UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

SCHOOL OF BIOLOGICAL SCIENCES

MODELLING THE RELATIONSHIP BETWEEN THE WEST AFRICAN MANGROVE OYSTER (*Crassostrea tulipa*, L.1819) AND THE AQUATIC AND CLIMATIC ENVIRONMENT FOR USE AS A BIO-INDICATOR IN THE DENSU ESTUARY

BY

SANDRA AKUGPOKA ATINDANA

(10638040)

THIS THESIS IS SUBMITTED TO UNIVERSITY OF GHANA, LEGON, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF PHD IN FISHERIES SCIENCE DEGREE

DEPARTMENT OF MARINE AND FISHERIES SCIENCES

SEPTEMBER, 2021

DECLARATION

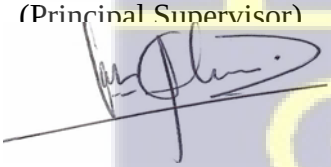
I hereby declare this thesis as the result of original research conducted by Sandra Akugpoka Atindana, of the Department of Marine and Fisheries Sciences, University of Ghana, under the supervision of Professors Francis K. E. Nunoo, Patrick K. Ofori-Danson and Dr. Samuel Addo and that no part of it has been presented for another degree in this University or elsewhere.

…….. Date: 15th September, 2021

Sandra Akugpoka Atindana
(PhD student)

Date: 15th September, 2021

……..
Prof. Francis K. E. Nunoo
(Principal Supervisor)



……..
Prof. Patrick K. Ofori-Danson
(Supervisor) Date: 15th September, 2021

…….. Date: 15th September, 2021

Dr. Samuel Addo
(Supervisor)

ABSTRACT

Crassostrea tulipa (Lamarck, 1819) in the Densu estuary was investigated from March 2019 to August 2020 for aspects of its ecology; it's potential as a bio-indicator of environmental variability; and long-term effects of climate variability on shellfish production in Ghana's artisanal fisheries and its implication on sustainable management of oyster fisheries. Oyster samples were collected monthly and physicochemical parameters namely Temperature (^{O}C), Dissolved Oxygen (mg/L), pH, Total Dissolved Substances (mg/L), Conductivity (µS/cm) and Salinity ($^{0}/_{00}$) measured *in situ* in triplicates. Silicates, Total Alkalinity, Chlorophyll a, microbes (Total Viable Counts, faecal coliform and *Escherichia coli*) and heavy metals (Lead, Cadmium and Mercury) were measured *ex situ* following standards of APHA (2015). Relative abundance was measured as Catch Per Unit Effort (CPUE) and growth pattern determined using the TropFishR package in R programming software. The numerical and frequency of occurrence methods were used to determine its food habits. Species-environmental driver relationship was analyzed following Canonical Correspondence Analysis (CCA) approach using the Vegan package (version 2.5-4.) in R studio software (version1.3.1056). CPUE from experimental fishing was significantly ($p < 0.05$) higher (6-200; 233.33 ± 6.00 kg/hr/fisher/day) than commercial fishing (3-100;78.12 ± 7.11 kg/hr/fisher/day). CPUE was significantly higher ($p = 0.0161$) at low tide (115-500;50.10 ± 5.3 kg/hr/fisher/day) than high tide (6-200; 62.58 ± 3.12 kg/hr/fisher/day). CPUE was higher ($p = 0.023$) in the dry season (150.87 ± 1.12 kg/hr/fisher/day) than the rainy season (57.45 ± 0.55 kg/hr/fisher/day). *Crassostrea tulipa* has a fast growth rate ($K= 0.81$; $L\infty = 13.24$ cm). Higher condition index (60 %) was recorded in the rainy season than the dry season (39 %).

The diet of the oyster was predominated by golden algae (IRI=595), red algae (IRI=209), green algae (IRI=131.37) and diatoms (IRI =172). Densu estuary is a dynamic shallow system with high concentration of total alkalinity and aragonite. Water depth, silicates, *e coli* and revelle factor were significantly higher ($p < 0.05$) at high tide than low tide. Also, mean water depth, cadmium, total alkalinity, pH, carbon dioxide, lead, total carbon dioxide, carbon dioxide fugacity and chlorophyll a were significantly higher ($p<0.05$) in the rainy season than the dry season. The simple linear regression models for forecasting shell height, shell width, condition factor and relative abundance are respectively described as follows:

Shell Height (n=1800) = -0.006.673 faecal coliform (CFU/ml) **- 0.002933 Total carbon dioxide -0.0002556 carbon dioxide fugacity** The coefficient of determination, R^2, of 0.5226 explained about 52.26 % of the variability in shell height.

