm

3.5.3 Community Structure of Phytoplankton Species

The Plymouth Routines in Multivariate Ecological Research (PRIMER v6) software was used to analyze phytoplankton community structure through multivariate statistical approaches (cluster analysis). Cluster analysis was performed to group sampling zones and months based on similarities in their physicochemical conditions and phytoplankton communities, allowing patterns of ecological similarity or difference to be identified. Principal Component Analysis

(PCA) was used to reduce the complexity of the multivariate environmental dataset and to identify the dominant gradients influencing water quality in Anyanui Creek. Since several physicochemical variables (temperature, salinity, dissolved oxygen, pH, and nutrients) were measured simultaneously and are often interrelated, PCA provided a way to condense this information into fewer axes that explained the greatest variance. This allowed for clearer visualization of seasonal and spatial patterns, such as the clustering of months under similar conditions and the separation of months with unique environmental profiles. This analysis helped to address Objective 3.

3.5.4 Analysis of Physicochemical Parameters

To test for differences in physicochemical parameters across the sampling zones of Anyanui Creek, a one-way Analysis of Variance (ANOVA) was performed. This method was selected because it allows for the comparison of mean values of a continuous variable (e.g., salinity, temperature, dissolved oxygen, pH, nutrients) (Likando & Chipandwe, 2024) across more than two independent groups (the creek's zones). A significance threshold of $p < 0.05$ was applied to determine whether observed differences were statistically meaningful. Where significant variation was detected, Tukey's Honestly Significant Difference (HSD) post-hoc test was used to conduct pairwise comparisons between zones. This test was chosen because it controls Type I error (false positives) while identifying which specific groups differed from each other.

In addition, SPSS version 16.0 was used to perform correlation analyses between physicochemical parameters (e.g., temperature, salinity, pH, dissolved oxygen, and nutrients). This allowed for the examination of relationships between environmental variables and phytoplankton dynamics, addressing Objective 3.

CHAPTER 4

4.0 RESULTS

4.1 Phytoplankton Species Composition of the Anyanui Creek

Phytoplankton species composition of the Anyanui Creek was estimated based on the number of individuals per unit volume of water sampled. Fig. 4 shows the phytoplankton species identified and their percentage composition in the Anyanui Creek over the sampling period. Thirty-four (34) phytoplankton species belonging to three different taxonomic groups (diatoms, dinoflagellates, and cyanobacteria) were identified, among which diatoms were the most dominant (92.92%), followed by dinoflagellates (1.13%) and cyanobacteria (0.11%). Of the diatom group, the order of species prevalence was *Chaetoceros sp*. (36.85%) > *Nitzschia sp.* (15.28%) > *Coscinodiscus sp.* (9.36%) > *Entomoneis sp.* (5.21%) > *Lithodesmus sp.* (0.02%) ≈ *Detonula sp.* (0.02%).

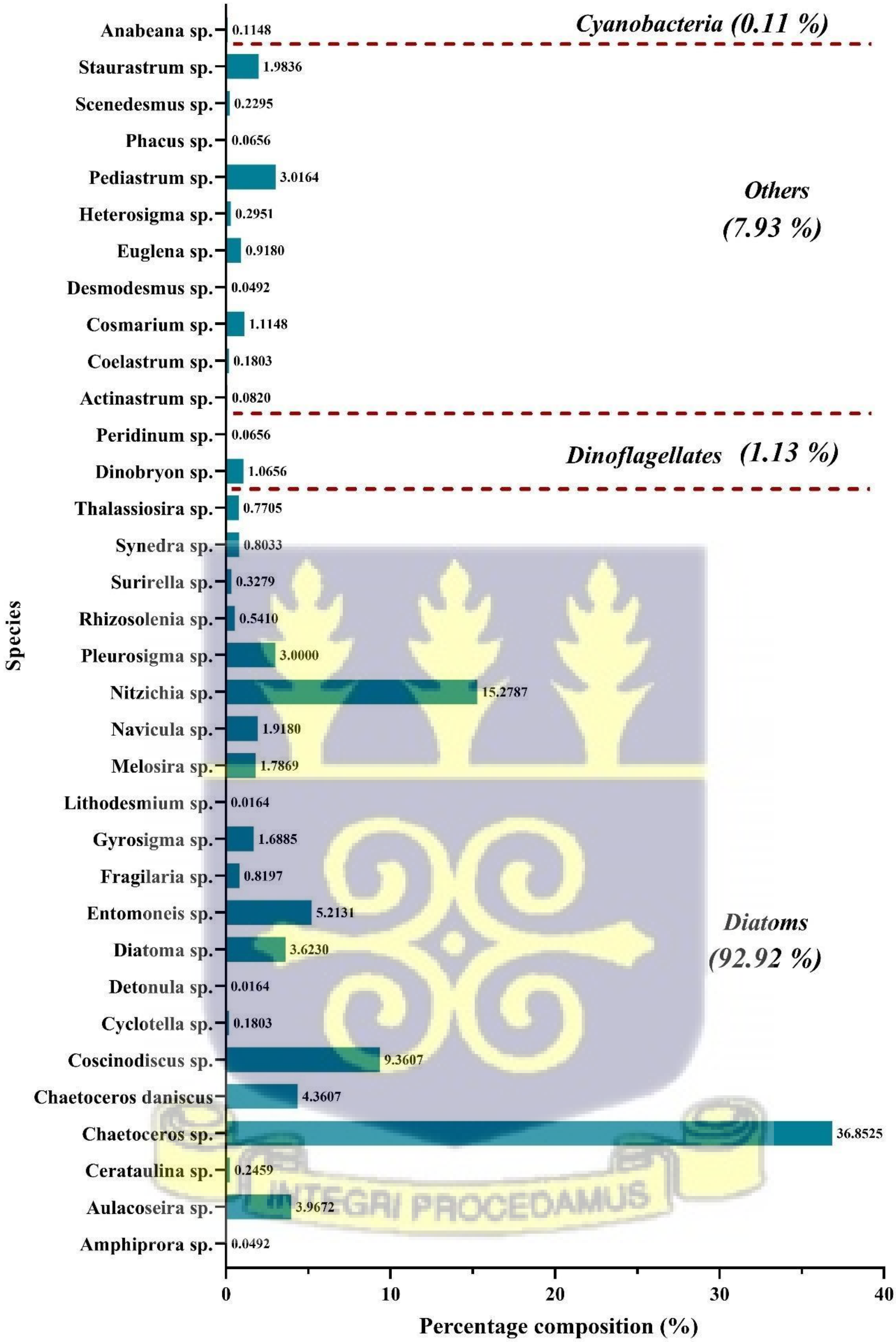

Fig. 4: Phytoplankton species and their percentage composition in the Anyanui Creek from April 2023 to March 2024

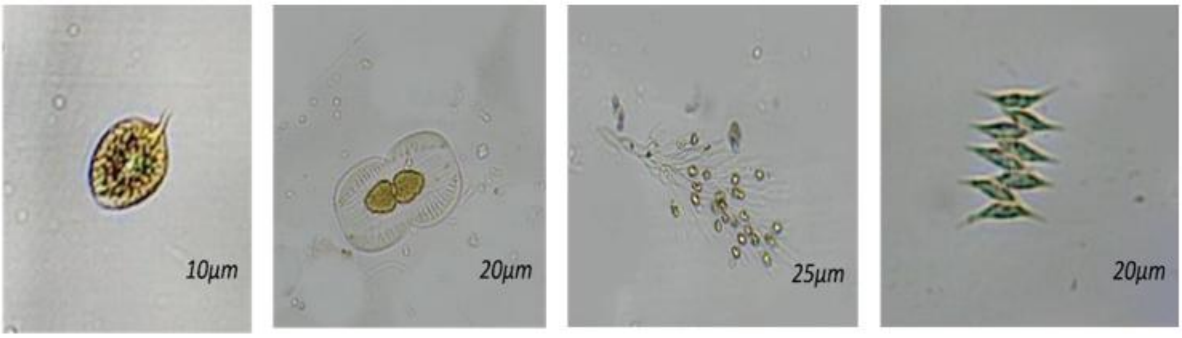

Fig 5a: Phacus sp Fig 5b: Entomoneis sp Fig 5c: Dinobryon sp Fig 5d: Scenedesmus sp

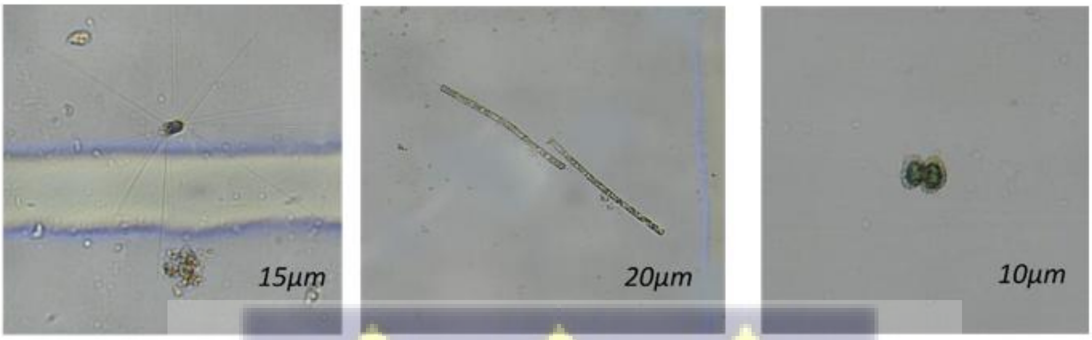

Fig 5e: Chaetoceros daniscus Fig 5f: Aulacoseira sp Fig 5g: Cosmarium sp

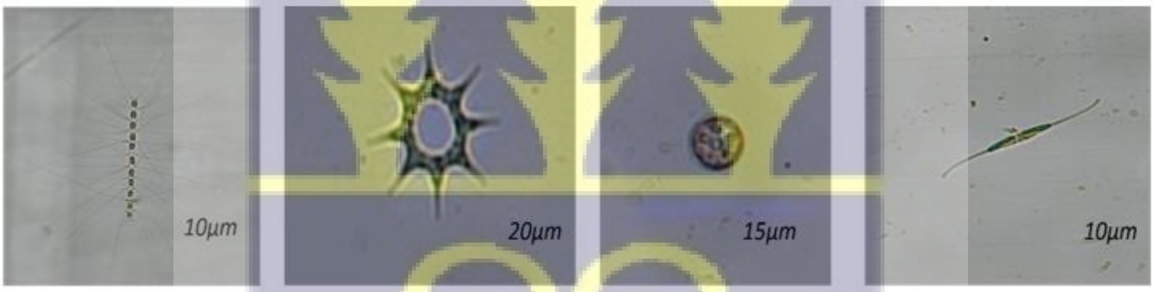

Fig 5h: Chaetoceros sp Fig 5i: Staurastrum sp Fig 5j: Coscinodiscus sp Fig 5k: Nitzichia sp

Fig. 5(a-k): Images of some phytoplankton species identified in the Anyanui Creek from April 2023 to March 2024

4.2 Marine and Freshwater Phytoplankton Species Composition

The identified phytoplankton species were categorized into marine and freshwater types and shown in Fig. 6. Marine phytoplankton species constitute 43.75% of the total species, of which 9.37% are toxin producers (*Anabeana sp., Peridinum sp., Nitzschia sp.*) and 34.38% are bloom-forming. Freshwater phytoplankton species constituted 56.25% of the total phytoplankton species, of which 3.13% are toxin producers and 53.12% are bloom-forming.

