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PHYTOPLANKTON DIVERSITY AND STOICHIOMETRIC NUTRIENT LIMITATION IN THE LAGOS HARBOUR AND ADJACENT SEA, SOUTHWESTERN NIGERIA

Elegbeleye, O. W.* **and Onyema, I. C.**
Department of Marine Sciences, University of Lagos, Nigeria.
*Corresponding author's email: owelegbeleye@gmail.com; Tel.: (+234)8025253343
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ABSTRACT

Harbours and their adjacent seas are increasingly stressed by maritime activities and development of coastal cities worldwide. This is especially true for the Lagos Harbour. The aim of this study was to investigate the trophic status, nutrient stoichiometry and phytoplankton assemblage of Lagos Harbour and the adjacent sea. Water and plankton samples were collected for a period of eighteen months from January 2015 to June 2016 between 06.00 and 11.00 hrs each time. Phytoplankton samples were investigated using a Leica DMLB microscope with 100x full oil immersion optics and 1.35 numerical aperture equipped with a Nikon Coolpix 995 CCD digital camera of 3.3 megapixel resolution. Relevant statistical tests such as Principal Components Analysis (PCA) were employed to determine major controlling water quality indices and Canonical Correspondence Analysis (CCA) for determination of the water quality indices that influenced the monthly and spatial phytoplankton occurrences. A total of 108 phytoplankton taxa belonging to five classes were recorded in this study. Bacillariophyceae comprised eighty-four (84) taxa (78%), Chlorophyceae had two (2) taxa (2%), Cyanophyceae were represented by 11 taxa (10%), Dictyochophyceae had one (1) taxon (1%) and Dinophyceae had 10 taxa (9%). CCA revealed a clear seasonal pattern; it also showed that phosphate was the major controlling factor in the Lower Lagos Harbour and the creeks in the months of July, August and September 2015. Trophic state index (TSI) using Carlson's indices revealed eutrophic to hypereutrophic conditions. The comparison of ambient nutrient ratios with Redfield ratio (N:P = 16:1) revealed clear spatial and temporal variations in the Lagos Harbour and adjacent sea. The significant difference shown by phosphate in the wet season could be linked to allochthonous and autochthonous inputs from rainfall.

Keywords: Harbour, Microscopy, Nutrient stoichiometry, Phytoplankton.

INTRODUCTION

The aquatic ecosystems are a precious resource, essential to humanity, and also to the function of our planet (Castro and Huber, 2005). The biodiversity, high productivity and ecosystem services provided by tropical coastal systems are noteworthy (Onyema, 2009). However, increasing population and utilization/exploitation of resources have subjected coastal ecosystems to many environmental challenges from human-induced impacts. Notably, harbours and their adjacent seas are increasingly stressed by maritime activities and development of coastal cities worldwide.

The Lagos Harbour is no exception in these regards, as worthy of note is the indiscriminate dredging and sand mining activities in the Lagos lagoon. There has also been an unprecedented land reclamation in this coastal water for the on-going development of the Eko Atlantic City. The effects of these anthropogenic activities could negatively impact the water quality indices and thereby interfere with the natural composition of aquatic bio-forms. Phytoplankton are sensitive bio-indicators of ecosystem general health, its nutrient status, eutrophication, pollutants and other anthropogenic impacts in aquatic environments (Barbosa *et al.*, 2010).

In particular, these organisms respond rapidly to wide range of pollutants and thus, can provide potentially useful early warning signals of deteriorating conditions and the possible causes (Graham *et al.*, 2009). The occurrences and density of different types of species of phytoplankton in the bodies of water are usually affected by water quality. The fundamental indicators of water quality are its physical (total dissolved solids, total suspended solids and water temperature) and chemical (chemical oxygen demand, dissolved oxygen, nutrients, pH and salinity) properties which are usually affected by the inputs entering into the aquatic ecosystem

(Falkowski *et al.*, 2008). This study aims at investigating phytoplankton species diversity and determine the factors influencing their abundance and distribution in the Lagos Harbour.

MATERIALS AND METHODS

Study Area

Lagos lagoon is an open tidal estuarine ecosystem situated within the low-lying coastal zone of Nigeria. It is located at the eastern part of the Lagos lagoon complex. It lies parallel to Epe lagoon and extends from part of Lekki lagoon. It falls within the rain forest belt characterized by a well-marked wet (May – October) and dry (November – April) seasons (Nwankwo, 2004a; Onyema, 2009; Chukwu, 2011; Edokpayi, 2017). The Lagos Harbour, which is part of the Lagos lagoon, is the only direct opening for the nine marginal Southwestern lagoons to the sea in Nigeria. To the West of the harbour are Yewa, Ologe Badagry, and Iyagbe lagoons. And to the east of the Lagos Harbour are the Kuramo, Lagos, Epe, Lekki and Mahin lagoons. Before now, coastal erosion was a major environmental menace at the Victoria beach in the Lagos Harbour. However, in 2013, Lagos State Government succeeded in building high-wave resistant groins (Great Wall of Lagos) at the Victoria beach to address this environmental challenge and at the same time, reclaim land in this aquatic ecosystem to allow for the construction of a new city, the Eko Atlantic City.

Sampling Stations

Twelve stations in three ecologically distinct zones (the horizontal gradient of the harbour channel, adjoining creeks and the open sea adjacent to the harbour) were selected (Table 1 and Figure 1). There are four stations each within these three ecological zones.

Table 1: Sampling Stations, Corresponding Global Positioning System (GPS) Coordinates and Average Secchi Depths

S/N	Stations	GPS coordinates	Average Secchi depth (meters)	Descriptions of locations and notes on anthropogenic activities/ecological interests
1	Lower Lagos Harbour (LH)	6.4655455°N, 3.3817855°E	1.10	Former sewage disposal site; fishing activities; receives wood shavings from Okobaba sawmill.
2	Upper Lagos Harbour (UH)	6.4418984°N, 3.4047894°E	2.10	Fishing activities; Jetty; boat cruises
3	Takwa bay (TB)	6.3998240°N, 3.3965815°E	2.40	Fishing activities; recreational activities; boat cruises; ongoing construction of Eko Atlantic City
4	Commodore Channel (CC)	6.3916082°N, 3.4007852°E	2.50	Mouth of the harbour to the sea; vessels' passage; Fishing activities; ongoing construction of Eko Atlantic City
5	Ijora Creek (IC)	6.4626541°N, 3.3765639°E	0.20	Naval dockyard; local settlements; fishing activities; riparian mangroves
6	Badagry Creek (BC)	6.4332895°N, 3.3697329°E	1.50	Tincan Island Port; Folawiyo Energy Tank; Human settlements; Fishing activities; riparian mangroves
7	Lighthouse Creek (LHC)	6.4237596°N, 3.3915698°E	0.50	Lagos Deep Offshore Logistics (LADOL) office site; dredging and sand mining activities
8	Five-cowrie Creek (FC)	6.4398202°N, 3.4015017°E	1.10	Fastest flowing creek in Southwestern Nigeria; Fishing activities; dredging and sand mining at the Moba end of the creek; boat cruises
9	Lighthouse Beach 1 (LHB1)	6.3894741°N, 3.3961648°E	2.70	Fishing activities; recreation
10	Lighthouse Beach 2 (LHB2)	6.3909665°N, 3.3938614°E	2.80	Vessels' anchorage; fishing activities
11	Great wall of Lagos 1 (GW1)	6.389474°N, 3.396165°E	2.80	Ongoing construction of Eko Atlantic City; fishing activities
12	Great wall of Lagos 2 (GW2)	6.4004850°N, 3.4257971°E	3.10	Vessels' anchorage; fishing activities; fishing activities