Shell Width (n = 1800) = -0.02262 faecal coliform (CFU/ml) **+ 0.00089 Total carbon dioxide -0.0000722 carbon dioxide fugacity**

Approximately 41.02 % (R^2) of the variability in shell width is attributable to faecal coliform, total carbon dioxide and carbon dioxide fugacity. Also, an R^2, of 0.5743 shows that 57.43 % of the changes in condition factor was explained by aragonite content and the model describing it is,

Condition Factor (n = 1800) = 65.646 Aragonite

About 26.05 % (R^2) of the oyster abundance is due to temperature.

Oyster Catch Per Unit Effort (n = 1080) = - 35.51973 Surface Water Temperature (^OC)

Also 91 % (R^2) of the variations in shellfish catch is due to temperature following the model.

Shellfish catch per unit effort = −7788.067 + (265.312 SST)

Except for mercury, small- sized oyster (2.5-3.5g) tissues significantly ($p < 0.05$) bio accumulated Pb and Cd than big- sized (4.5-5.4g) tissues. Lead, mercury, TVC, faecal coliform and *Escherichia coli* also bio accumulated in *C. tulipa* tissues more (BAF > 1) than in the water medium which suggests that it has the ability to provide a measurable response to changes in the estuarine environment. Therefore, *C. tulipa* in the Densu estuary has the ability to accumulate pollutants from the environment and its morphometric features could give clues on the state of environmental variables. *C. tulipa* is a good bioindicator for assessing; lead, mercury, Total viable counts, *E coli* and faecal coliform in the Densu estuary. Densu estuary is high in aragonite and total alkalinity. The predictor variables for; Condition factor is aragonite, shellfish catch is temperature and Shell height & Width are faecal coliform, total carbon dioxide and carbon dioxide fugacity. There is the occurrence of contamination and therefore the need for regular monitoring, enactment of control measures and depuration prior to consumption. Also, the use of refuse dam and sewage outlet should be prohibited. It is recommended that laboratory and field-controlled experiments be conducted on oyster responses to extremes of temperature, aragonite and total alkalinity. There is an urgent need for the collation of data on estuarine/lagoonal shellfisheries in Ghana by Fisheries Commission and other stakeholders on catch trends, gears, effort and income of artisanal oyster collectors.

DEDICATION

This research work is dedicated to YOD HAY WAH HAY (YaHWeH) for His divine presence and provision in my life (Daniel 11:32b).

ACKNOWLEDGEMENTS

Abba Father, see how far You have brought me! I am eternally grateful. To my supervisors, Professor Francis K. E. Nunoo, Professor Patrick K. Ofori-Danson and Dr. Samuel Addo of the Department of Marine and Fisheries Sciences, you have been so phenomenal in your individual capacities in guiding, mentoring and supervising this piece without which, would not have seen the light of day. Thank you very much and God richly bless you.

I am grateful to the University for Development Studies and the Department of Fisheries and Aquatic Resources Management for granting me study leave with pay and supporting the study, the Ga East Municipal Assembly for offering me the GETFUND scholarship during the research phase of the study, and all staff of the Department of Marine and Fisheries Sciences, University of Ghana for the academic training and rich source of experience. I am thankful to Dr. Emmanuel Lamptey and staff of ENVARSERVE for encouraging me to pursue a PhD in Legon and assisting in the laboratory analyses respectively. My profound gratitude goes to my husband Mr. Roland A. Akayagre, my sons Caleb A. Asapaka, Glory Y. Asapaka, daughter Excellencia Y. Asapaka and mother, Stella A. Apasnaba for the unflinching support, encouragement and prayers throughout the programme. While you held the torch, God kept the flame burning. God bless you.

I appreciate Dr. Tetteh Akiti of SNAS-UG, Dr. Evans K. Arizi of UCC, Dr. Mrs.Eunice Asamoah, Dr. Berchie Asiedu, Mr. Charles Teye and Mr. James Akomeah of blessed memory for their support. A word of gratitude to all individuals and parties for their cooperation, particularly the oyster collectors at Densu, Promise Hunya, the staff of Development Action Association (DAA) and all local fishers who facilitated in the data collection.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