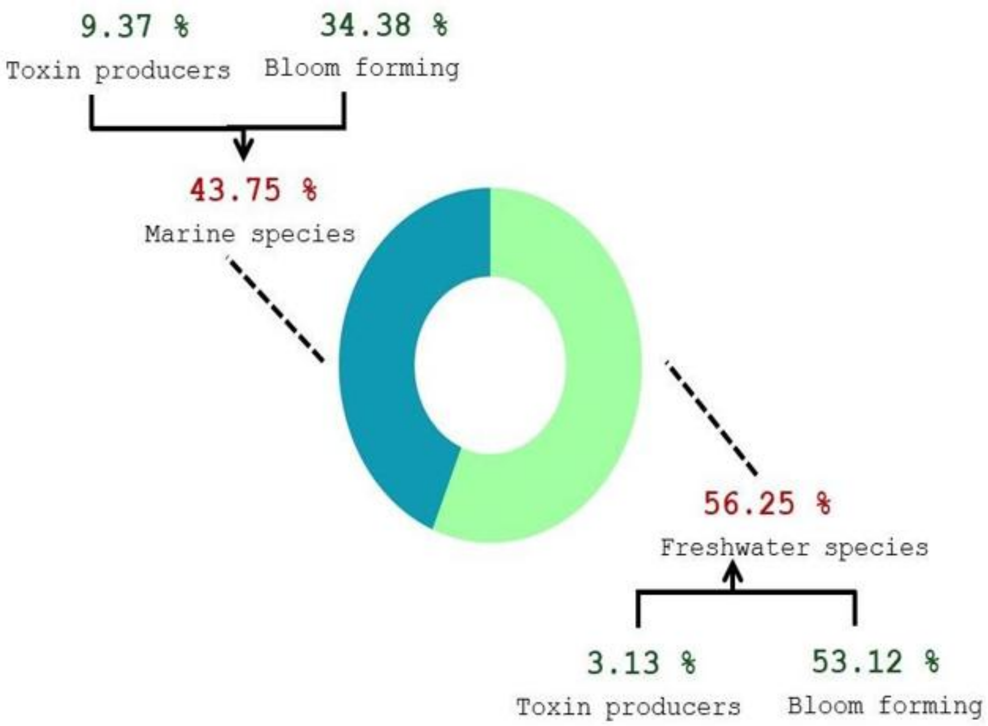

Fig. 6: Marine and freshwater phytoplankton species composition in the Anyanui Creek showing the proportions of bloom-formers and toxin producers.

4.3 Species Diversity

4.3.1 Shannon-Wiener Diversity

The Shannon-Wiener diversity index (H') varied across the three zones throughout the study period (Fig. 7). Phytoplankton diversity peaked in April 2023 in Zone C (downstream), at a value of 3.04, whereas the lowest diversity, recorded at 1.38, occurred in September 2023 in Zone B (midstream). Zone C generally exhibited relatively higher diversity values, particularly during April 2023, July 2023, and March 2024. Zone A showed moderate diversity, whereas Zone B had the lowest diversity values across most months. The recorded diversities were both significantly different statistically ($p=0.0007$) between the three zones (spatially) and over the study period (temporally) at $p<0.0001$. This was followed by Tukey's multiple comparisons tests, which also showed significant differences between Zones A and B. However, differences between Zones B and C, and Zones A and C were insignificant.

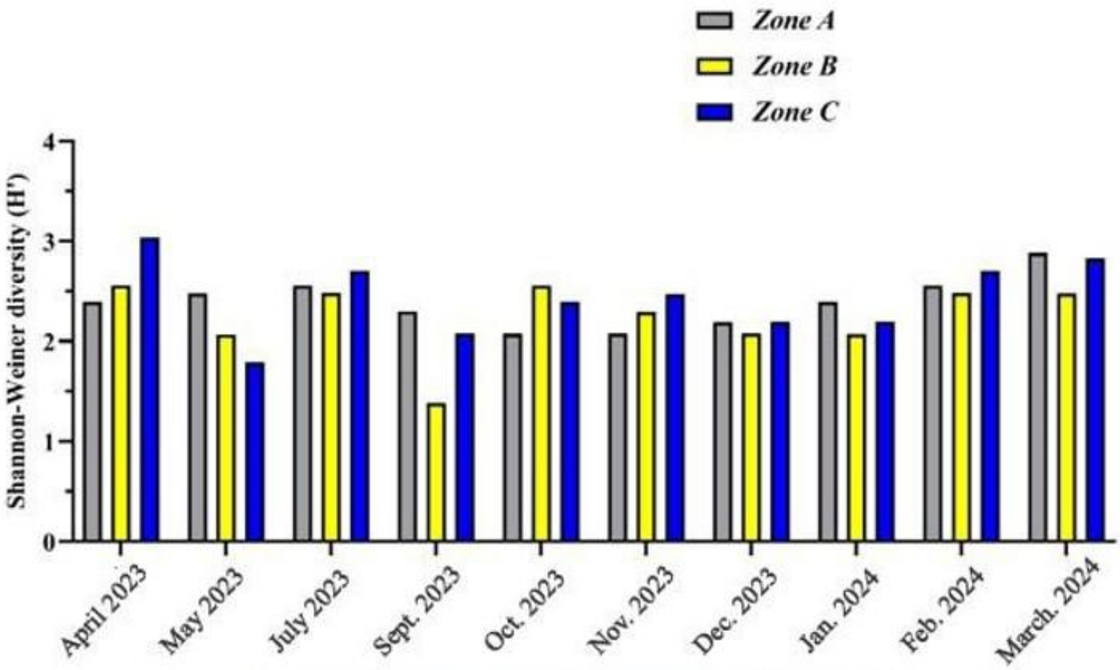

Fig. 7: Shannon-Weiner diversity indexes for phytoplankton species from different sampling zones in the Anyanui Creek in each sampling month

4.3.2 Pielou's Evenness (J')

Pielou's Evenness Index (J') was used to assess the uniformity of species distribution across different zones each month. Pielou's Evenness index was close to 1, ranging from 0.995 to 0.999 (Fig. 8). The recorded diversities were not significantly different statistically (p=0.4704) between the three zones (spatially) and over the study period (temporally) at p=0.1397.

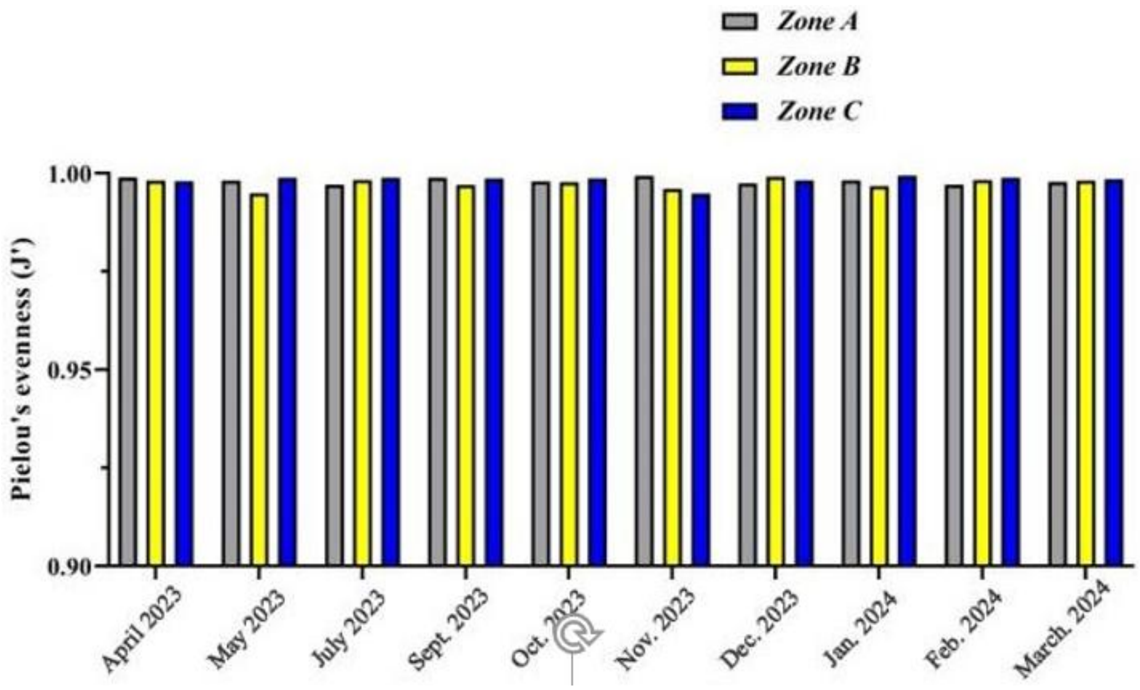

Fig. 8: Pielou's evenness (J') for phytoplankton species from different sampling zones in the Anyanui Creek in each sampling month

4.3.3 Margalef Species Richness (d)

Fig. 9 shows the Margalef species richness for the three zones during the study months. The Margalef species richness varied significantly between the zones during the sampling period, ranging from 0.76 (Zone B during September 2023) to 3.54 (Zone C during April 2023). There was no regular pattern in the Margalef species richness across the zones and months. The recorded diversities were both significantly different statistically ($p=0.0016$) between the three zones (spatially) and over the study period (temporally) at $p<0.0001$. This was followed by Tukey's multiple comparisons tests, which also showed significant differences between Zones A and B. However, differences between Zones B and C, and Zones A and C were insignificant.