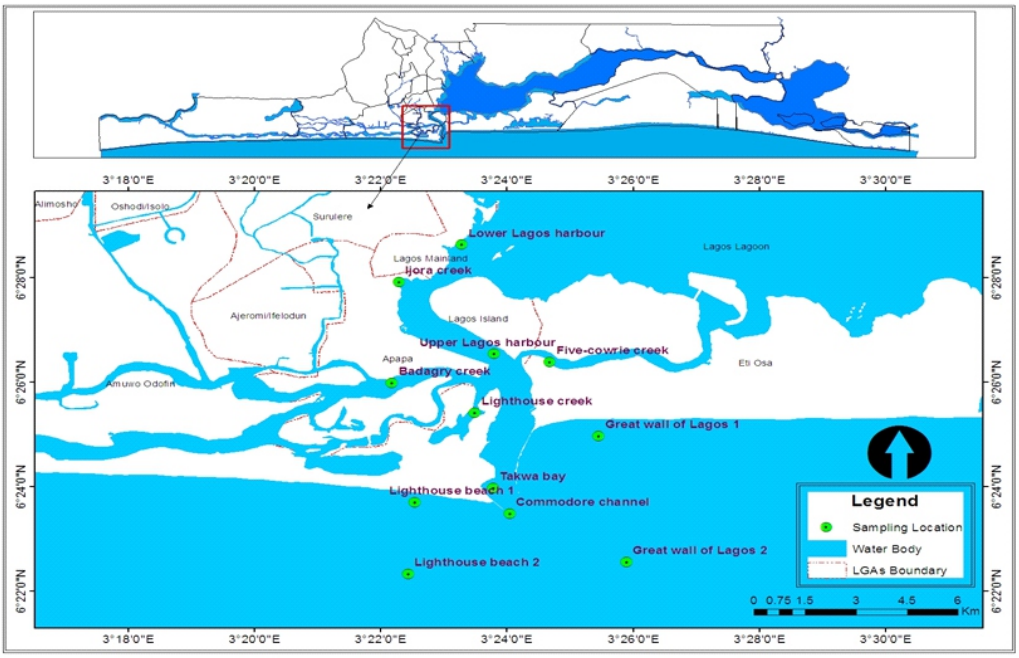

Figure 1: The Lagos Harbour and Adjacent Sea showing Study Sites

Collection of Samples

Water Samples

Monthly sampling was conducted and water samples were collected for a period of eighteen months from January 2015 to June 2016 between 06.00 and 11.00 hours each day. Replicate samples were collected at every site on each occasion for the analyses of nutrients and all other water quality parameters. Integrated surface water samples were collected between 0 – 1 m depth. Samples for dissolved oxygen were fixed *in-situ* with Winkler's reagents (APHA, 2005).

Plankton Samples

Samples were collected using standard plankton net of mesh size 55 µm. The plankton net was towed horizontally from a motorized boat at low speed (< 4 knots) for 5 minutes and the filtered plankton were emptied into well-labelled plastic container with a screw-cap. The plankton samples were preserved with 4% formalin and transferred to the laboratory for further analysis as described by Nwankwo (2004b) and Julius and Theriot (2010).

Microscopic Analysis of Phytoplankton

In the laboratory, fixed phytoplankton samples were allowed to settle and concentrated to 50 ml. The samples were investigated using a Leica DMLB microscope with 100x full oil immersion optics and 1.35 numerical aperture equipped with a Nikon Coolpix 995 CCD digital camera (3.3 megapixel resolution). Phytoplankton abundance was estimated in cells/filaments/trichomes per liter of seawater using a modified enumeration method described by Perry (2003). Confirmation of species identification were done using relevant texts (Nwankwo, 2004b; Al-kandari *et al.*, 2009; Alvarez-Blanco and Blanco, 2014).

Statistical Analyses

Relevant statistical tests such as one-way Analysis of Variance (ANOVA) to determine the levels of variations in water quality parameters across stations; Principal Components Analysis (PCA) to determine major controlling water quality indices; Bray-Curtis Analysis of Similarities (ANOSIM) to determine cohorts in study sites; Canonical Correspondence Analysis (CCA) and Pearson's correlation coefficient for determination of the water quality indices that influenced the monthly and spatial phytoplankton occurrences were employed. All statistical analyses were done using Excel, Paleontological Statistics (PAST) (Hammer *et al.*, 2001) and Statistical Package for Social Sciences (SPSS).

Trophic Status Evaluation

The Trophic State Index (TSI) developed by Carlson (1977) was adopted for this study. Mean values of three variables – chlorophyll *a* (chl a), phosphate (TP) and Secchi depth (SD) were used to calculate TSI within a numerical trophic continuum. The formulae for calculating TSI values for chlorophyll a, reactive phosphorus and Secchi depth are stated below.

TSI chlorophyll a = 9.81 1n(chl) + 30.6;
TSI reactive phosphorus = 14.42 1n(TP) + 4.15;
TSI Secchi depth = 60-14.41 1n(SD).
Therefore;

$$Carlson'sTSI = \frac{TSI(Chla) + TSI(TP) + TSI(SD)}{3} \quad (1)$$

Stoichiometric Nutrient Limitation

The Redfield Nitrate: Phosphate ratio of 16:1 was used as a benchmark for differentiating Nitrate-limitation from Phosphate-limitation. This ratio assumes that phytoplankton is Nitrate-limited (N-limited) at $N:P < 16$ and that it is Phosphate-limited (P-limited) at $N:P > 16$.

RESULTS

Physicochemical Properties of Surface Waters

The mean variations and analysis of variance (ANOVA) of physicochemical parameters of the surface water in the Lagos Harbour and adjacent sea during wet and dry seasons of the sampling period are presented in table 2. Data are presented as means ± standard error (SE). The peak of rainfall (449.3 mm) was recorded in June, 2015. Whereas salinity, Total Dissolved Solids, Dissolved Oxygen were found to be higher in the dry season, Biochemical Oxygen Demand and phosphate recorded higher values in the wet season than in dry season.

Principal Component Analysis (PCA) depicted that clusters were determined based on similar controlling factors. PCA grouped the twelve sampling stations into two clusters (Figure 2). Cluster 1 (LH – Lower Lagos Harbour, BC – Badagry Creek, LHC – Lighthouse Creek, IC – Ijora Creek, FC –Five-cowrie Creek, UH – Upper Lagos Harbour) and Cluster 2 (TB – Takwa Bay, CC – Commodore Channel, LHB1 – Lighthouse Beach 1, LHB2 – Lighthouse Beach 2, GW1 – Great Wall of Lagos 1 and GW2 – Great Wall of Lagos 2). The PCA explained 98.73% for component 1, 1.24% for component 2 and 0.03% for component 3 of the total variation of the studied ecosystems, while the Eigen values are 5.67E+07, 713442 and 15745.8 for components 1, 2 and 3 respectively. Total Dissolved Solids (TDS), Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) were controlling factors in stations grouped as Cluster 1 whereas stations grouped as Cluster 2 were majorly influenced by salinity, nitrate, Total Suspended Solids (TSS), phosphate, Dissolved Oxygen, conductivity and air temperature.