ABBREVIATION	ACRONYM
APHA	- American Psychological Health Association
AIC	- Akaike Information Criterion
BAF	- Bio-accumulation Factor
Balk	- Buffer alkalinity
CCA	- Canonical Correspondence Analysis
CPUE	- Catch Per Unit Effort
$C0_2$	- Carbon dioxide
$C0_3$	- Carbonates
$HC0_3$	- Bicarbonates
CI	- Condition Index
CF	- Condition Factor
Chla	- Chlorophyll a
Cd	- Cadmium
DAA	- Development Action Association
DO	- Dissolved Oxygen
Dsi	- Dissolved silicates
DIC	- Dissolved Inorganic Carbon
ELEFAN	- Electronic Length Frequency Analysis
EPA	- Environmental Protection Agency (United States)
$FC0_2$	- Carbon dioxide Fugacity
FAO	- Food and Agriculture Organisation
FAO/FiSAT FAO ICLARM	- Fish Stock Assessment Tool
GSS	- Ghana Statistical Service

Hg	- Mercury
IRI	- Index of Relative Importance
IUBS	-International Union of Biological Sciences
DMAFS	-Department of Marine and Fisheries Sciences
MoFAD	- Ministry of Fisheries and Aquaculture Development
NERR	- National Estuarine Research Reserve
NOAA	- National Oceanic and Atmospheric Administration
NRC	- National Research Council
NTU	- Nephelometric Turbidity Unit
OH	- Hydroxyl ions
Pb	- Lead
$pC0_2$	- Partial pressure of carbon dioxide
SDG	- Sustainable Development Goals
SE	- Standard Error
SLR	-Sea Level Rise
Si	- Silicates
Si Alk	- Silica Alkalinity
SH	- Shell Height
SL	- Shell Length
SW	- Shell Width
SFMP	-Sustainable Fisheries Management Project
TDS	- Total Dissolved Substances
TVC	-Total Viable mesophilic Counts
TCO_2	-- Total carbon dioxide
USD	- United States Dollar

USEPA	-United States Environmental Protection Agency
VIF	-Variance Inflation Factor
VBGF	-von Bertalanffy Growth Function
WAMO	- West African Mangrove Oyster
WHO	- World Health Organization

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background

Oysters are a source of nutrients in the form of protein to many people in West Africa including Ghana (Sutton et al., 2012). The shells provide calcium and are used in the preparation of poultry and livestock feeds. In addition, the shells serve as an ingredient in paint preparations, a rough base for footpaths, cement for building and raw material for pharmaceutical industries (Obodai, 1999; Ansa & Bashir, 2007). Ecologically, sessile organisms like oysters are important in the aquatic food chain. Oysters are filter feeders and while they feed on plankton, they help improve on water quality. The settling behavior of oyster spats with time, form reefs which provide structured habitat in estuaries and lagoons for many fish species and crabs.

In Ghana, the West African Mangrove Oyster (WAMO) is widely distributed occurring in mangroves, sediments and compact substrates of coastal water bodies (Obodai, 1999; Ampofo -Yeboah, 2014). In the country, oyster populations in estuaries and lagoons are declining. As at 1996, about nine (9) out of the 41 wetland ecosystems lost their oyster populations (Yankson & Obodai, 1999). The statistics is likely to increase as the study dates back to two (2) decades ago with this possibly to be exacerbated by recent state of increase in pollution of Ghana's water resources. Meanwhile, there is a huge potential for most of these wetlands to be used for culture of oysters on commercial basis for economic gains to the country as practiced in some countries like the Gambia, Egypt and Australia (Obodai, 1999). Furthermore, according to Yankson & Obodai, (1999), 48 % of the estuaries and lagoons in Ghana were found to be suitable for commercial cultivation of

oysters suggesting a high potential for their use for aquaculture to augment catches from the wild which the Densu estuary is no exception.

The Densu estuary in Ghana is a habitat for *Crassostrea tulipa*, Lamarck 1819 **(**West African Mangrove Oyster). The population is currently harvested for commercial use and support the livelihood of riparian coastal communities. There exist several studies on oyster fisheries in Ghana and elsewhere. Most of these studies are centred on oyster socio-economics, biology and culture potential of oysters (e.g Ansa & Bashir, 2007; Mekawy & Madkour, 2013; Asare, Obodai & Acheampong, 2019). Meanwhile, there is no information on the interactions between the size and abundance of the wild mangrove oyster (*Crassostrea tulipa*) with the environment for use as an indicator of natural aquatic variability in the Densu estuary.