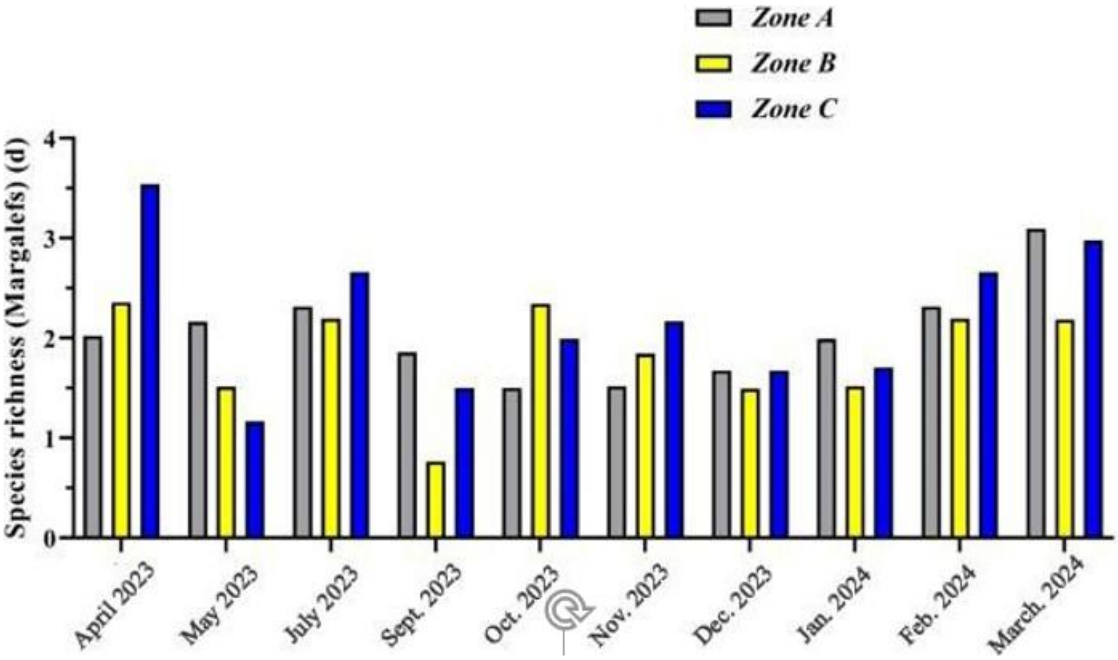

Fig. 9: Margalef Species richness (d) for phytoplankton from different sampling zones in the Anyanui Creek in each sampling month

4.3.4 Spatial Distribution

The percentage distribution of phytoplankton, categorized by their taxonomic groups in the upstream (Zone A), midstream (Zone B), and downstream (Zone C) regions over the entire sampling period, is illustrated using a donut diagram.

Fig. 10 shows the distribution of phytoplankton taxonomic groups upstream region (Zone A). The results showed that diatoms dominated in the phytoplankton community, accounting for 85.51% of the total species composition, dinoflagellates constituted 3.11%, cyanobacteria were absent, while other species from various taxonomic groups constituted 11.38% of the species composition.

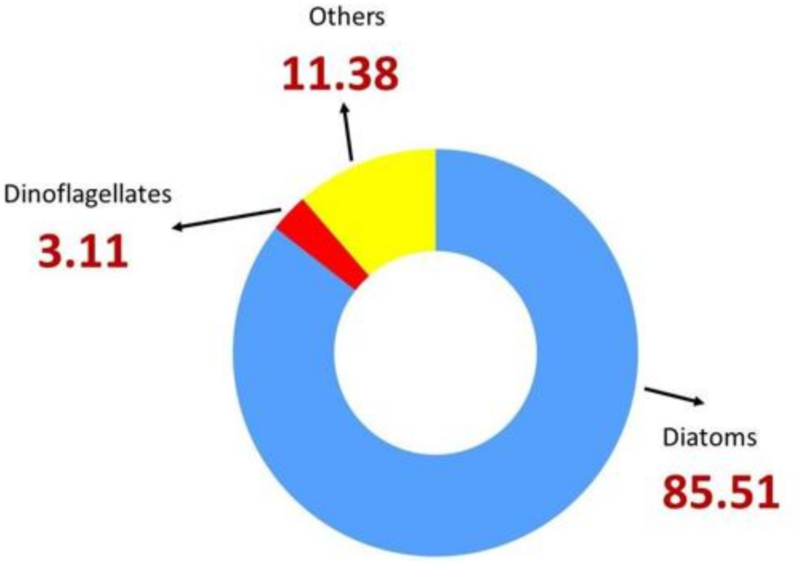

Fig. 10: Distribution of phytoplankton taxonomic groups in the upstream (Zone A) of the Anyanui Creek from April 2023 to March 2024

Fig. 11 shows the distribution of phytoplankton taxonomic groups in the midstream region (Zone B). Like Zone A, diatoms dominated the midstream zone (Zone B) and accounted for 94.28% of the phytoplankton distribution. Dinoflagellates were less prominent, accounting for only 0.35%, whereas cyanobacteria had the lowest representation at 0.21%. Other taxonomic groups contributed 5.16% of the total phytoplankton species composition.

Fig. 11: Distribution of phytoplankton taxonomic groups in the midstream (Zone B) of the Anyanui Creek from April 2023 to March 2024

Fig. 12 shows the distribution of phytoplankton taxonomic groups in the downstream region (Zone C). Like Zones A and B, Zone C was dominated by diatoms, constituting 91.68% of the total phytoplankton species. Dinoflagellates and cyanobacteria were present in equal proportions, with each constituting 0.17% of the total phytoplankton species. Other species from various taxonomic groups constitute 7.98% of the total phytoplankton species.

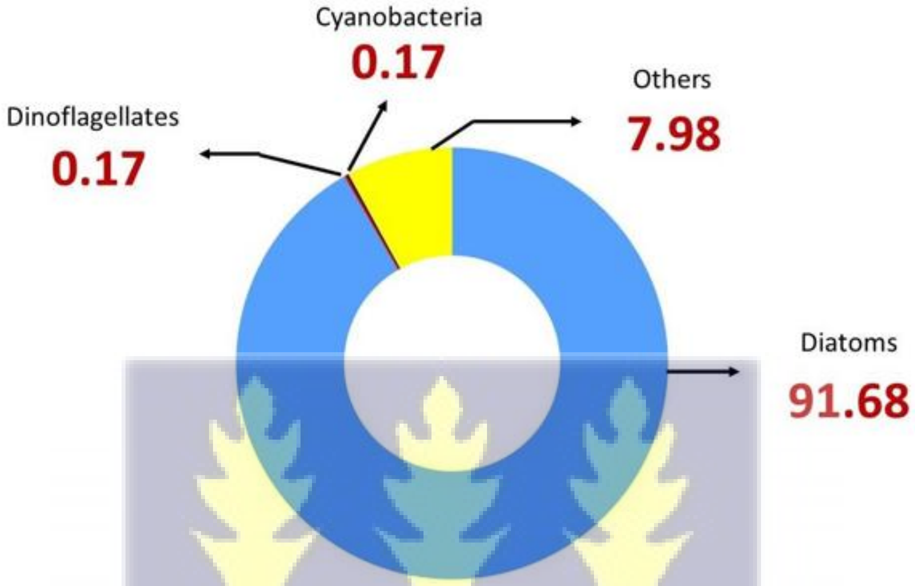

Fig. 12: Distribution of phytoplankton taxonomic groups in the downstream (Zone C) of the Anyanui Creek from April 2023 to March 2024

4.3.5 Cluster Analysis of the spatial distribution of phytoplankton communities

A dendrogram was constructed to assess the similarity between the zones based on the phytoplankton species composition across the three zones (Fig. 13). The results showed two main clusters at a Bray-Curtis similarity level of approximately 84%. Zones B (midstream) and C (downstream) had greater similarity at approximately 83% and constituted one cluster. Zone A (upstream) had a lower similarity to Zones B and C and constituted a separate cluster.

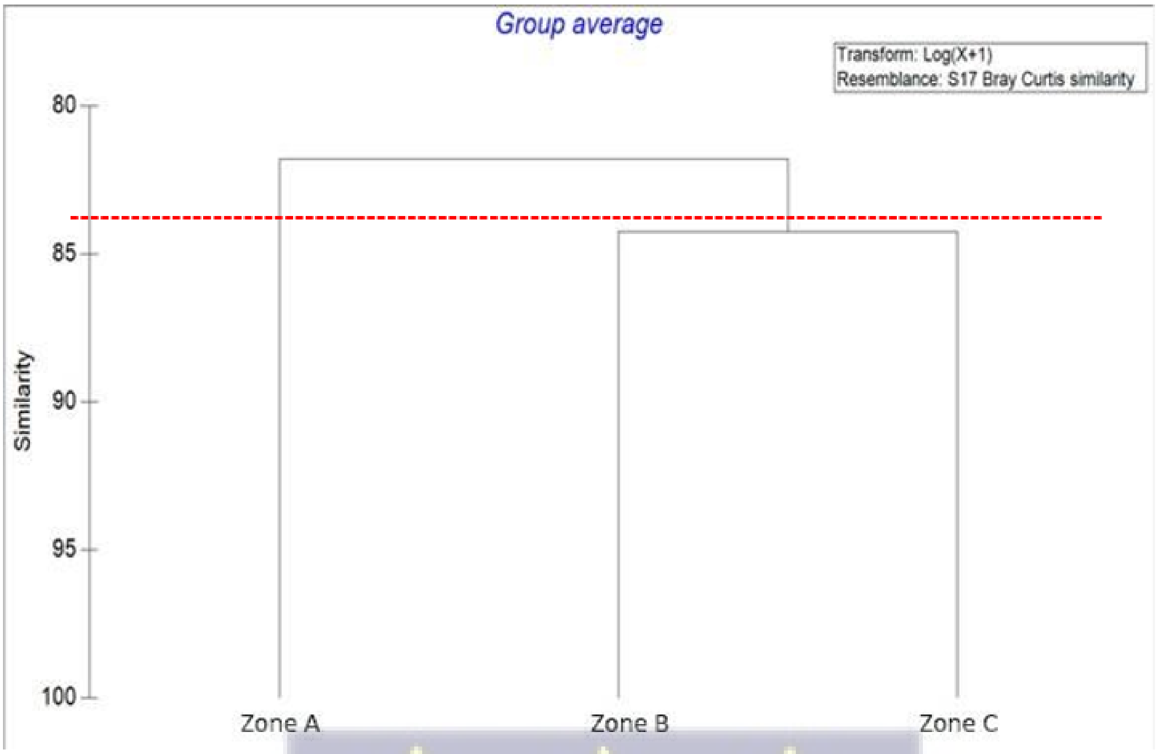

Fig. 13: A dendrogram showing the similarity between Zones A, B and C of the Anyanui Creek based on the phytoplankton species composition

4.3.6 Cluster Analysis of the Temporal Distribution of Phytoplankton Communities

Fig. 14 shows the similarity between the sampling months based on the phytoplankton species composition. The results showed three distinct clusters at a Bray-Curtis similarity of approximately 75%.