Table 2: ANOVA of Mean ±SE Values of Some Physicochemical Parameters of Surface Water in the Lagos Harbour during Dry and Wet Seasons (January 2015 – June 2016)

Dry Season

Parameter	LH *n=10*	UH *n=10*	TB *n=10*	CC *n=10*	IC *n=10*	BC *n=10*	LC *n=10*	FC *n=10*	LHB1 *n=10*	LHB2 *n=10*	GW1 *n=10*	GW2 *n=10*	F-Stat. Sig. Value
Air Temp(°C)	29.40 ±0.36	30.90 ±0.46	29.70 ±0.45	30.15 ±0.55	29.25 ±0.33	29.55 ±0.31	29.40 ±0.39	31.20 ±0.49	29.80 ±0.54	30.15 ±0.47	30.10 ±0.53	30.50 ±0.47	*1.846* *0.055*
Water Temp(°C)	28.45 ±0.35	29.00 ±0.56	29.02 ±0.56	28.85 ±0.56	28.15 ±0.51	28.75 ±0.40	28.70 ±0.43	29.15 ±0.56	29.40 ±0.47	28.95 ±0.52	29.10 ±0.57	29.10 ±0.57	*0.426* *0.941*
pH	7.57 ±0.09	7.75 ±0.05	7.83 ±0.07	7.75 ±0.07	7.74 ±0.06	7.42 ±0.08	7.58 ±0.09	7.68 ±0.07	7.99 ±0.02	8.02 ±0.02	7.94 ±0.04	7.96 ±0.04	*8.905** *0.000*
Cond (µS/cm)	33698 ±353 9	38662 ±2937	43380 ±2446	43180 ±2722	36820 ±3801	35622 ±2703	35640 ±2153	38450 ±1882	47470 ±1576	47380 ±1675	45320 ±1579	46290 ±1290	*4.132** *0.000*
TSS (mg/L)	3.71 ±1.87	1.45 ±0.43	1.31 ±0.43	1.73 ±0.71	1.65 ±0.58	1.75 ±0.63	2.13 ±1.12	1.40 ±0.53	1.33 ±0.45	1.11 ±0.35	1.30 ±0.31	1.01 ±0.26	*0.863* *0.578*
TDS (mg/L)	21624 ±242 9	25660 ±2103	28580 ±1701	28311 ±1953	24050 ±2606	22841 ±1915	23224 ±1454	24927 ±1343	31293 ±1133	31168 ±1194	29672 ±1166	30393 ±961	*4.001** *0.000*
Salinity (‰)	19.83 ±2.20	23.07 ±1.85	26.06 ±1.55	26.86 ±0.96	21.79 ±2.34	20.95 ±1.63	21.51 ±1.49	22.82 ±1.20	28.77 ±0.89	28.68 ±0.94	27.70 ±0.81	28.49 ±0.61	*5.229** *0.000*
DO (mg/L)	5.91 ±0.18	5.93 ±0.19	6.04 ±0.18	5.96 ±0.19	5.89 ±0.18	5.89 ±0.17	5.92 ±0.22	5.82 ±0.20	5.96 ±0.20	5.95 ±0.20	5.97 ±0.17	6.02 ±0.18	*0.098* *1.000*
BOD (mg/L)	1.56 ±0.28	1.25 ±0.22	1.16 ±0.21	1.14 ±0.15	1.56 ±0.50	1.55 ±0.24	1.69 ±0.22	1.65 ±0.50	1.04 ±0.11	1.03 ±0.12	1.34 ±0.24	1.24 ±0.23	*0.738* *0.700*
COD (mg/L)	6.60 ±0.75	5.30 ±0.65	4.70 ±0.68	5.70 ±0.72	7.30 ±1.51	7.30 ±0.80	7.70 ±0.91	8.20 ±2.03	4.40 ±0.56	4.60 ±0.43	4.70 ±0.79	4.90 ±0.84	*1.979** *0.037*
Nitrate (mg/L)	6.56 ±1.07	6.82 ±0.84	5.44 ±0.69	5.60 ±1.02	5.23 ±0.86	7.12 ±1.08	7.44 ±0.99	6.13 ±0.91	5.85 ±0.89	5.62 ±0.75	6.52 ±1.11	4.97 ±0.81	*0.714* *0.723*
Phosphate (mg /L)	1.17 ±0.46	0.50 ±0.14	0.52 ±0.07	0.72 ±0.17	0.66 ±0.10	0.62 ±0.10	0.89 ±0.27	0.51 ±0.08	0.49 ±0.08	0.45 ±0.09	0.48 ±0.11	0.68 ±0.21	*1.223* *0.280*
Silica (mg/L)	3.90 ±1.01	2.58 ±0.52	1.81 ±0.23	2.24 ±0.23	3.38 ±0.63	2.65 ±0.41	2.40 ±0.46	3.09 ±0.54	1.65 ±0.22	1.64 ±0.19	2.47 ±0.36	2.27 ±0.29	*2.040** *0.031*

Wet Season

Parameter	LH *n=8*	UH *n=8*	TB *n=8*	CC *n=8*	IC *n=8*	BC *n=8*	LC *n=8*	FC *n=8*	LHB1 *n=8*	LHB2 *n=8*	GW1 *n=8*	GW2 *n=8*	F-Stat. Sig. Value
Air Temp(°C)	27.63 ±0.39	29.63 ±0.75	28.69 ±0.47	28.75 ±0.46	27.56 ±0.33	28.13 ±0.35	28.25 ±0.33	29.69 ±0.78	28.81 ±0.46	28.94 ±0.45	28.94 ±0.45	29.06 ±0.60	*1.815* *0.064*
Water Temp(°C)	28.00 0.39	29.31 ±0.51	29.00 ±0.53	28.94 ±0.52	27.94 ±0.36	28.25 ±0.41	28.25 ±0.41	29.38 ±0.53	29.13 ±0.48	29.13 ±0.48	29.19 ±0.50	29.13 ±0.48	*1.275* *0.253*
pH	7.51 ±0.12	7.76 ±0.09	7.81 ±0.11	7.91 ±0.08	7.61 ±0.09	7.46 ±0.10	7.51 ±0.12	7.54 ±0.09	7.96 ±0.06	7.99 ±0.04	7/97 ±0.06	7.98 ±0.06	*5.855** *0.000*
Cond (µS/cm)	21120 ±3718	31343 ±2989	35842 ±2823	37290 ±3214	20446 ±2626	23783 ±1987	21536 ±1590	26868 ±2344	42034 ±1592	43034 ±1199	40853 ±2491	42942 ±2114	*13.432** *0.000*
TSS (mg/L)	2.56 ±1.36	2.80 ±1.89	1.31 ±0.53	1.13 ±0.32	1.18 ±0.18	1.50 ±0.64	2.18 ±0.79	2.26 ±1.39	1.63 ±0.79	1.29 ±0.56	0.84 ±0.17	0.89 ±0.24	*0.533* *0.875*
TDS (mg/L)	16400 ±3144	18028 ±2038	19591 ±1489	20349 ±2279	17627 ±3220	19319 ±2686	18427 ±2717	21150 ±2171	20531 ±2388	26508 ±616	24579 ±1431	27241 ±1327	*2.416** *0.012*
Salinity (‰)	12.61 ±1.25	17.94 ±2.14	20.28 ±1.91	25.01 ±1.52	11.96 ±1.73	13.29 ±1.38	12.68 ±0.95	15.69 ±1.12	25.96 ±0.97	26.59 ±0.80	26.25 ±0.83	26.95 ±0.75	*21.376** *0.000*
DO (mg/L)	5.66 ±0.13	5.79 ±0.18	5.89 ±0.16	5.81 ±0.14	5.70 ±0.07	5.68 ±0.11	5.78 ±0.17	5.65 ±0.14	5.84 ±0.16	5.91 ±0.16	5.81 ±0.11	5.86 ±0.13	*0.402* *0.951*
BOD (mg/L)	2.71 ±0.61	1.96 ±0.29	1.85 ±0.15	0.98 ±0.03	3.10 ±0.82	2.61 ±0.43	1.74 ±0.17	1.59 ±0.34	1.23 ±0.17	0.96 ±0.04	0.96 ±0.04	0.95 ±0.05	*4.570** *0.000*
COD (mg/L)	6.63 ±1.07	4.75 ±0.92	5.13 ±0.85	4.00 ±0.73	5.88 ±0.91	5.88 ±1.08	6.00 ±0.73	6.25 ±1.03	3.25 ±0.41	3.63 ±0.50	3.25 ±0.25	3.25 ±0.41	*2.694** *0.005*
Nitrate (mg/L)	5.30 ±0.38	5.92 ±1.36	6.37 ±1.77	5.30 ±1.60	4.97 ±0.55	4.57 ±0.62	5.49 ±0.77	4.68 ±0.70	4.48 ±1.09	4.78 ±1.18	4.49 ±1.62	4.14 ±1.09	*0.327* *0.978*
Phosphate (mg /L)	3.18 ±0.78	1.29 ±0.34	1.16 0.24	0.94 ±0.18	2.64 ±0.61	2.28 ±0.77	2.60 ±0.94	1.24 ±0.31	0.92 ±0.17	0.79 ±0.14	0.87 ±0.15	0.79 0.16	*3.141** *0.001*
Silica (mg/L)	2.74 ±0.76	2.17 ±0.36	1.52 ±0.27	1.51 ±0.32	3.49 ±0.49	3.07 ±0.42	3.23 ±0.48	2.40 ±0.46	1.36 ±0.34	1.61 ±0.43	1.32 ±0.35	1.32 ±0.32	*3.533** *0.000*