Water quality factors, invertebrates, algae, foraminefera, birds, macrophytes and fish have been the conventional proxies used in Ghana for assessing environmental health and managing aquatic systems (Ndanu, 1998; Essuman & Nortsu, 2008; Mahu, 2010; Amoah et al., 2011; Debrah et al., 2011; Apau et al., 2012; Klake et al., 2012; Osei et al., 2013; Anim-Gyampoh et al., 2013; Ansah et al., 2018; Asare et al., 2018; Botwe, 2018; Okyere & Nortey, 2019).

The high mobility of birds, fin fish, short life span of algae, frequent changes in water quality requiring a longer period of monitoring, presents a challenge to their sustainable usage. However, oysters are sedentary organisms that are cosmopolitan in nature, has the ability to filter pollutants and store biogeochemical data thereby reflecting the health of estuarine environments better than other known aquatic bio indicators (Amoah et al., 2011).

In many regions of the world, extensive studies have been carried out on oysters and mussels as ecological indicators of environmental variability (Rudolf et al., 1995; Kirby et al.,1998; Harper et al.,2000; Brander 2007; Barbour et al., 2010; Mekawy & Madkour, 2013; Crampton et al., 2016). However, in Ghana scanty scientific studies have been done on the use of oysters (Katikiro & Macusi, 2012; Parker et al., 2013; Zougmore et al., 2016). Also, it has been documented (Mekawy & Madkour, 2013. Crampton et al., 2016) that as filter feeders, oysters filter a lot of pollutants and are considered as good indicators of environmental changes in water. Conversely, due to the possibly different environmental conditions of the Densu estuary, and the rising need for identification of proxies in the current environmental uncertainty, there is a need to undertake this current research to guide stakeholders to make informed decisions on the possible adoption or otherwise of the West African Mangrove Oyster as an early warning signal of changes in estuarine environments for the development, management and sustainable exploitation of oyster fisheries in Ghana.

1.2 Problem Statement and Relevance of Study

Out of ten estuaries investigated by Yankson & Obodai (1999) in the coast of Ghana for their suitability for culture of oysters, two, namely the Densu and Lower Volta are located in the Greater Accra Region. The Densu estuary is the most important in terms of Oyster fishery in the region (Entsua-Mensah, 1998). It currently supports a thriving commercial oyster fishery under the Development Action Association (DAA) project funded by USAID and remains an important coastal water body in Greater Accra. Information on aspects of the ecology of *C. tulipa* bordering on food habits of the West African Mangrove Oyster and its interaction with the natural environment in the Densu estuary is lacking. Also, despite scientific proofs on the detrimental impacts of estuarine acidification on oysters, there is dearth of information on the influences of acidification factors on the Densu oyster population in Ghana.

There are indications that many coastal wetlands along the Gulf of Guinea Large Marine Ecosystem (GLME) of Ghana which the Densu estuary estuary is no exception is under increasing threat of contamination from incessant human activities such as oil drilling, farming activities, improper disposal of waste from household and industrial sources (McGlade et al., 2002). Several works reiterate the deteriorating state of the Densu estuary and its tributary with impacts arising from nutrient and trace metal loads (Entsua-Mensah,, 1998; Karikari & Ansa Asare 2006; Fianko et al. 2010; Mahu, 2010). Feedback from oyster collectors in Densu indicates oyster size and harvest have currently reduced. Currently most of the brackish systems in Ghana which had thriving oyster populations are recording decreases (Obodai et al., 1999; personal communication, Yankson, 2016). The declining state of oyster stocks in the country and the concurrent contamination of the delta give concern for detailed studies to heighten the need for conservation and urgent management attention.

No known study on the Densu estuary and any other coastal wetland in Ghana has attempted to investigate the interactions between *C. tulipa* and the aquatic environment for use as a proxy of environmental changes. Meanwhile, in this period of climate change and variability, estuaries are classified as highly vulnerable due to their close tie to the sea (World Bank, 2017). The likely impacts will stem from rise in the sea level, changing temperature and estuarine acidification. These impacts are likely to have profound effects on shell bearing organisms like the West African oyster. According to reports of the regional climate vulnerability studies by the World Bank (2017), Ghana will be significantly impacted by variability in climate. The impacts will arise from high annual temperatures from heat stress and precipitation with warming which will impact greatly on fisheries resources in sub-Saharan Africa.

Despite these envisaged challenges, the uniqueness of this sub-artisanal fishery lies in the fact that, although fishing is generally recognized as a male-dominated field in Ghana, the harvesting, processing and marketing of oysters is dominated by women (Ebinimi & Bashir, 2007; Bagne et al., 2011; Carney et al., 2017; Chuku, 2019). These roles of women in the oyster industry have contributed significantly to the reduction of poverty and enhanced food security within deprived communities (Goodwin et al., 2012; Darboe, 2015). Sustainable management of the fishery will ensure a continual nutritional and economic support to this vulnerable group and the society as a whole.