March 2024 and April 2023 formed the first cluster at a similarity of approximately 52%. January 2024, July 2023, and February 2024 formed the second cluster at a similarity of approximately 83%, whereas November 2023, September 2023, May 2023, October 2023, and December 2023 formed the third cluster at approximately 75%.

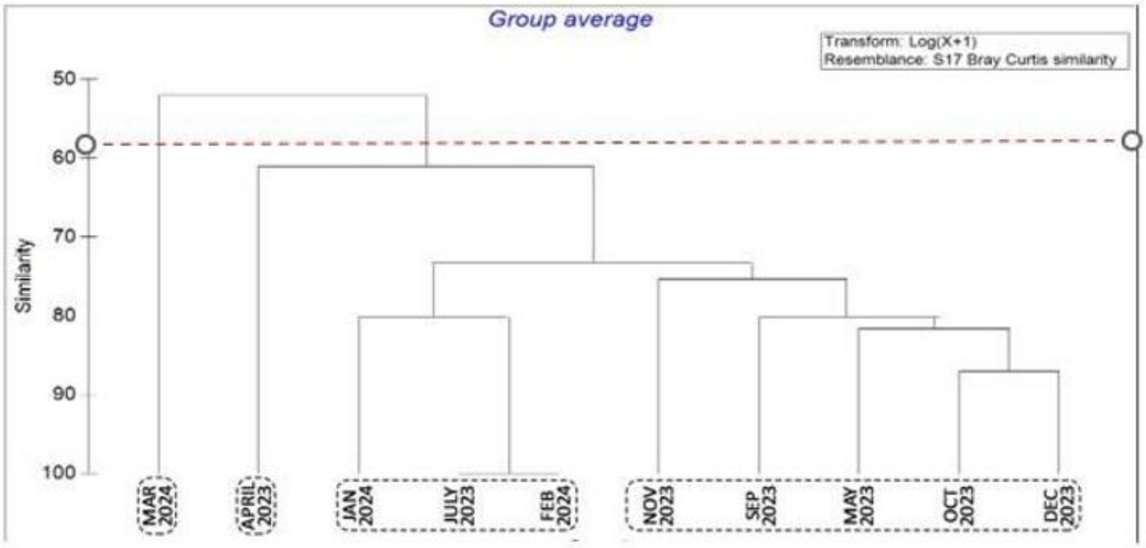

Fig. 14: A dendrogram showing the similarity between the sampling months based on the phytoplankton species composition in the Anyanui Creek

4.4 Spatio-temporal variation in Physicochemical Parameters

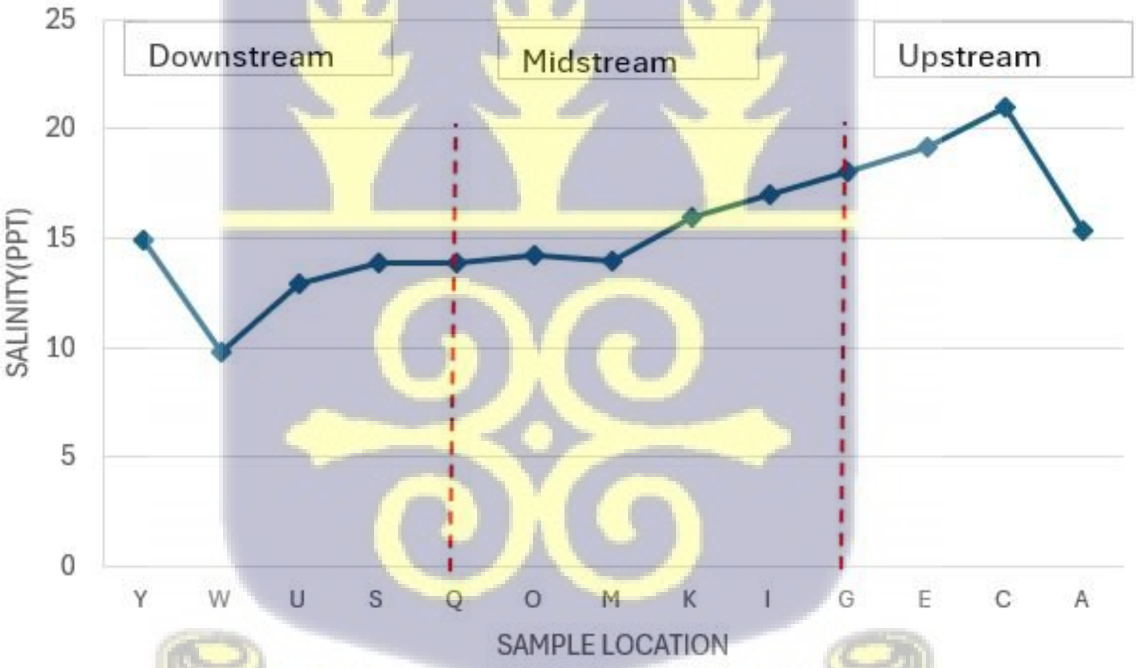

Fig. 15: Zonation of the Anyanui Creek based on salinity measurements conducted in March 2023

A preliminary study was conducted in March 2023 to assist in the zonation of the site into upstream (Zone A), midstream (Zone B), and downstream (Zone C) sections. The salinity levels were measured along the distance using a Horiba probe as a basis for the zonation. Zone A exhibited the highest salinity, followed by Zone B, with Zone C having the lowest salinity.

Under natural estuarine conditions, the downstream zone near the sea is expected to show higher salinity than the upstream zone, due to direct marine influence. However, in the Anyanui Creek system, recent hydrological and geomorphological changes have altered this gradient.

The Keta Lagoon, which connects partly with the ocean, introduces water with moderate salinity into the upper part of the system. At the same time, the downstream section near the ocean has experienced tidal constriction, as the main channel has narrowed and become partially blocked. This constriction reduces the free exchange of seawater into the lower creek. Additionally, newly constructed channels now link the system with the Volta River, allowing greater input of freshwater from downstream. As a result, instead of the expected marine intrusion, the lower portions of the creek are increasingly dominated by freshwater from the Volta River, while the upper sections receive moderately saline water from the Keta Lagoon. This reversal explains why the observed salinity distribution appears "upside down" the upstream (Zone A) records higher salinity values than the downstream (Zone C), contrary to classical estuarine patterns.

4.4.1 Temperature

Fig. 16 shows the water temperatures (°C) in the different zones of the Anyanui Creek during the sampling months. Recorded temperatures ranged from 29.04 °C to 33.97 °C. In all three zones, the highest temperatures were recorded in May 2023, and the lowest temperature was recorded in September 2023. The highest temperature was recorded in Zone A (upstream), whereas the lowest temperature was recorded in Zone B (midstream). One-way analysis of variance (ANOVA) revealed no significant temperature differences ($p=0.634$) across the three zones over the study period.

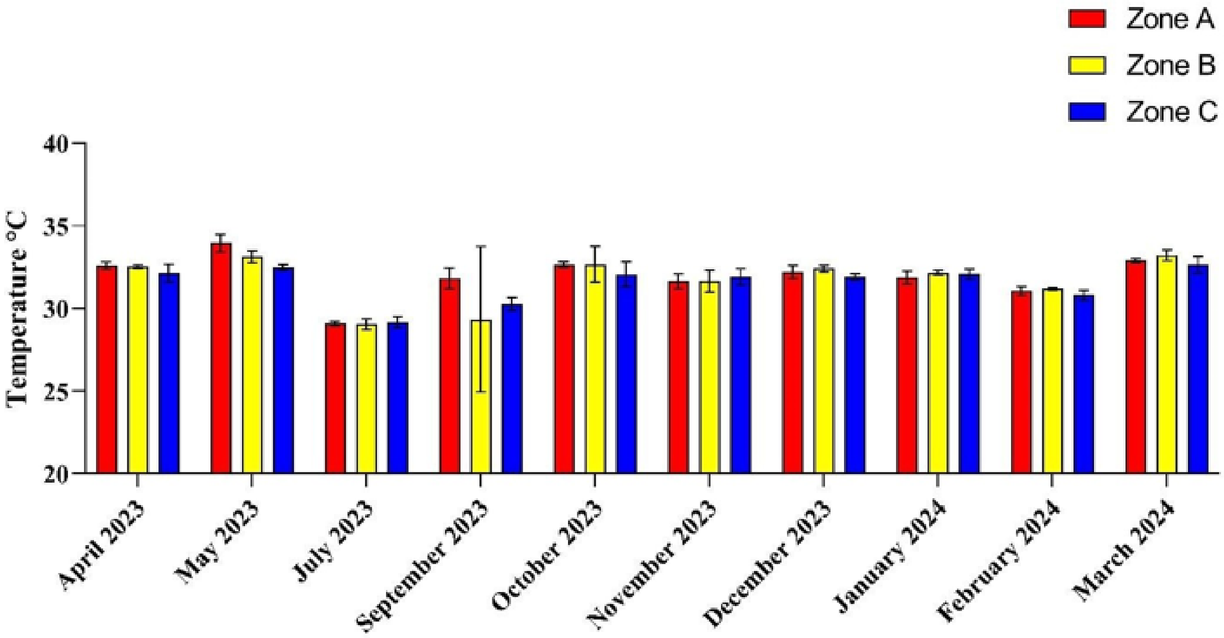

Fig. 16: Monthly water temperatures (°C) in different zones of the Anyanui Creek from April 2023 to March 2024

4.4.2 Salinity

The monthly water salinity in the different zones of Anyanui Creek is shown in Fig. 17. The salinity ranged from 3.91ppt to 14.06. Zone A (upstream) had higher salinity levels compared to the other zones, except in March 2024, with a peak of 14.06 ppt in September 2023. Zones B (midstream) and C (downstream) had relatively lower salinity, with values ranging between 3.91 and 10 ppt across the months. One-way analysis of variance indicated a significant difference (p=0.002) in salinity across the zones. This was followed by Tukey's multiple comparisons tests, which also showed significant differences between Zones A and B, and A and C. However, salinity differences between Zones B and C were insignificant.