n = Number of Observations per parameter; Cond= Conductivity (µS/cm); DO= Dissolved Oxygen (mg/L); BOD= Biochemical Oxygen Demand (mg/L); COD= Chemical Oxygen Demanded (mg/L); TSS= Total Suspended Solids (mg/L); TDS= Total Dissolved Solids (mg/L); *represents F-statistically significant level at $P \leqslant 0.05$. IC= Ijora Creek, BC= Badagry Creek, LC= Lighthouse Creek, FC= Five Cowrie Creek, LH= Lower Lagos Habour, UH= Upper Lagos Habour, TB=Takwa Bay, CC= Commodore Channel, LHB1= Lighthouse Beach 1, LHB2=Lighthouse Beach 2, GW1= Great Wall of Lagos 1, GW2= Great Wall of Lagos 2

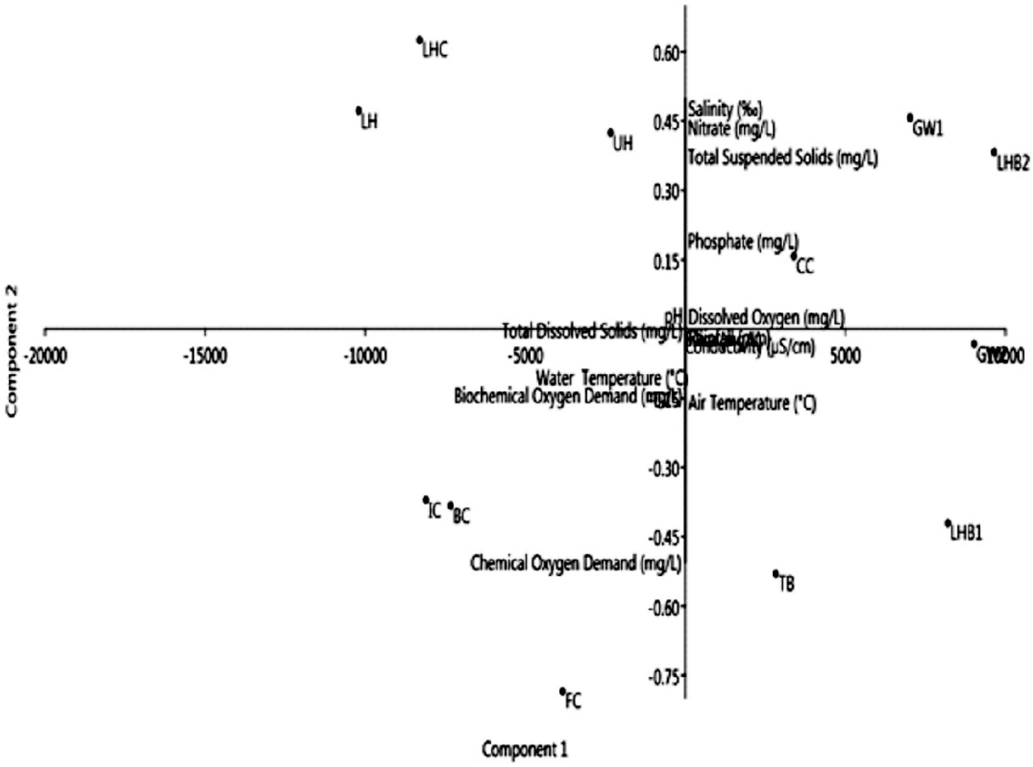

Figure 2: PCA Score Plot of Physicochemical Parameters Operating in the Lagos Harbour and Adjacent Sea, Southwest, Nigeria

LH – Lower Lagos Harbour, UH – Upper Lagos Harbour, TB – Takwa Bay, CC – Commodore Channel, IC – Ijora Creek, BC – Badagry Creek, LHC – Lighthouse Creek, FC – Five-cowry Creek, LHB1 – Lighthouse Beach 1, LHB2 – Lighthouse Beach 2, GW1 – Great Wall of Lagos 1, GW2 – Great Wall of Lagos 2

Phytoplankton Species Diversity and Abundance

A total of 108 phytoplankton taxa belonging to five classes were recorded in this study. Bacillariophyceae (diatoms) comprised eighty-four (84) taxa (78%), Chlorophyceae (green algae) had two (2) taxa (2%), Cyanophyceae (blue-green algae) were represented by 11 taxa (10%), Dictyochophyceae (silicoflagellates) had one (1) taxon (1%) and Dinophyceae (dinoflagellates) had 10 taxa (9%).

Generally, diatoms were found to be the most abundant group across seasons for all stations (Figures 3 and 4). However, in the wet season, Ijora, Badagry, Lighthouse and Five-cowrie creeks recorded higher numerical abundance of cyanobacteria compared to other phytoplankton group. In terms of numerical abundance, Badagry creek recorded the highest number of species. Tables 3 and 4 are the diversity indices for dry and wet seasons respectively. In the wet season, the Lighthouse beach 2 (in the sea) was found to be the most diverse in terms of species.

However, the creeks had the most diverse composition of phytoplankton species in the dry season. At taxon level, of ecological concern was the bloom (30,000-45,000 trichomes per ml) of a blue-green alga, *Oscillatoria tenuis* in the wet months of July, August and September, 2015 at Ijora, Badagry, Lighthouse and Five-cowrie creeks. The bloom was observed in August and September, 2015 at Lower Lagos Harbour. These blooms were responsible for the higher phytoplankton abundance recorded in the months of July, August and September, 2015 (Figure 5).

Analysis of Similarities (ANOSIM) Based on Phytoplankton

Bray-Curtis analysis of similarity grouped the twelve sampling stations into three statistically significant clusters using phytoplankton composition as a basis (Figure 6). Cluster 1 (LHB2 - Lighthouse Beach 2, GW2 – Great Wall of Lagos 2), cluster 2 (UH – Upper Lagos Harbour, TB – Takwa Bay, CC – Commodore Channel, LHB1 – Lighthouse Beach 1, GW1 – Great Wall of Lagos 1) and cluster 3 (IC – Ijora Creek, BC – Badagry Creek, LHC – Lighthouse Creek, FC – Five-cowry creek and LH – Lower Lagos Harbour).

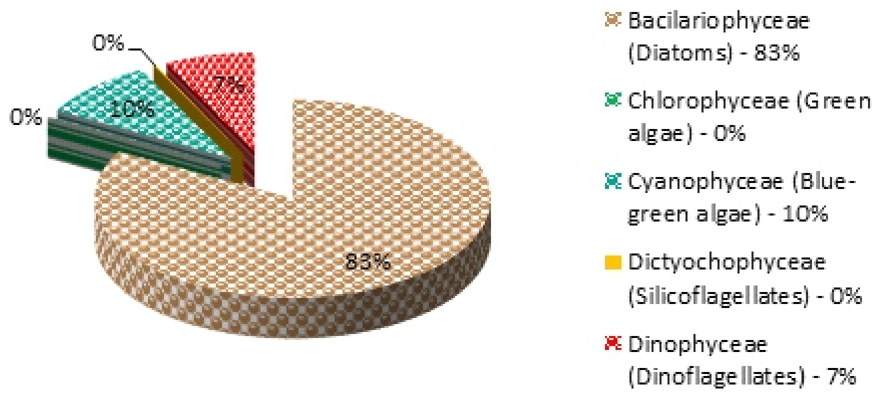

Figure 3: Percentage Composition of Phytoplankton in the Lagos Harbour and Adjacent Sea During the Dry Season (January 2015 – June 2016)