Therefore, for a viable management and development of the oyster industry as well as its culture, there is a need to acquire scientific knowledge on the environment and aspects of the biology of the species. This work will not only be useful for the management of the fishery but will inform frontiers of knowledge on the growth and use of the oyster as an early warning signal of environmental perturbations.

The findings of this research will be useful in policy formulation by being leveraged into the Ghana national fisheries policy in its bid to enhancing and deepening marine stock recovery as planned in the 2020 Ghana budget and economic policy.

1.2 Objectives

The main aim of this study is to assess the possible use of the West African Mangrove Oyster (*Crassostrea tulipa*) as a bio-indicator of aquatic environmental variability to enhance sustainable management of the fishery in the perspective of global environmental change in Ghana.

1.2.1 Specific Objectives

The specific objectives of the study are to:

I. Study aspects of the ecology of the West African Mangrove Oyster in the Densu estuary necessary for its conservation

II. Assess the potential use of *C. tulipa* as a bio-indicator of environmental variability of the Densu estuary

III. Model projections of long-term effects of climate variability on artisanal shellfisheries production and its implications for sustainable management of oyster fisheries.

1.3 Research Questions

a) Does *Crassostrea tulipa* catch vary with season and tide in Densu estuary?

b) Is there seasonal variation in condition factor of *Crassostrea tulipa*?

c) Is there (dis)similarity in gut contents and food items in water?

d) How is *C. tulipa* abundance influenced by physicochemical parameters of the environment?

e) Does seasonality and tidal changes in physicochemical parameters have influences on CPUE?

f) Is the concentration of heavy metals and microbes significantly different among different sizes of oyster?

g) Is there a significant correlation between heavy metals and microbial content in tissues and water?

h) Which aspects of the biodata on the shell fish best serve as bio indicators?

i) What are the major determinant climate factors influencing artisanal shell fish production in Ghana?

The following hypotheses were therefore tested based on the set objectives:

1. H0: Tide and season does not influence the abundance of *Crassostrea tulipa*
2. H0: There is no seasonal variation in condition factor of *C. tulipa*
3. H0: There is no similarity in food items found in guts and estuarine water
4. H0: Physicochemical parameters have no effect on size of *C. tulipa*
5. H0: Seasonal and tidal changes in physicochemical parameters have no influence on oyster catch.
6. H0: Tide and season does not influence the abundance of *C. tulipa*

7. H0:The concentration of heavy metals and microbes are not different among different sizes of oyster

8. H0: The concentration of heavy metals and microbes are not different among different sizes of oyster

9. 9. H0: There is no correlation between heavy metals and microbial content in meat and water.

9. 10. H0: There are no major determinant climate factors influencing marine artisanal shell fish production in Ghana.

1.4 Delimitation of the Study

Densu estuary is not the only estuary where oysters thrive in coastal Ghana. It was however, selected because of the presence of an active commercial oyster fishery and the fishery being one of the main sources of livelihood support for nearby coastal communities. Although in literature there are many other water quality parameters which could have been monitored, it was empirically unattainable to monitor all so the study was restricted to studying the correlation between oyster abundance and size with some species of microbes, heavy metals, chlorophyll a, estuarine acidification and Physicochemical Parameters. These environmental parameters were chosen based on existing land use activities around the site, the ecology of the West African Mangrove Oyster and human health implications.

1.5 Limitations of the Study

A motorized canoe was used for catch assessment in the experimental fishing because it was the available fishing craft of the oyster collector. Although this limitation was uncontrollable, their influences precluded any scientific interferences. The incidences influenced mainly the scale of the research and only emphasizes the complexity of sampling techniques in open aquatic systems which are prone to natural harsh

conditions and disasters.

1.6 Organisation of the Study

There are a total of six chapters in this thesis. Chapter 1 is an introduction to the whole concept of the study, highlighting the background of the study and stating the problem and relevance of the study, objectives, research questions, hypotheses to be tested, delimitations and limitations.

Chapter 2 is a review of literature relevant to the study. In-depth review of the literature on classification of oysters, population parameters, hydrodynamics of estuaries affecting oyster abundance, impacts of estuarine acidification on oysters, conventional bio indicators in use and a review of studies on ecology and biology of brackish populations in Ghana was presented.