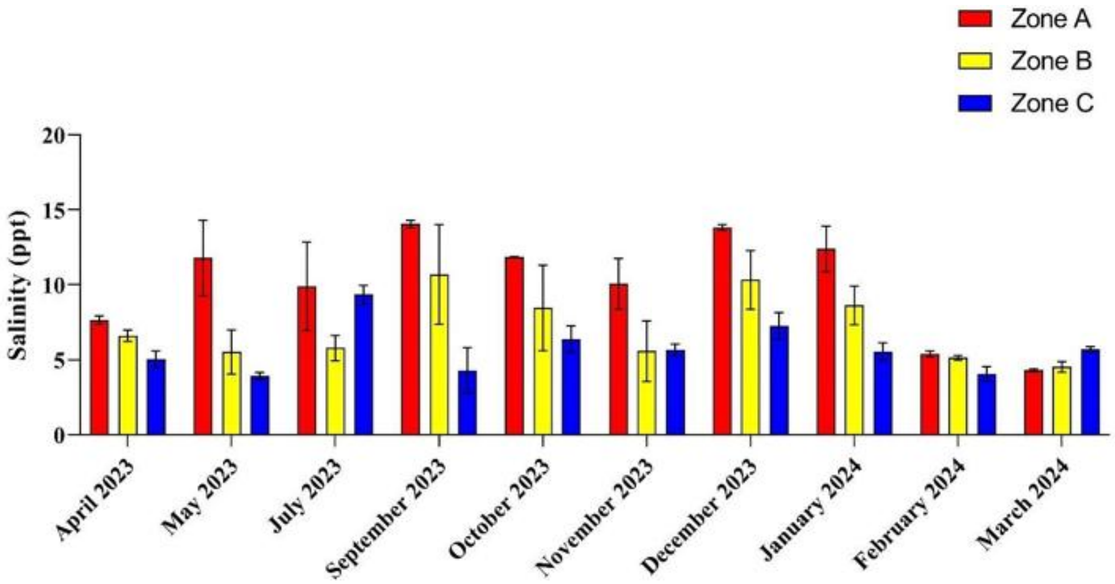

Fig. 17: Monthly water salinity in different zones of the Anyanui Creek from April 2023 to March 2024

4.4.3 pH

Fig. 18 shows the monthly water pH in the different zones of the Anyanui Creek from April 2023 to March 2024. There were slightly alkaline conditions across all the zones, with pH levels ranging between 7.11 and 8.46. All three zones recorded relatively high pH levels (≈ 8.1-8.3) in July 2023. One-way ANOVA indicated no significant difference (p=0.292) in the monthly pH across these zones.

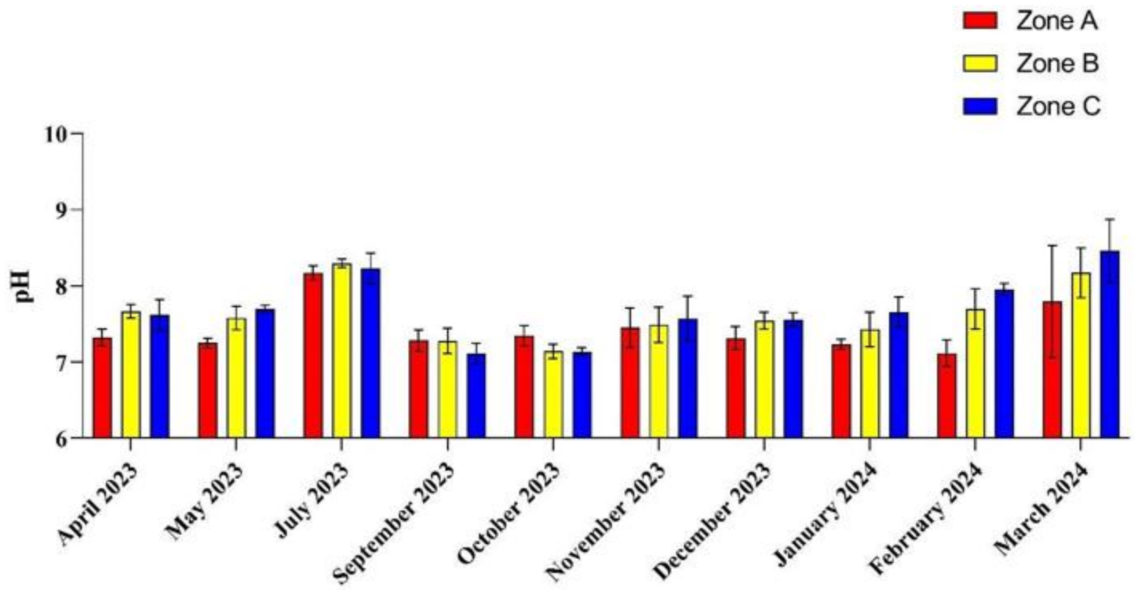

Fig. 18: Monthly pH in different zones of the Anyanui Creek from April 2023 to March 2024

4.4.4 Dissolved Oxygen Concentrations

The monthly dissolved oxygen (DO) concentrations in the different zones of the Anyanui Creek are presented in Fig. 19. The DO levels varied significantly across the zones and months, ranging from 0.12 to 9.04. The highest DO was recorded in Zone C (downstream) in March 2024. Significantly lower DO levels were observed in November and December 2023, which dropped close to 0 mg/L. One-way ANOVA indicated a significant difference (p=0.032) in DO levels across the zones during the study period. This was followed by Tukey multiple comparison tests, which showed significant differences between Zones A and C but no significant differences between Zones B and C, and Zones A and B.

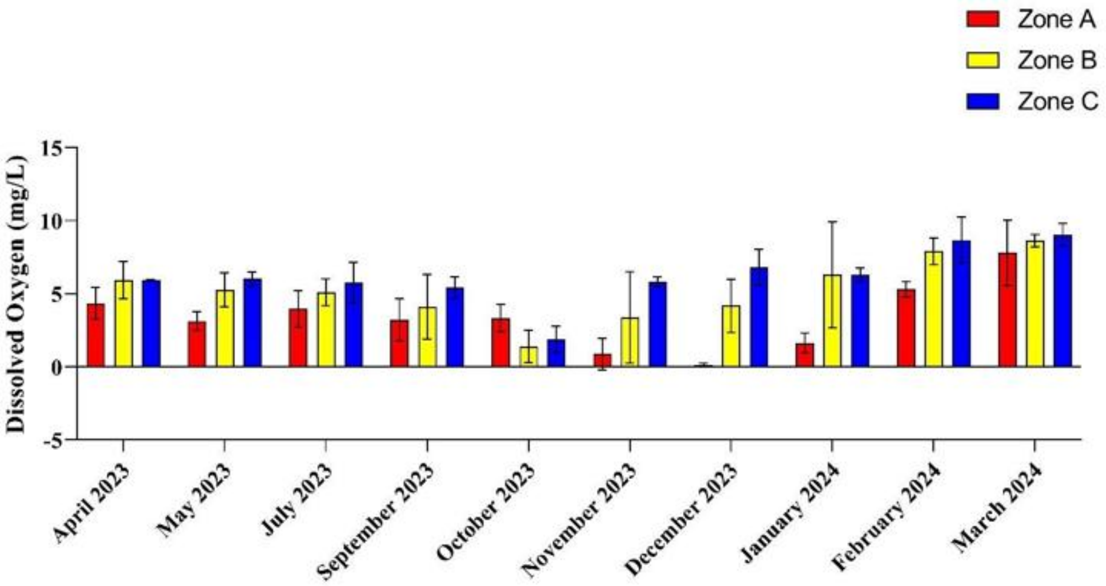

Fig. 19: Monthly dissolved oxygen concentrations in different zones of the Anyanui Creek from April 2023 to March 2024

4.4.5 Nitrate

Fig. 20 presents the monthly nitrate concentrations in the different zones of Anyanui Creek from April 2023 to March 2024. The concentrations ranged from 6.75 µg/L (in Zone A during October 2023) to 1024.85 µg/L (in Zone A during November 2023). There were no marked temporal variations in the nitrate concentrations with notable peaks in November 2023, particularly in Zones B (midstream) and C (downstream). The nitrate concentration was below the detection limit in all the zones in October 2023. One-way ANOVA indicated no significant differences (p=0.864) in nitrate levels across the zones.

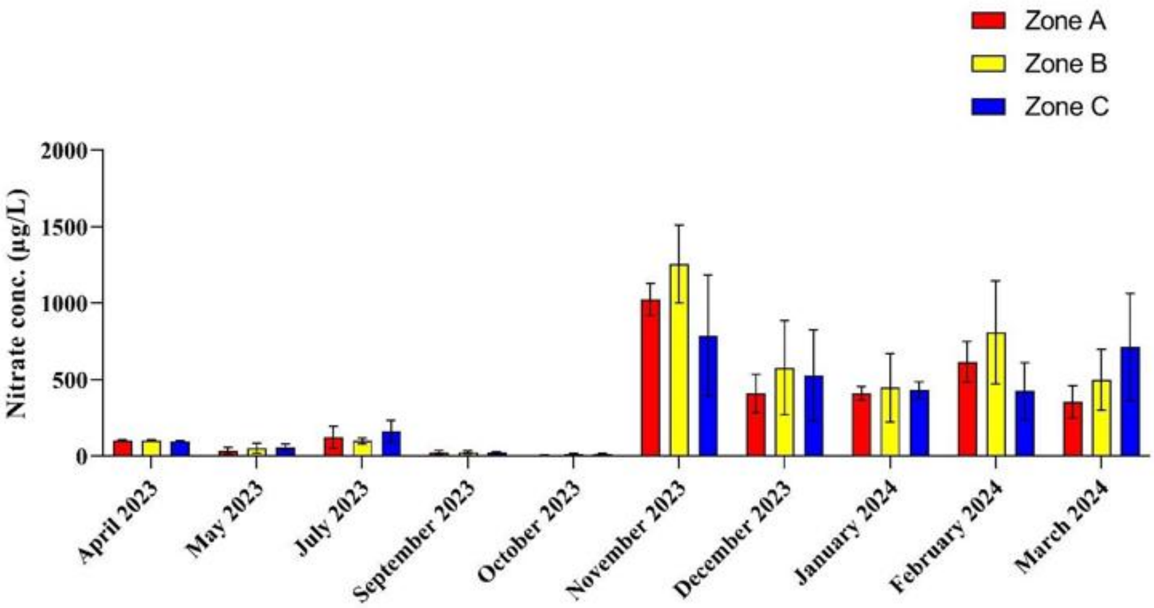

Fig. 20: Monthly nitrate concentrations in different zones of the Anyanui Creek from April 2023 to March 2024

4.4.6 Phosphate

The monthly phosphate (PO_4^{3-}) concentrations in the different zones of the Anyanui Creek are shown in Fig. 21. High phosphate concentrations were observed in April and July 2023 in all the zones. Zone C (downstream) showed the highest phosphate concentration of 125.26 µg/L. The lowest phosphate concentrations in all the zones were measured in October 2023 and February 2024, ranging from 1.20 to 1.80 µg/L. One-way ANOVA indicated no significant difference (p=0.906) in phosphate concentrations across the zones.