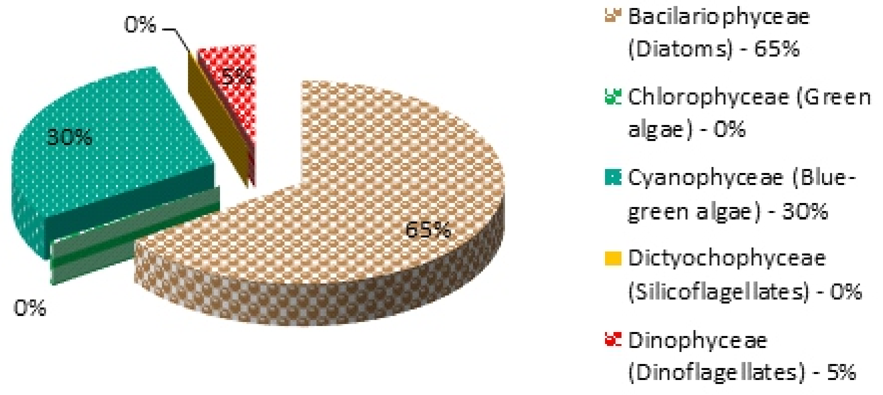

Figure 4: Percentage Composition of Phytoplankton in the Lagos Harbour and Adjacent Sea in the Wet Season (January 2015 – June 2016)

Table 3: Algal Diversity Indices at Sampled Sites in the Lagos Harbour and Adjacent Sea During Dry Season (January 2015 – June 2016)

	LH	UH	TB	CC	IC	BC	LHC	FC	LHB1	LHB2	GW1	GW2
Taxa_S	106	104	104	104	**106**	**106**	**106**	**106**	104	100	104	101
Simpson_1-D	0.9806	0.9735	0.9761	0.9761	0.9812	0.983	0.9825	0.983	0.9711	**0.9866**	0.9724	**0.9867**
Shannon_H	4.222	4.078	4.146	4.145	4.237	4.306	4.289	4.309	4.038	4.428	4.106	**4.43**
Evenness_e^H/S	0.6434	0.5678	0.6077	0.6072	0.6527	0.6995	0.6876	0.7015	0.5453	**0.838**	0.5839	0.8313
Menhinick	0.7933	0.5704	0.5928	0.5929	0.8079	0.7402	0.7425	0.7448	0.5913	0.974	0.6607	**0.9924**
Margalef	10.73	9.893	9.967	9.967	10.77	10.58	10.58	10.59	9.962	10.69	10.18	**10.82**
Equitability_J	0.9054	0.8781	0.8928	0.8926	0.9085	0.9234	0.9197	0.924	0.8694	**0.9616**	0.8841	0.96

Table 4: Algal Diversity Indices at Sampled Sites in the Lagos Harbour and Adjacent Sea During Wet Season (January, 2015 – June, 2016)

	LH	UH	TB	CC	IC	BC	LHC	FC	LHB1	LHB2	GW1	GW2
Taxa_S	79	100	100	100	79	89	88	87	99	**102**	100	101
Simpson_1-D	0.8667	0.9688	0.9713	0.9714	0.7632	0.8439	0.8411	0.8273	0.9643	**0.985**	0.9606	0.9847
Shannon_H	3.042	3.858	3.919	3.92	2.614	3.061	3.048	2.965	3.77	**4.376**	3.776	4.362
Evenness_e^H/S	0.2652	0.4735	0.5036	0.5042	0.1727	0.2398	0.2394	0.223	0.4381	**0.7798**	0.4363	0.7763
Menhinick	0.518	0.5259	0.5444	0.5441	0.4307	0.4464	0.4435	0.4483	0.5466	**1.104**	0.6603	1.092
Margalef	7.758	9.433	9.495	9.494	7.483	8.309	8.222	8.162	9.425	**11.16**	9.86	11.04
Equitability_J	0.6963	0.8377	0.8511	0.8513	0.5981	0.6819	0.6807	0.664	0.8204	**0.9462**	0.8199	0.9451

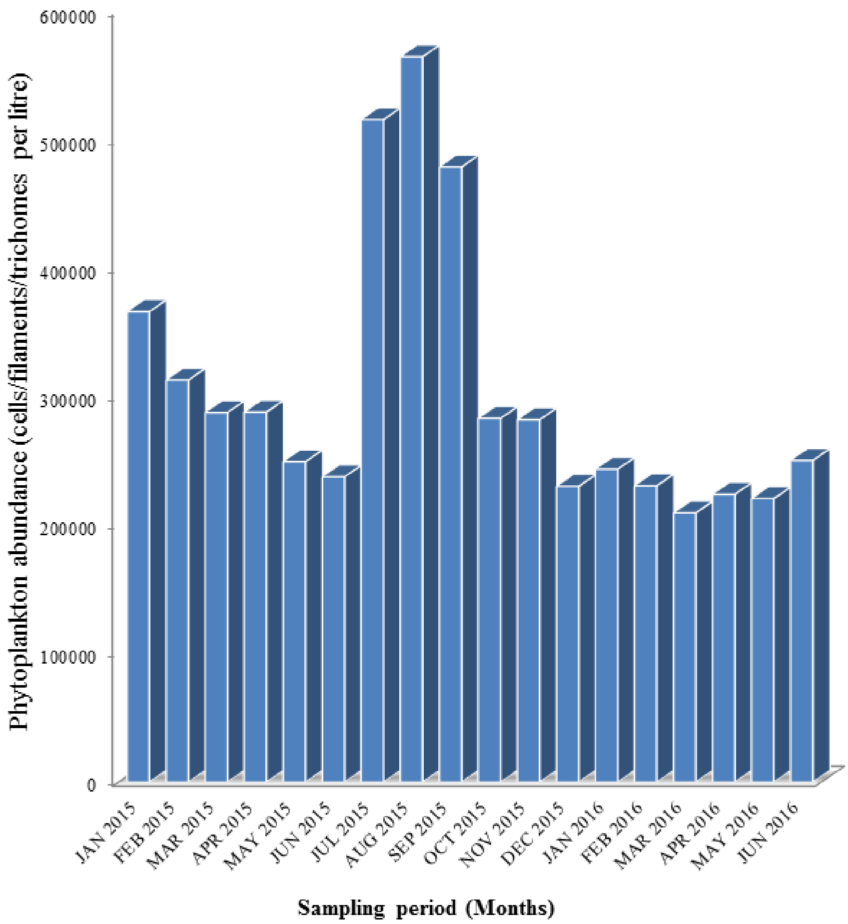

Figure 5: Monthly Variations in Phytoplankton Abundance in the Lagos Harbour and Adjacent Sea, Southwest, Nigeria (January 2015 – June 2016)

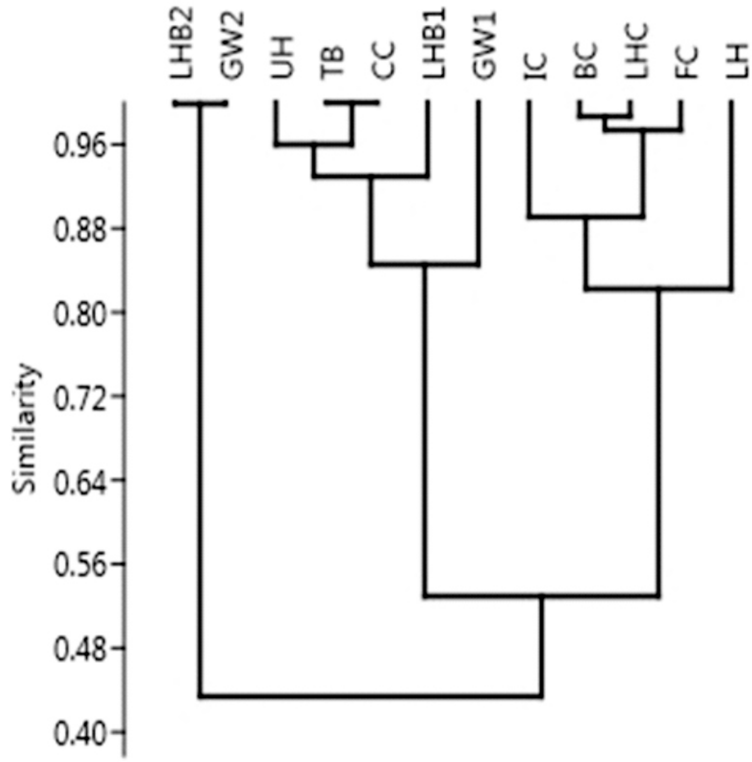

Figure 6: Bray-Curtis Analysis of Similarity in Phytoplankton Composition of the Lagos Harbour and Adjacent Sea, Southwest, Nigeria (January 2015 – June 2016)