Chapter 3, presents introduction on the relevance of assessing aspects of ecology of the West African Oyster**.** The materials and methods employed in assessing commercial and experimental catch, growth pattern, feeding regime and condition index are elaborated. The results are presented on charts and tables followed by a detailed discussion.

Chapter 4, investigates the relationship between physicochemical parameters and the morphometric factors of the West African Oyster and the establishment of the use of *C. tulipa* as a bio-indicator using physicochemical parameters. The materials and methodology used in gathering data, data analytical procedures and tools, results and discussions are elaborated into detail.

Chapter 5 presents an introduction, methodology, results and discussions on modelling projections of long-term effects of climate variability on shellfish production in

Ghana's artisanal fisheries sub sector and the implications on management of oyster fisheries.

Chapter 6 presents general conclusions and recommendations of the study.

CHAPTERTWO

2.0 LITERATURE REVIEW

This chapter reviews relevant literature for the study. It discusses into detail the taxonomy, classification and distribution of oysters, population parameters, hydrodynamics of estuaries in relation to oysters, climatic factors influencing oyster growth, effects of ocean acidification on estuaries and bivalves, bio indicators of estuarine environments and review of conventional and aquatic bio indicators. An in-depth review of studies on ecology and biology of brackish populations in Ghana is presented.

2.1 Taxonomy, Classification and Distribution of Oysters

The classification of oysters was first done by Linnaeus in 1958. This was an attempt to describe some species of oysters including Ostrea. Among bivalve molluscs, oysters are known to belong to the class Bivalvia, subclass Pteriomorphia, order Ostreida, and superfamily Ostreoidea (Linnaeus, 1958). This resulted from a broad definition of the genus Ostrea and many bivalves across different families.

A detailed study of the fossil and living oysters by Stenzel (1971) showed that oysters can be classified according to shell morphology and anatomic characters into the families Gryphaeidae and Ostreidae (Liu et al., 2011; Salvi et al., 2014; Raith et al., 2016). The oyster fossils revealed that both families have no recognizable intermediate type (Triassic) suggesting the two oyster families might be diphyletic (Stenzel 1971; Liu et al., 2011). Further to this, molecular data obtained from phylogenetic analyses reiterated the separation of the two families but not the diphyletic origin of Ostreoidea. Conclusively in all analyses, the two distinct branches of a single monophyletic clade of oysters are Gryphaeidae and Ostreidae (Liu et al., 2011; Salvi et al., 2014; Raith et al., 2016; Salvi &

Mariottini, 2017). In 1971, the family Gryphaeidae was divided into three subspecies: Gryphaeinae, Exogyrinae, and Pycnodonteinae by Stenzel. Except for the family Pycnodontidae where all living species are placed, the remaining first two subfamilies are extinct. And with the family Ostreidae, the author classified it into two subfamilies, Lophinae and Ostreinae, both containing extinct species. On the other hand, Quayle in 1989, grouped all oysters of the world into one family called the Ostreidae under three main groups or genera called Ostrea, Crassostrea and Pycnodonta. Later, Torigoe (1981) considered Gryphaeidae as a fossil-only family and elevated subfamily Pycnodonteinae to family Pycnodonteidae.

Crassostrea and Saccostrea were later moved out of Ostreinae and a new subfamily, Crassostreinae established (Torigoe,1981). In 1985, Crassostreinae was accepted as a sub family under Ostreidae while the sub family Pycnodonteinae was retained under Gryphaeidae and several new genera proposed under Ostreinae and Lophinae (Harry, 1985). Later, Angell (1986) confirmed the existence of many genera of living oysters in literature but concluded that the genera Crassostrea, Saccostrea and Ostrea contain the most commercially important species.

Li (2013) in a quest to support his findings with molecular data on these groups, revealed new phylogenetic structures needful for taxonomic consideration. The study of Li (2013) showed high levels of divergence between Crassostrea and Saccostrea and proposed that Saccostrea be placed into a separate subfamily Saccostreinae.

The works of Salvi et al. (2014) further confirmed the significant differences between the two families Crassostrea and Saccostrea. The author concluded by proposing a new subfamily Saccostreinae.