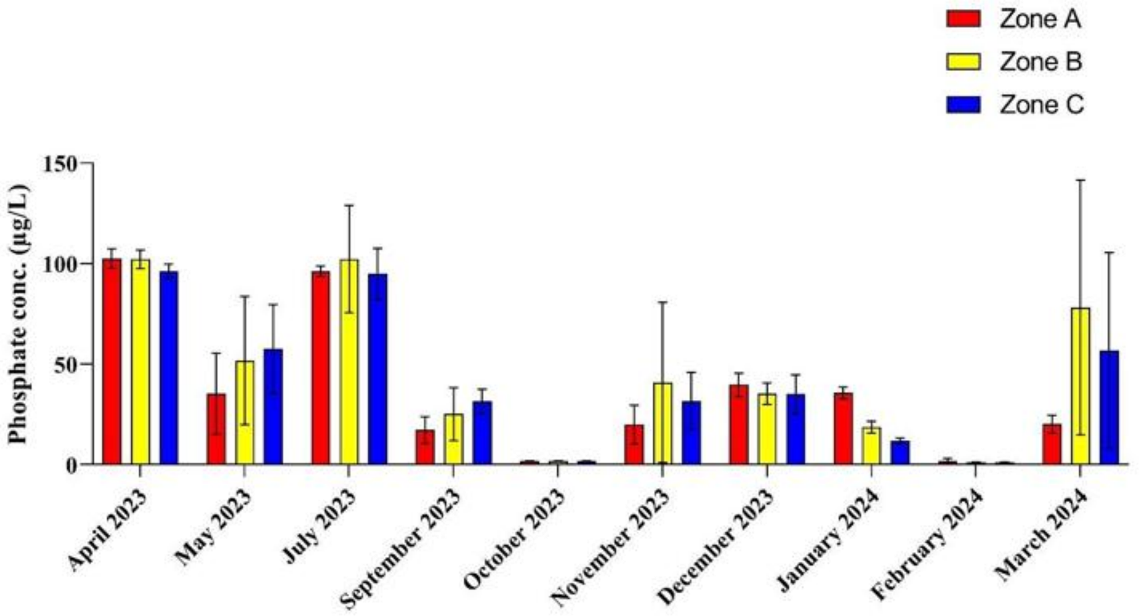

Fig. 21: Monthly phosphate concentrations in different zones of the Anyanui Creek from April 2023 to March 2024

4.4.7 Ammonium

Fig. 22 shows the monthly ammonium concentrations in the different zones of the Anyanui Creek. The highest ammonium concentration (2002.69µg/L) was observed in Zone A (upstream) during December 2023, and the lowest concentration (35.62µg/L) was observed in Zone B (midstream) during March 2023. One-way ANOVA indicated no significant difference (p=0.613) in the phosphate concentrations across the zones.

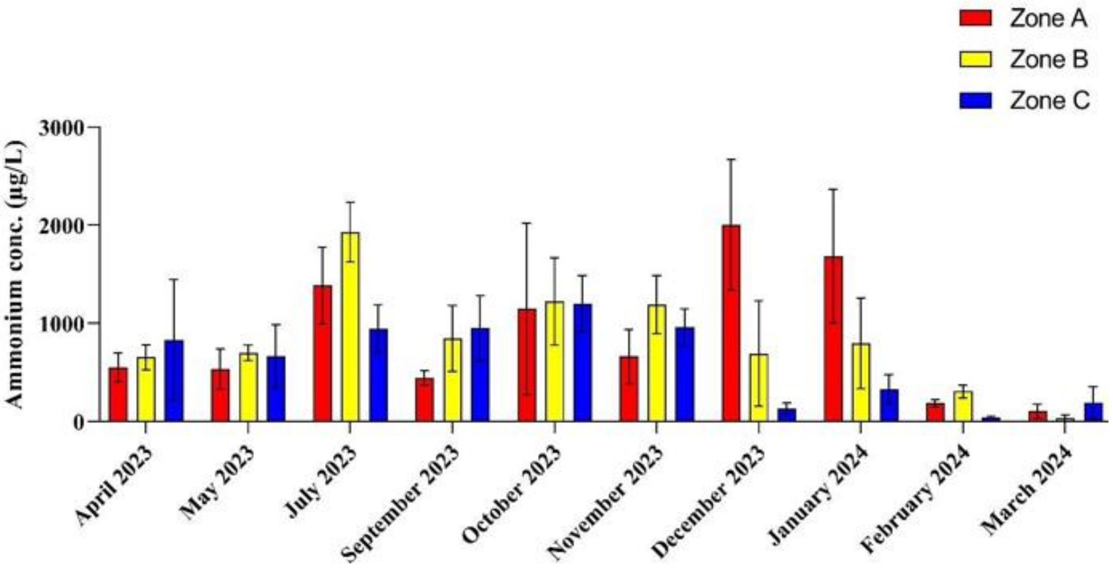

Fig. 22: Monthly ammonium concentrations (µg/L) in different zones of the Anyanui Creek from April 2023 to March 2024

4.4.8 Silicate

Silicate concentrations were high throughout the sampling period, ranging between 3208.89 and 6574.61 µg/L (Fig. 23). The highest mean silicate concentration was recorded during July 2023 (Zone A), with the lowest levels recorded in January 2024 (Zone C). One-way ANOVA indicated no significant difference (p=0.971) in silicate level across these zones.

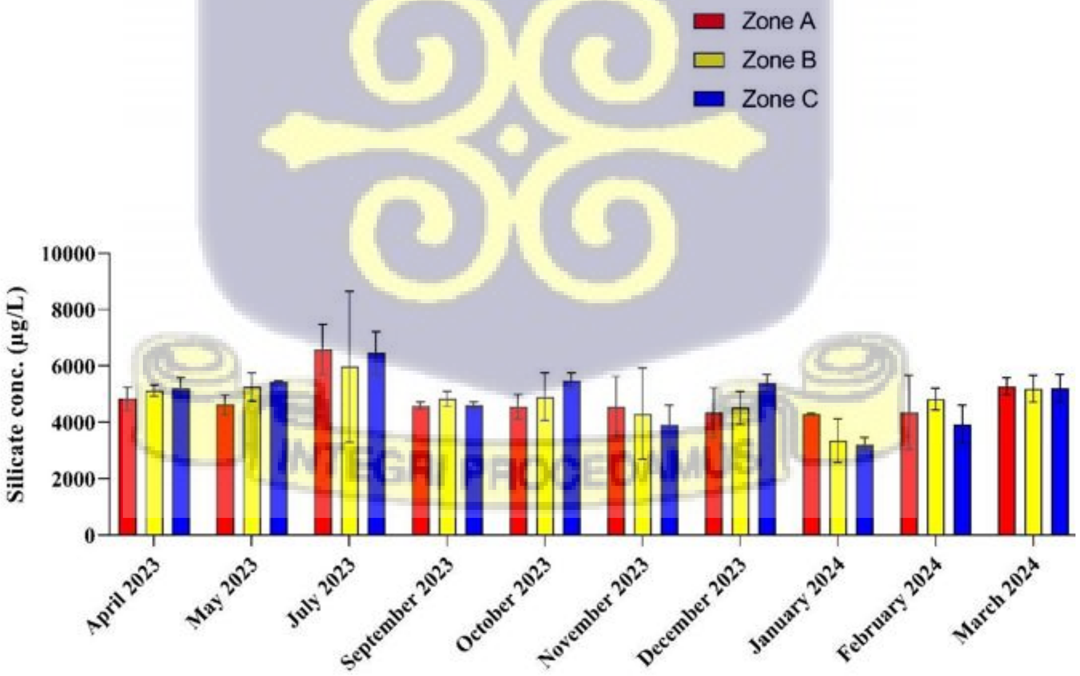

Fig. 23: Monthly ammonium concentrations (µg/L) in different zones of the Anyanui Creek from April 2023 to March 2024

4.5 Correlation between Physicochemical Parameters and Phytoplankton Species

Pearson correlation analysis (2-tailed) was performed to evaluate the relationship between physicochemical parameters (temperature, DO, pH, salinity, phosphate, silicate, ammonium, and nitrate) and the abundance of phytoplankton species (*Chaetoceros sp., Chaetoceros daniscus, Coscinodiscus sp., Entomoneis sp., and Nitzschia sp.*) in Anyanui Creek as set out in Table 1. These phytoplankton species were selected for further analysis primarily because they represented the most abundant taxa in the Anyanui Creek, thereby contributing substantially to overall community structure and dynamics. While correlation does not imply causation, it provides a first-level statistical assessment of how parameters co-vary across temporal and spatial scales. With respect to phytoplankton, correlating dominant taxa with environmental variables helps identify which parameters may act as potential drivers of abundance.

The results showed a significant negative correlation between salinity and DO ($r = -0.689$, $p < 0.01$), ammonium and DO ($r = -0.586$, $p < 0.01$), temperature and ammonium ($r = -0.394$, $p < 0.05$), silicate and nitrate ($r = -0.443$, $p < 0.05$) and nitrate and phosphate ($r = -0.373$, $p < 0.05$). Significant positive correlations were observed between pH and DO ($r = 0.607$, $p < 0.01$), and silicate and phosphate ($r = 0.556$, $p < 0.01$). Significant positive correlations were also observed between *Chaetoceros daniscus* and DO ($r = 0.402$, $p < 0.05$), and *Nitzschia sp.* and ammonium ($r = 0.467$, $p < 0.01$). In contrast, *Nitzschia sp.* negatively correlated with DO ($r = -0.381$, $p < 0.05$), whereas no significant correlations were found between *Chaetoceros sp., Coscinodiscus sp., Entomoneis sp.,* and the analyzed environmental variables.