LH= Lower Lagos Habour, UH= Upper Lagos Habour, TB= Takwa Bay, CC= Commodore Channel, IC= Ijora Creek, BC=Badagry Creek, LHC= Lighthouse Creek, FC= Five Cowrie Creek, LHB1= Lighthouse Beach 1, LHB2= Lighthouse Beach 2, GW1= Great Wall of Lagos 1, GW2=Great Wall of Lagos 2

Effects of Water Physicochemical Parameters on Phytoplankton

In order to identify the major factors which influenced phytoplankton distribution and abundance at study sites, various statistical tools were applied. Canonical Correspondence Analysis revealed a clear seasonal pattern; it also showed that phosphate was the major controlling factor in the Lower Lagos Harbour (LH), Ijora (IC), Badagry (BC), Lighthouse (LHC) and Five-cowrie (FC) creeks in the months of July, August and September, 2015 (Figure 7).

The results from Pearson's product coefficient between nutrients and abundance of phytoplankton are presented in table 5. There existed significant positive correlations between phosphate and the abundances of blue-green (Cyanophyceae) and green algae (Chlorophyceae); on the other hand, amount of phosphate had significant negative impact on dinoflagellates (Dinophyceae) and silicoflagellates (Dictyochophyceae). Silica had significant positive relationship with green algae; also, its effect on silicoflagellates was profoundly positive.

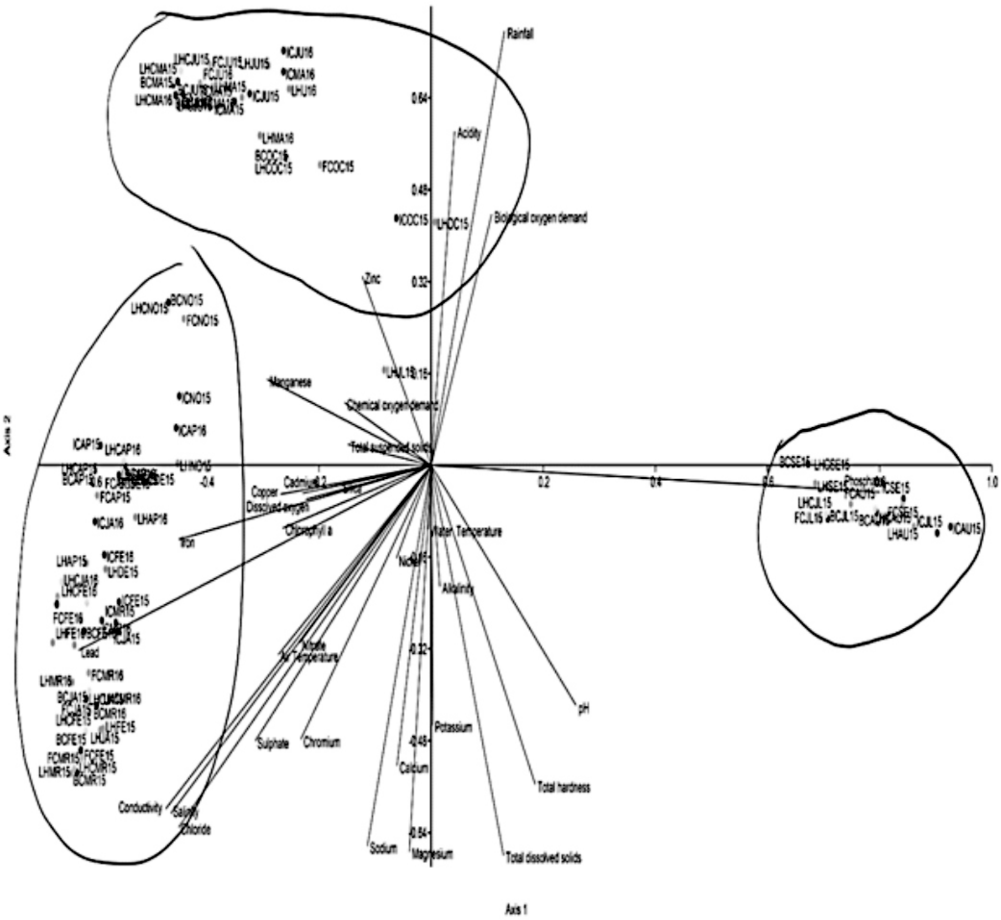

Figure 7: Canonical Correspondence Analysis of physico-chemical parameters in the Lower Lagos Harbour and the creeks adjoining the Harbour (January 2015 – June 2016)

NB: The first two letters connote the name of station, next two letters indicate the month and the last two digits represent the year of sampling. Example: ICAU15 means Ijora Creek in August 2015

Table 5: Relationship (as a measure of effect) between some Nutrients (Nitrate, Phosphate, Silica, and Sulphate) and Abundance of Phytoplankton Taxonomic Groups

	Nitrate n=216	Phosphate n=216	Silica n=216	Sulphate n=216	Bacillariophyceae n=216	Chlorophyceae n=216	Cyanophyceae n=216	Dictychophyceae n=216	Dinophyceae n=216
Nitrate	5.64^m (3.04^s)				-0.044^r (0.517^p)	-0.102^r (0.137^p)	-0.08^r (0.244^p)	0.011^r (0.875^p)	0.051^r (0.457^p)
Phosphate		1.05^m (1.21^s)			0.089^r (0.190^p)	**0.653^{r*} (0.000^p)**	**0.756^{r*} (0.000^p)**	**-0.196^{r*} (0.004^p)**	**-0.231^{r*} (0.001^p)**
Silica			2.35^m (1.52^s)		-0.048^r (0.486^p)	**0.195^{r*} (0.004^p)**	0.081^r (0.235^p)	**-0.189^{r*} (0.005^p)**	-0.077^r (0.258^p)
Sulphate				1729.24^m (483.66^s)	0.071^r (0.302^p)	**-0.416^{r*} (0.000^p)**	**-0.344^{r*} (0.000^p)**	**-0.161^{r*} (0.018^p)**	**-0.186^{r*} (0.006^p)**
Bacillariophyceae					18812^m				
Chlorophyceae						61^m			
Cyanophyceae							4951^m		
Dictychophyceae								37^m	
Dinophyceae									1490^m

The mean of each variable with their respective standard deviation is on the diagonal of the table with superscripts m and s. The calculated r values with respective p-values are above the diagonals, n= number of observations.

Trophic State Index

Trophic state index (TSI) using Carlson's indices revealed eutrophic to hypereutrophic conditions. Whereas stations such as Takwa Bay (TB), Commodore Channel (CC), Lighthouse Beach 1 and 2 (LHB1 and LHB2), Great Wall of Lagos 1 and 2 (GW1 and GW2) were found to be within the lower boundary of classical eutrophy (TSI = 50 – 60), Lower Lagos Harbour (LH), Badagry (BC), Lighthouse (LC) and Five-cowrie creeks (FC) were observed to be hypereutrophic (TSI = 70 – 80). On the other hand, Ijora creek was found to be extremely hypereutrophic with TSI of 83. Figure 8 shows the profile of trophic states for sampled stations in the Lagos Harbour and adjacent sea.