The genera Striostrea were originally placed under the subfamily Ostreinae. Contrary to this, Raith et al. (2016) found that *Striostrea prismatica* was highly varied from other Ostreinae species in mitochondrial DNA sequences. The author later suggested the new subfamily Striostreinae with the single genus Striostrea. This ideology was supported by Salvi and Mariottini (2017). On the basis of morphological characters, the subfamilies Lophinae and Lstreinae are well documented and studied (Stenzel, 1971; Torigoe, 1981; Harry, 1985 as cited in Guo et al., 2018). On the basis of phylogenetic analyses, brooding oysters from these families (land ostreinae) are often intertwined, and so suggested to be combined (Salvi et al., 2014; Raith et al., 2016). Anatomically, the main difference between the Ostreinae species and Lophinae species is the intestine looping around the stomach (Torigoe, 1981; Li & Qi, 1994). In terms of taxonomy, there is little scientific documentation on Ostreinae and Lophinae. Therefore, it is confusing and unscientific to merge the two subfamilies. Currently, many biologists suggest the two subfamilies be kept independent of each other and accept the Ostreidae: Crassostreinae, Lophinae, Ostreinae, Saccostreinae, and Striostreinae as sub families (Bayne et al., 2017; Bayne et al., 2018; Guo et al., 2018).

Among all these families, the number of extinct oyster species is difficult due to taxonomic confusions and inadequacies from shell morphological features. In terms of speciation, there are twelve species of the family Pycnodonteinae. Saccostrea species which are small- to medium-sized rock oysters are extremely different and difficult to classify due to their small- sized and close attachment to rocks and shells of Saccostrea. The family Crassostreinae contains about 26 species, including others that have not been genetically confirmed: *Crassostrea cuttackensis, Crassostrea aequatorialis, Crassostrea iredalei* and *Crassostrea tulipa.*

In literature, two species names have often been used to refer to the West African

Mangrove Oyster (WAMO), *Crassostrea tulipa* (Lamarck, 1819) and *Crassostrea gasar* (Dautzenberg, 1891). A study by Lapegue et al. (2002) on the genetic analysis of the mitochondrial DNA, revealed that the two scientific names referred to the same organism. However, in literature, the use of the name *C. tulipa* is usually preferred to *C. gasar* due to the precedence of the former to the latter. On the basis of nomenclature of the species, Yankson (1991) addressed the earlier confusion by giving a comprehensive discussion on the subject, which ended with the recommendation of referring to the West African Mangrove Oyster as *C. tulipa*. As a result, the species name *C. tulipa* was used in this document.

Crassostrea tulipa is found along the West coast of Africa (Sutton et al., 2012) (Plate 1). It is distributed between Senegal and Angola. Apart from the bloody cockle, *Anadara senilis*, *C. tulipa* is the next economically important bivalve mollusc in the West African sub region (Nickles, 1950). In Ghana, *C. tulipa* is not rare to be found. It occurs in not less than 90 % of the existing coastal wetland systems (Sutton et al., 2012). The West African mangrove oyster, *C. tulipa* (Lamarck, 1819) occurs in the tropics and has high tolerance to extremes of salinity changes. Therefore, it is referred to as a euryhaline organism. The species can grow well in shallow (2 to 5 m deep) brackish areas such as mangrove swamps and sheltered places. The maturity period for WAMO is approximately 7 – 9 months (Ansa & Bashir, 2007). It attaches itself to stilt roots of red mangrove ecosystems. Along these suitable habitats, oysters survive and thrive well by using their foot to attach themselves to roots of mangroves, surfaces of firm substrate such as sand, rocks/stones and shells of organisms.

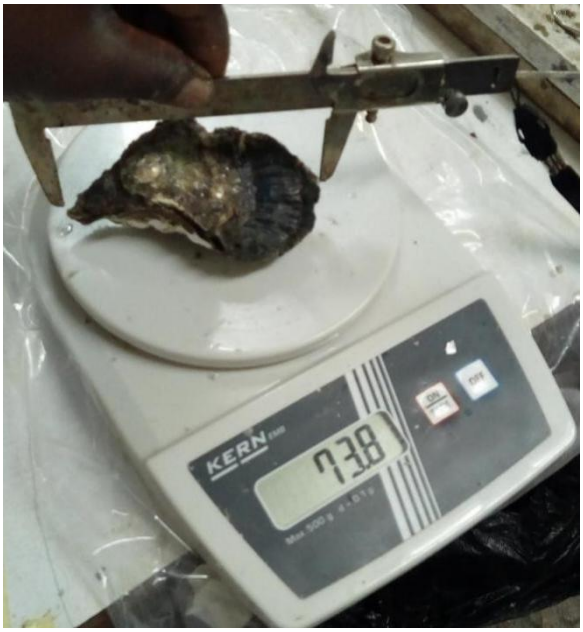


Plate 1: *Crassostrea tulipa* specimen from Densu estuary, 2019

Morphology of oysters in terms of shape and size also change in response to variations in the estuarine environment (Juliana et al., 2008). Under crowded conditions the shells may be thin and long, broken and pitted under fouling conditions and small and white if the oyster is growing in low salinity areas. The significant contribution of bivalve fisheries and its potential globally calls for efficient methods of assessment to safeguard rational production over time (Gosling, 2015). In a given environment, the most frequently used measure of an organism's vitality is its growth. According to Gosling (2004), growth is said to be an increase in the longest measurement of the shell. Among bivalves, age is used as a direct estimate of size. Therefore, growth is representative of changes in body size and as such its proportional to shell volume, shell length or shell height (Dame, 2002).