Table 1: Correlation Matrix for Environmental Variables and Phytoplankton Species in the Anyanui Creek

	Temperature	**Salinity**	**Dissolved Oxygen**	**pH**	**Phosphate**	**Nitrate**	**Ammonium**	**Silicate**	**Chaetoceros sp**	**Chaetoce ros daniscus**	**Coscinodiscus sp**	**Entomoneis sp**	**Nitzchia sp**
Temperature	1												
Salinity	0.046	1											
Dissolved Oxygen	-0.042	**-.689****	1										
pH	-0.346	-0.307	**0.607****	1									
Phosphate	-0.007	-0.107	0.153	0.358	1								
Nitrate	-0.045	-0.196	0.1	0.104	**-.373***	1							
Ammonium	**-0.394***	0.338	**-0.586****	-0.024	0.242	-0.08	1						
Silicate	-0.218	-0.021	0.087	0.297	**.556****	**- 0.443***	0.166	1					
Chaetoceros sp	0.059	-0.115	-0.022	-0.171	0.2	-0.317	0.014	-0.106	1				
Chaetoceros daniscus	0.315	-0.266	**0.402***	0.305	0.075	0.23	-0.244	0.058	-0.204	1			
Coscinodiscus sp	0.134	-0.172	-0.184	-0.305	-0.063	0.206	0.14	-0.073	0.172	0.162	1		
Entomoneis sp	-0.279	0.155	-0.162	-0.065	-0.018	-0.022	0.137	0.168	-0.121	-0.226	-0.117	1	
Nitzchia sp	0.152	0.354	**-0.381***	-0.154	-0.181	-0.039	**0.467****	-0.057	-0.007	-0.273	-0.013	-0.007	1

***. Correlation is significant at the 0.05 level (2-tailed).**

****. Correlation is significant at the 0.01 level (2-tailed)**

4.6 PCA of Environmental Variables

Principal Component Analysis (PCA) was performed to identify the major environmental gradients influencing water quality. The first two principal components explained 64.6% of the total variance, with PC1 accounting for 34.6% and PC2 for 30.0% of the variation. The PCA biplot (Fig. 24) shows that PC1 was mainly influenced by dissolved oxygen (DO), nitrate (NO_3^-), temperature, and pH, while PC2 was driven largely by salinity, ammonium (NH_3), and silicate (SiO_3). Seasonal clustering was evident, with March 2024 and February 2024 positioned strongly on the positive side of PC1, associated with higher DO and nitrate. In contrast, July 2023 separated along the negative side of PC2, linked with salinity and NH_3. The months of September, October, November, and December 2023 clustered on the negative side of PC1.

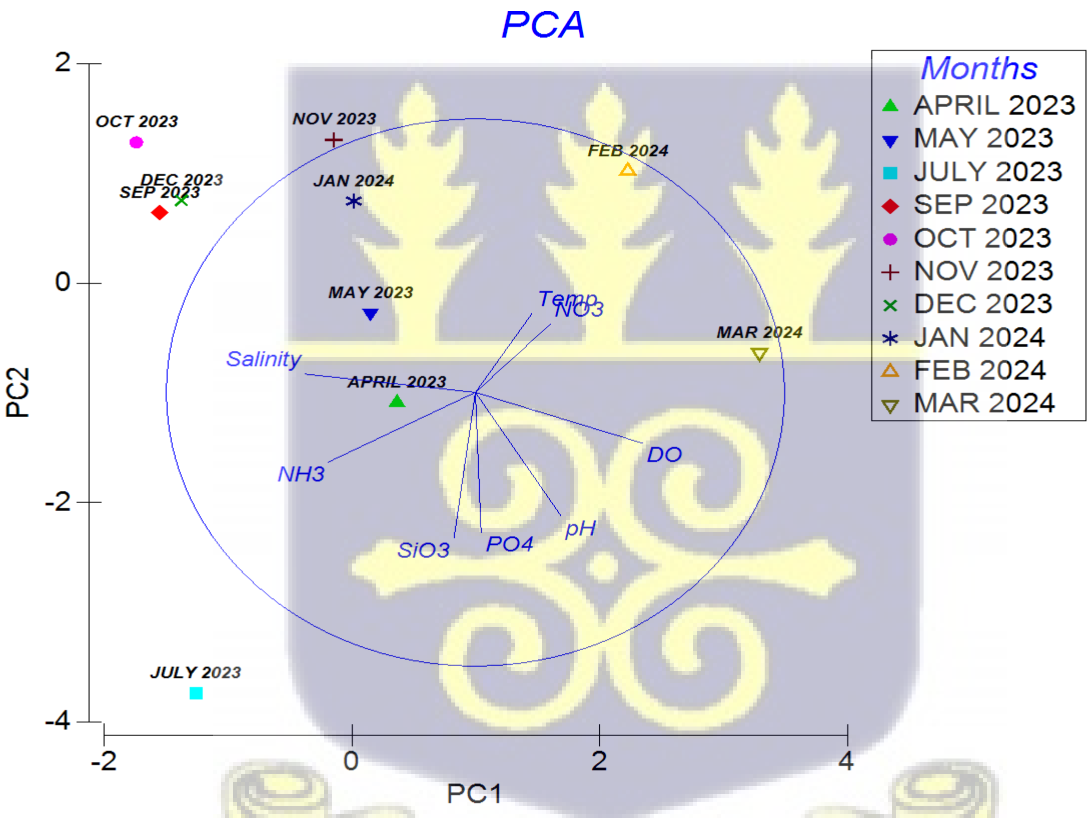

Fig. 24: PCA biplot showing the variability in physicochemical parameters across the sampling months in Anyanui Creek.

CHAPTER 5

5.0 DISCUSSION

5.1 Phytoplankton Species Composition

Thirty-four (34) phytoplankton species were identified in the present study, of which diatoms constituted 92.92% (Fig. 4). The dominance of diatoms among phytoplankton species in the Anyanui Creek agrees with findings of similar studies in other aquatic ecosystems (Brogueira et. al., 2007; Muylaert et. al., 2009; Baek et. al., 2015). Diatoms are vital contributors to primary production in aquatic ecosystems due to their highly efficient photosynthetic systems and rapid growth rates (Lavaud, 2007). Diatoms require silica for building their cell walls, which gives them an advantage in silica-rich waters as they can quickly absorb and use available silica (Inomura et. al., 2023). Dinoflagellates and cyanobacteria do not require silicate, and their growth is therefore not directly constrained by its availability. However, in silicate-rich environments, diatoms have a competitive advantage due to their rapid growth and silica-dependent frustule formation. Dinoflagellates and cyanobacteria are not directly disadvantaged by silicate itself since they don't need it, but they may be indirectly outcompeted in silicate-rich conditions because diatoms flourish under those circumstances. Among the diatoms, *Chaetoceros sp.* was the most abundant species, constituting 36.85% of the total phytoplankton species. This species is bloom-forming and possesses competitive advantages related to environmental adaptability (Bosak et al., 2016) and nutrient availability (Da Rosa & Copertino, 2022). *Chaetoceros sp.* has spines that may harm the gills of feeders (Gopinathan et al., 2007). The composition of marine (43.75%) and freshwater (56.25%) phytoplankton species (Fig. 6) emphasizes the uniqueness of Anyanui Creek. The higher percentage of freshwater species indicates that Anyanui Creek is a predominantly freshwater ecosystem, which can be attributed to freshwater inflows from the upstream area. The predominance of freshwater taxa reflects the influence of downstream freshwater inflows from the Volta River system, which dilute salinity and create conditions favorable for freshwater phytoplankton. Interestingly, salinity patterns within the creek deviated from the classical estuarine gradient, as the downstream area recorded relatively lower salinity compared to the upstream area. This inversion is likely attributable to the combined influence of Keta Lagoon, which introduces brackish water upstream, and the sandbar constriction at the downstream end of the creek, which restricts seawater intrusion and reduces mixing with ocean water. Such hydrological alterations modify the spatial distribution of salinity and, consequently, phytoplankton composition (Xu et al., 2022). Significant proportions of freshwater (53.12%) and marine (34.38%) phytoplankton species are bloom-forming species (Fig. 6). This is of ecological concern due to the role of bloom-forming phytoplankton in eutrophication (Pinckney et. al., 2001) and its adverse consequences, such as hypoxia and deterioration in water quality that threaten aquatic life. The occurrence of these bloom-forming species suggests nutrient enrichment from anthropogenic sources and terrestrial runoff (Van Meerssche & Pinckney, 2019) in the Anyanui Creek. The presence of toxin-producing marine (9.37%) and freshwater (3.13%) phytoplankton species in the Anyanui Creek highlights the potential risks to organisms along the aquatic food chain including humans. These toxin-producing phytoplankton species can disrupt food webs and threaten higher trophic levels, including humans (Hernández-Becerril et. al., 2007). Monitoring and managing these toxin-producing phytoplankton populations are essential for preventing harmful algal bloom events and associated oxygen depletion, fish kills, and economic losses in the estuary.

5.2 Species Diversity

Species diversity is commonly assessed by evaluating the species abundance, richness, and evenness. It can also be quantified using a combined proportional metric like the Shannon-Wiener index (H′), which integrates both richness and evenness (Stirling and Wilsey, 2001). Studies have indicated a strong positive correlation between richness (d) and the Shannon-Wiener index (H′). Species diversity can fluctuate due to ecological processes such as competition, succession, and predation, which may alter the index by impacting evenness while leaving species richness unchanged (Stirling and Wilsey, 2001). In Anyanui Creek, a clear relationship between species richness and the Shannon-Wiener diversity index was found, with the lowest species richness recorded in September 2023 and the highest in April 2023, reflecting similar trends in the Shannon-Wiener index.

Balloch et al. (1976) identified the Shannon-Wiener diversity index as an effective indicator of water quality. Hendey (1977) linked the Shannon-Wiener index to pollution levels in diatom communities and established a scale where values from 0 to 1 indicated high pollution, 1 to 2 indicated moderate pollution, 2 to 3 indicated low pollution, and 3 to 4 indicated incipient pollution. Wu (1984) later utilized phytoplankton as a bioindicator of water quality in Taipei, Taiwan, and observed that the phytoplankton diversity index frequently corresponded with pollution levels. Generally, it was found that a higher diversity index value indicated lower pollution, which is consistent with the findings of Margalef (1964, 1967, 1968). The Shannon-Wiener diversity index for the Anyanui Creek ranged from 1.38 to 3.04, indicating a low pollution state of the creek waters (Hendey, 1977). The relevance of these findings is to demonstrate how the Shannon-Wiener diversity index can be applied as a bioindicator of water quality in Anyanui Creek. Thus, these results provide evidence of relatively good water quality in the creek, while also validating phytoplankton diversity as a practical tool for ongoing monitoring and management of estuarine health. Pielou's evenness index (J'), which ranged between 0.995 and 0.999, suggests a highly uniform species distribution across the Anyanui Creek. This high evenness also indicates a stable phytoplankton community during the study period.

5.3 Species Distribution

Cluster analysis of the zones (Fig. 13) showed Zone A (upstream) as being distinct from Zones B (midstream) and C (downstream), which can be attributed to the absence of cyanobacteria in Zone A (Fig. 10) and their presence in Zones B (Fig. 11) and C (Fig. 12). The clustering also suggests that the environmental conditions in the midstream and downstream zones support the growth of cyanobacteria. For example, the absence of cyanobacteria in Zone A may be attributed to the relatively high salinity observed in this zone. Cyanobacteria thrive in low-salinity environments and were found in Zones B and C, where the salinity was low. The phytoplankton distribution showed the presence of diatoms and dinoflagellates in all the zones, with the former dominating.

Cluster analysis of the month based on species composition showed four main clusters (Fig. 14), indicating marked differences in species composition during March 2024 (Cluster 1), April 2023 (Cluster 2), July 2023, January 2024, February 2024 (Cluster 3), and May, September, October, November, and December 2023 (Cluster 4). The species composition during these months may be influenced by changes in environmental factors such as temperature and nutrient levels. The clustering of the months provided suggests temporal dynamics of phytoplankton species composition in the Anyanui Creek, which has practical implications for estuary management.