Stoichiometric Nutrient Limitation

The comparison of ambient nutrient ratios with Redfield ratio (N:P = 16:1) revealed clear spatial and temporal variations in the Lagos Harbour and adjacent sea. There was a high nitrate limitation during the wet months, however, stations in the sea (Lighthouse Beach 2, Great Wall of Lagos 1 and 2) and the harbour channel, with the exception of the creeks, experienced phosphate limitation in May and June, 2015. On the other hand, the dry months were seen to record spatial variations in nitrate-phosphate ratios. Figure 9 depicts the nutrient stoichiometry between nitrate and phosphate for the study sites.

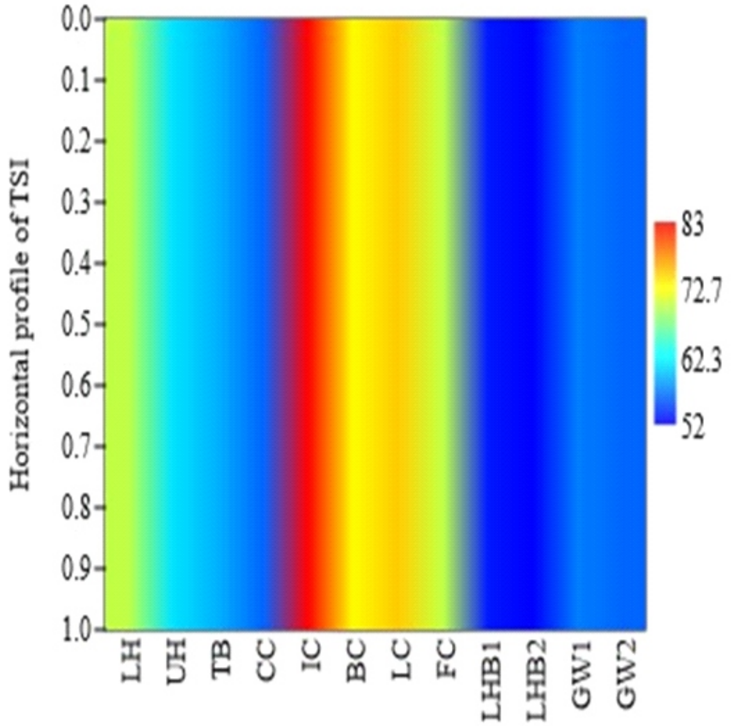

Figure 8: Profile of Trophic State Index, TSI along the Lagos Harbour and Adjacent Sea (January 2015 – June 2016)

LH= Lower Lagos Harbour, UH= Upper Lagos Harbour, TB= Takwa Bay, CC= Commodore Channel, IC= Ijora Creek, BC=Badagry Creek, LC= Lighthouse Creek, FC= Five Cowrie Creek, LHB1= Lighthouse Beach 1, LHB2= Lighthouse Beach 2, GW1= Great Wall of Lagos 1, GW2=Great Wall of Lagos 2

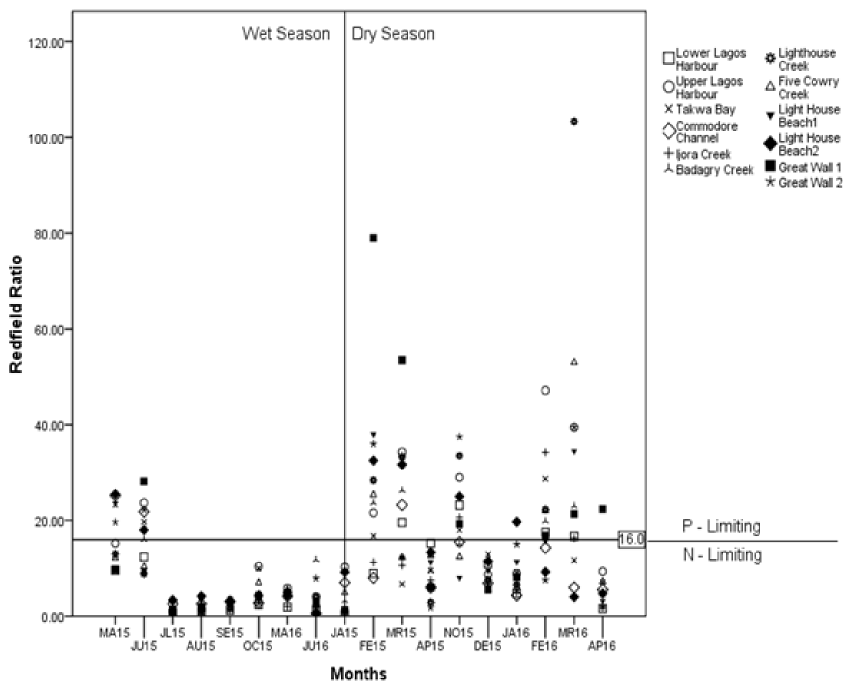

Figure 9: Nutrient Stoichiometry of Surface Water in the Sea Adjacent to Lagos Harbour (January 2015 – June 2016)

NB: LH=Lower Lagos Harbour, IC=Ijora creek, BC=Badagry creek, LHC=Lighthouse creek, FC=Five-cowry creek; JA=January, FE=February, MR=March, AP=April, MA=May, JU=June, JL=July, AU=August, SE=September, OC=October, NO=November, DE=December, 15=Year 2015, 16=Year 2016

DISCUSSION

Over the years, ecological studies have shown that phytoplankton community structure respond to fluctuations in water quality parameters (Nwankwo, 2004a; Reynolds, 2006; Opute and Kadiri, 2013). The physicochemical parameters investigated in this study from January 2015 to June 2016 clearly indicated seasonal changes that were closely related to the distributive pattern of rainfall for the West African region, which in turn, determined phytoplankton composition and abundance in the Lagos Harbour and adjacent sea.

According to Brown and Kusemiju (2002), rainfall pattern in the tropics is responsible for the dry (November – April) and wet (May – October) seasons experienced in West Africa. Rainfall is also known to be the major controlling factor for the distribution of terrestrial and aquatic organisms in the tropics. The Principal Component Analysis from this study, reaffirmed the significant role that is played by rainfall in this region. The salinity regime of the study sites, during this investigation, ranged from low brackish to marine conditions (5.2 – 32.3‰). According to Onyema (2008), there is an existence of environmental gradient determined by salinity in the Lagos lagoon and adjoining tidal creeks. The low brackish water conditions recorded during the wet season and high brackish conditions recorded in the dry season may be attributed to environmental gradients typical of transitional zones.

Higher values of total suspended solids were recorded in the wet months. This observation is attributable to high levels of organic matters brought into the harbour by run-offs from adjoining wetlands. Total Dissolved Solids (TDS) levels in stations which are in closer proximity to the construction site of the Eko Atlantic city, were significantly higher than those reported for the stations with lesser proximity to this city in both dry and wet seasons. This could be attributed to the aftermath effects of massive sand-filling which took place for the ongoing construction of this city. This influence was reflected in the composition of phytoplankton species which was dominated by pennate diatoms such as *Achnanthes brevipes*, *Achnanthes longipes*, *Cocconeis diaphana*, *Cocconeis littoralis*, *Cocconeis placentula* and *Tryblionella coarctata*. These species are known to tolerate higher dissolved solids concentrations (Graham *et al*., 2009). The significant difference shown by phosphate in the wet season could be linked to re-suspension of sediments, which are known to be a haven for phosphate in aquatic ecosystems. A pointer to this was the observed highest value of total suspended value recorded in June 2015, which coincided with the peak of rainfall in the same month of that year.

The significant effects of phosphate in the wet months, which was reflected on the abundance of cyanobacteria species and the eventual bloom of *Oscillatoria tenuis* in July, August and September 2015 was noteworthy. This bloom was largely associated with the creeks adjoining the Lagos Harbour as revealed by the Canonical Correspondence Analysis. This could be attributed to sediment re-suspension as a result of dredging and sand-mining activities in the lagoon system. The relative dominance of diatoms (Bacillariophyceae) in terms of abundance and diversity in all stations and across seasons reported, in this study is in agreement with earlier works done in the Lagos lagoon system (Nwankwo, 2004a; Onyema, 2007; Balogun and Ladigbolu, 2010; Nwankwo *et al*., 2012). Diatoms, which are known to be good indicators of coastal ecosystems (Julius *et al*., 2006; Graham *et al*., 2009), were found to be dominated by tychoplanktonic forms which can tolerate varying degrees of salinity and dissolved solids unlike the typical purely marine planktonic species that were reported for the Lagos harbor by Hendey (1958). From this observation, it could be inferred that habitat modification has altered phytoplankton composition in the Lagos Harbour and the adjoining water bodies.

Trophic status analyses using Carlson's Trophic State Index (TSI) showed eutrophic to hyper-eutrophic conditions. The hyper-eutrophic conditions observed at stations in close proximity to the lagoonal water could be as a result of the introductions of allochthonous inputs and human-induced autochthonous eutrophication. In eutrophic waters, blue-green algae are known to be prevalent (Graham *et al*., 2009; Opute and

Kadiri, 2013). On the other hand, frequent noxious algal blooms are features of hyper-eutrophic conditions (Carlson, 1977; Edmundson and Carlson, 1998). The numerical counts of blue-green algae from the present study are in agreement with the trophic assessments of eutrophic and hyper-eutrophic waters. The stoichiometric nutrient limitation which revealed a clear nitrate limitation in the wet months could be attributed to rapid utilization of reactive nitrogen and an excessive phosphorus supply which could have resulted from the effects of dredging and sand-mining activities following a heavy rainfall recorded in June 2015. In the dry months however, there were fluctuations in the ambient nutrient stoichiometry between nitrate and phosphate. These observations could be linked to varying degrees of environmental and human-induced stress on sampled stations.

Contrary to earlier reports that nitrate is the limiting nutrient in coastal waters of Nigeria (Nwankwo, 2004a), the present study revealed that seasonal and spatial patterns, as well as human activities are major factors influencing which nutrient will be limiting at any point in time.

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Appendix 1: Checklist of Phytoplankton Taxa in the Lagos Harbour and Adjacent Sea (January 2015 – June 2016)

Class 1: Bacillariophyceae

1 *Achnanthes brevipes* C. Agardh
2 *Achnanthes eureka* Alvarez-Blanco & Blanco
3 *Achnanthes longipes* C. Agardh
4 *Achnanthidium exiguum* Grunow
5 *Actinocyclus subtilis* W. Gregory
6 *Actinoptychus splendens* Shadbolt
7 *Amphora hyalina* Kutzing
8 *Amphora ovalis*
9 *Asterionella japonica* Cleve
10 *Aulacoseira granulata var angutissima* Ehrenberg (Plate 5)
11 *Aulacoseira* sp.
12 *Bacillaria paxillifer* O. F. Muller
13 *Bacteriastrum delicatulum* Cleve
14 *Biddulphia aurita* Lyngbye
15 *Biddulphia obtusa* Kutzing
16 *Biddulphia sinensis* Greville
17 *Caloneis* sp.
18 *Chaetoceros atlanticum* Cleve
19 *Chaetoceros convolutus* Castracane
20 *Chaetoceros decipens* Cleve
21 *Chaetoceros radicans* F. Schutt
22 *Cocconeis diaphana* W. Smith (Plate 6)
23 *Cocconeis littoralis* R. Subrahmanyan
24 *Cocconeis placentula* Ehrenberg
25 *Coscinodiscus centralis* Ehrenberg
26 *Coscinodiscus excentricus* Ehrenberg
27 *Coscinodiscus jonesianus* Greville
28 *Coscinodiscus lineatus* Ehrenberg
29 *Coscinodiscus radiatus* Ehrenberg
30 *Cyclotella caspia* Grunow
31 *Cyclotella meneghiniana* Kutzing (Plate 4)
32 *Cyclotella stylorum* Brightwell
33 *Diploneis* sp.
34 *Ditylum brightwelli* Grunow
35 *Endictya oceanica* Ehrenberg
36 *Eunotogramma marinum* W. Smith
37 *Fragilaria construens* Ehrenberg
38 *Fragilaria* sp.
39 *Gomphonema* sp.
40 *Grammatophora marinum* Lyngbye
41 *Guinardia flaccida* Castracane
42 *Gyrosigma* sp.
43 *Halamphora* sp.
44 *Hemidiscus cuneiforms* Wallich
45 *Hyalosynedra laevigata* Grunow
46 *Licmophora lyngbyei* Kutzing
47 *Licmorpha abbreviata* C. Agardh
48 *Mastogloia binotata* Grunow
49 *Mastogloia cuneata* Meister
50 *Mastogloia emarginata* W. Smith
51 *Mastogloia* sp.
52 *Melosira moniliformes* O. F. Muller
53 *Melosira mummuloides* Ehrenberg
54 *Navicula cryptocephala* Kutzing
55 *Navicula expansa* Hagelstein
56 *Navicula formenterae* Cleve
57 *Navicula mutica* Kutzing
58 *Navicula rhyncocephala* Kutzing
59 *Navicula* sp.
60 *Nitzschia linearis* W. Smith
61 *Nitzschia longissima* Brebisson
62 *Nitzschia palea* Kutzing
63 *Nitzschia sigma* Kutzing
64 *Odontella* sp.
65 *Palmerina hardmaniana* Greville
66 *Parlibellus delognei* Van Heurck
67 *Pinnularia major* Kutzing
68 *Plagiogramma* sp.
69 *Pleurosigma angulatum* J. T. Quekett
70 *Pleurosigma* sp.
71 *Podosira montagnei* Kutzing
72 *Pseudonitzschia* sp.
73 *Rhizosolenia styliformes* T. Brightwell
74 *Stephanodiscus* sp.
75 *Surirella recedens*
76 *Synedra crystallina* C. Agardh
77 *Synedra* sp.
78 *Synedra ulna* Nitzsch
79 *Terpsinoe muscica* Ehrenberg
80 *Thalasiothrix* sp.
81 *Thalassionema longissima* Cleve & Grunnow
82 *Thalassiosira* sp.
83 *Trachyneis* sp.
84 *Tryblionella coarctata* Grunow

Class 2: Chlorophyceae

1 *Gonatozygon monoteanium*
2 *Spirogyra africanus* F. E. Fritsch

Class 3: Cyanophyceae

1 *Anabaena spiroides* Klebhan
2 *Lyngbya martensiana* Meneghini ex Gomont
3 *Microcystis aeruginosa* Kutzing
4 *Microcystis flos-aque* Wittrock
5 *Nostoc* sp.
6 *Oscillatoria curviceps* C. Agardh ex Gomont
7 *Oscillatoria limosa* C. Agardh
8 *Oscillatoria magaritifera* Kutzing
9 *Oscillatoria* sp.
10 *Oscillatoria tenius* C. Agardh ex Gomont
11 *Oscillatoria trichodes*

Class 4: Dictyochophyceae

1 *Dictyocha fibula* Ehrenberg

Class 5: Dinophyceae

1 *Ceratium bicephalum*
2 *Ceratium furca* Ehrenberg
3 *Ceratium fusus* Ehrenberg
4 *Ceratium macroceros* Ehrenberg
5 *Ceratium* sp.
6 *Ceratium trichoceros* Ehrenberg
7 *Ceratium tripos* O. F. Muller
8 *Dinophysix* sp.
9 *Gymnodinium* sp.
10 *Prorocentrium* sp.

Appendix 2: Monthly Rainfall values (mm) in Lagos State, Southwest, Nigeria, for the sampling period (January, 2015 – June, 2016)

2015												2016					
Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June
0.1	28 .2	33.8	74.1	216.1	449.3	207.1	45.9	96.6	200.4	48.7	4.1	25.6	5.4	164.4	84	167.3	331.8