5.4 Effects of Physicochemical Parameters on Species

The correlation results (Table 1) indicated significant relationships between certain environmental parameters and the phytoplankton species in the Anyanui Creek. The study demonstrates a strong negative correlation between salinity and dissolved oxygen ($r = -0.689$, $p < 0.01$), indicating that dissolved oxygen concentrations decrease as salinity levels increase. Thus, higher salinity, potentially driven by tidal influences, may reduce oxygen availability in the water column and adversely affect the aquatic organisms. Temperature was negatively correlated with ammonium ($r = -0.394$, $p < 0.05$), which indicates that higher temperatures coincide with reduced ammonium levels. This pattern can be attributed to ecological and biogeochemical processes that intensify under warmer conditions. Elevated temperatures typically enhance the metabolic and photosynthetic activity of phytoplankton, leading to increased assimilation of ammonium as a preferred nitrogen source (Hirel & Lea, 2001). In addition, microbial processes such as nitrification are often accelerated at higher temperatures, converting ammonium into nitrite and nitrate and thereby reducing its availability in the water column. Within shallow estuarine systems, seasonal warming may also coincide with enhanced nutrient cycling and uptake due to increased stratification and biological activity. The relevance of this observation lies in its implications for nitrogen dynamics and phytoplankton competition: as ammonium becomes depleted during warmer periods, species capable of utilizing alternative nitrogen sources, such as nitrate, may gain a competitive advantage. This highlights the role of temperature not only as a direct environmental variable but also as a regulator of nutrient availability, with potential consequences for community composition and seasonal succession of phytoplankton.

pH and dissolved oxygen were positively correlated ($r = 0.607$, $p < 0.01$), indicating that more oxygenated waters are generally more alkaline. This relationship may be explained by the higher photosynthetic activity of phytoplankton, which releases oxygen and can increase pH levels through the uptake of CO_2. The negative correlation between ammonium and dissolved oxygen ($r = -0.586$, $p < 0.01$) suggests that higher ammonium concentrations are associated with lower oxygen availability, likely due to eutrophication processes where excessive nutrients lead to oxygen depletion. In many aquatic systems, such a pattern is often attributed to eutrophication, where excessive nutrient inputs stimulate algal growth and subsequent decomposition depletes oxygen. However, in this study, there was no clear evidence of eutrophication in Anyanui Creek, as indicated by the absence of persistent algal blooms or hypoxic conditions. Therefore, while the observed correlation resembles eutrophication-driven dynamics, it is more plausible that the relationship reflects natural nutrient cycling processes rather than anthropogenic nutrient enrichment. For example, ammonium accumulation could result from organic matter remineralization under lower-oxygen conditions, or reduced nitrification efficiency when oxygen availability declines (Hsiao et al., 2014). Conversely, higher oxygen concentrations during periods of greater mixing or primary production may be associated with increased uptake and transformation of ammonium (Glibert et al., 2016). Thus, the correlation highlights important interactions between nitrogen cycling and oxygen dynamics in the creek, but eutrophication is unlikely to be the underlying explanation in this case. The positive correlation between silicate and phosphate ($r= 0.556$, $p < 0.01$) indicates that these nutrients varied together across sampling periods, suggesting common sources or simultaneous biogeochemical cycling. This co-variation is ecologically significant because both silicate and phosphate are essential for diatom growth. In systems dominated by diatoms, as observed in Anyanui Creek, the simultaneous availability of these nutrients may alleviate limitations and promote their proliferation. However, when either nutrient becomes limiting, diatom growth can be suppressed, potentially opening ecological space for non-siliceous groups such as dinoflagellates or cyanobacteria (Brzezinski et al., 2011).

From a nutrient competition perspective (Tilman, 1982; Sommer, 1985), phytoplankton species coexistence and succession are governed by the relative supply ratios of limiting nutrients. The nitrate concentration in the study area showed clear seasonal variability across the sampling months. From April 2023 to October 2023, nitrate levels remained consistently low, corresponding to the wet season when high rainfall and surface runoff likely caused dilution of nutrients in the water column. In contrast, nitrate concentrations increased sharply from November 2023 to March 2024, coinciding with the dry season. This rise could be attributed to reduced freshwater inflow, leading to higher nutrient retention and possible inputs from agricultural runoff or organic matter mineralization during low-flow conditions. The negative correlation between silicate and nitrate ($r = –0.443$, $p < 0.05$) reflects the interplay of nutrient cycling and phytoplankton uptake within Anyanui Creek. Diatoms, which require both silicate and nitrate for growth, often deplete these nutrients at different rates depending on environmental conditions. During periods of high silicate availability, diatom proliferation may lead to rapid nitrate drawdown, while in contrast, when silicate becomes limiting, nitrate may remain in the water column unused. This inverse relationship may also arise from the distinct sources and cycling pathways of these nutrients, with silicate primarily derived from riverine inputs and sediment resuspension, and nitrate often supplied through runoff or microbial regeneration. Consequently, fluctuations in the Si:N ratio influence competitive interactions within the phytoplankton community (Dortch et al., 2001), where balanced ratios favor diatom dominance, while imbalances may create opportunities for non-siliceous taxa. Thus, the observed negative correlation does not necessarily imply direct competition but rather highlights how differences in nutrient supply and consumption shape community structure in the creek.

The correlation analysis between environmental factors and phytoplankton species abundance provided key insights into species-environment interactions. The abundance of *Chaetoceros daniscus* was positively correlated with dissolved oxygen ($r = 0.402$, $p < 0.05$), indicating that this species thrives in well-oxygenated conditions. This suggests that *Chaetoceros daniscus* may be more abundant in areas where photosynthetic activity is high, possibly linked to periods of higher nutrient availability and stable environmental conditions (Minggat et al., 2021). Conversely, *Nitzschia sp.* was negatively correlated with dissolved oxygen ($r = -0.381$, $p < 0.05$) and positively correlated with ammonium ($r = 0.467$, $p < 0.01$), suggesting that this species prefers environments with lower oxygen levels and higher ammonium concentrations (Li et al., 2020). This implies that *Nitzschia sp.* is more adapted to eutrophic conditions, where elevated nutrient levels coincide with oxygen depletion. The absence of significant correlations between *Chaetoceros sp.*, *Coscinodiscus sp.*, *Entomoneis sp.*, and the measured environmental parameters suggests that these species may be more resilient to changes in the monitored conditions or influenced by other environmental factors not captured in this analysis. These species may have broader ecological niches, allowing them to persist under varying environmental conditions (Jiandong et al., 2015), or they may be affected by unmeasured factors such as light availability, hydrodynamics, or interspecies competition.

5.6 Drivers of Phytoplankton Communities

The PCA results highlight clear seasonal variability in water quality parameters across the study period. The strong contribution of PC1 (34.6%) reflects the importance of dissolved oxygen, nitrate, temperature, and pH in structuring water quality conditions, with higher oxygen and nutrient levels distinguishing the dry season months (February–March 2024). This suggests enhanced nutrient availability and oxygenation during this period, possibly linked to mixing and reduced stratification (Donald et al., 2013). PC2 (30.0% of the variance) reflects the role of salinity, ammonium, and silicate in influencing water chemistry, which differentiated the mid-rainy season (July 2023). The association of ammonium with high salinity suggests potential inputs from terrestrial runoff or tidal intrusion, processes often intensified during rainy seasons (Hasan et al., 2022).

The clustering of late 2023 months (September–December) along the negative side of PC1 indicates a transitional period, possibly marked by reduced nutrient inputs and lower DO compared to early 2024. The distinct separation of July 2023 further highlights rainfall-driven variability in nutrient and salinity dynamics (Drupp et al., 2011).

While PCA does not directly identify causal relationships with phytoplankton abundance, the analysis isolates the dominant environmental gradients that underpin community dynamics. The association of DO and nutrient variables with seasonal peaks suggests that phytoplankton diversity and abundance in Anyanui Creek are likely regulated by nutrient availability and oxygen conditions, whereas shifts in salinity mark transitional periods between wet and dry seasons.

CHAPTER 6

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This study assessed phytoplankton species composition, diversity, spatial distribution, and the influence of physicochemical parameters on dominant species in Anyanui Creek. Thirty-four (34) phytoplankton species were identified, which were predominantly diatoms. This highlights the role of diatoms as primary producers in Anyanui Creek. *Chaetoceros sp*. was the most abundant species identified, indicating its competitive advantage over the other species and its potential impact on filter-feeding organisms. The presence of both marine and freshwater species reflects the unique hydrology of Anyanui Creek, where freshwater inflows and lagoon water influence phytoplankton composition across zones. A substantial proportion of these species are bloom-formers, indicating high risk of eutrophication in the Anyanui Creek due to nutrient enrichment, likely from anthropogenic sources. The presence of toxin-producing phytoplankton species highlights potential risks to aquatic life and human health and hence, the need for their monitoring to prevent harmful algal blooms. Species diversity indices suggest moderately low water pollution in the Anyanui Creek.

Cyanobacteria distribution in the Anyanui Creek appeared to be influenced by salinity as they were absent in the low-salinity upstream area (Zone A) but present in the midstream (Zone B) and downstream (Zone C) areas. Cluster analysis revealed variations in phytoplankton species composition across different times of the year, reflecting the influence of environmental factors such as temperature and nutrient availability on phytoplankton dynamics. Correlation analysis highlighted significant relationships between environmental factors and phytoplankton abundance. Species-specific responses to these parameters were also observed, with *Chaetoceros daniscus* thriving in oxygen-rich environments, whereas *Nitzschia sp.* were favored by higher ammonium levels and lower oxygen concentrations. These findings contribute valuable insights into the dynamics of phytoplankton communities in Anyanui Creek, which is essential for effective management of the Anyanui Creek.

6.2 Recommendation

To maintain the ecological integrity of Anyanui Creek, a comprehensive approach to monitoring and management is recommended.

- Additional parameters such as dissolved organic carbon, trace metals, and micronutrients should be measured for a more complete understanding of nutrient–phytoplankton interactions.
- Beyond taxonomic diversity, assessments of pigment composition, primary production rates, and physiological responses should be included to link phytoplankton structure with ecosystem processes.
- DNA metabarcoding or similar approaches could complement microscopy by identifying cryptic or rare taxa that may have been overlooked.
- Regular monitoring across years would capture interannual variability and help assess the impacts of climate change, hydrological changes, and human activities.
- Nutrient enrichment bioassays and controlled experiments should be conducted to establish causative relationships between nutrient inputs and harmful algal bloom formation.

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