There is a seemingly general confusion with the shell orientation and dimension of bivalve terminologies in literature. On shell orientation of bivalves, terminologies like anterior and posterior have been used inconsistently even with a given species.

Hoggarth (1987) reported that the identification of anterior and posterior ends of the bivalve shell could be speculative in dealing with juveniles and less studied (fossil) groups.

According to Bailey (2009), the dominance of posterior elongation among bivalves has fostered a bias, where it is spontaneously assumed that the long end of the shell is the posterior and confusing right and left shells.

The confusion in shell dimension, where a given dimension is given different names abounds in literature. Particularly in oysters, the height is determined as the distance between the hinge and the opposite shell margin (Gosling, 2015). Meanwhile, the same dimension has been termed length (Gordon et al., 2017). However, per the conventional shell dimensions according to Galtsoff (1964) and Gosling (2015), the height is the distance from the opposite shell margin to the hinge line; while the widest part across the shell at 90 degrees to the height is the length and the width is measured at the thickest part of the two shell valves. These conventional definitions of oyster shell dimensions by these authors were adopted in this study.

Thus, the longest dimension of the shell is the height in oysters (Plate 3). Determining growth of bivalves using shell size requires precision. Depending on measurements of single shells to generalize growth of a population can be problematic and may result into complications. This is so because differences in environmental and reproductive conditions may affect growth of these bivalves. Also, variations in growth of shells and soft body tissue will not allow for an equal comparison of these morphometric parameters (Dame, 1972 as cited by Dame, 2002). Thus, generally among bivalves, determination of size relationships using weight of soft body tissue and shell dimensions and usually results in allometric growth patterns (Dame, 2002). There is therefore the need to combine linear shell measurements with weights in the study of the growth of bivalves.

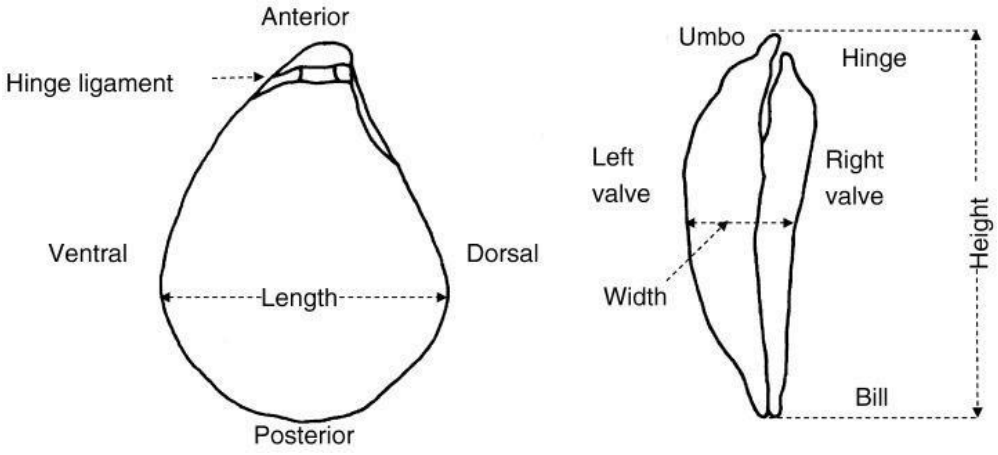


Plate 2: Anatomical features of *C. tulipa* (Wikipedia.com)

Dame (2002) identified four methods useful in assessing growth in bivalves. These are the tracking size frequency distributions, size changes in marked individuals, using biomass and observing radioactive tracer uptake in estimating shell growth rings. Quayle & Newkirk (1989) and Bayne (2017) on the other hand presented five methods for assessing shell growth, namely: measurements of shell dimension of randomly sampled specimens, sequential measurements of tagged individuals, measurements of growth rings (upon validation), acetate peels of cut shells and changes in stable isotope ratios within the shell.

The use of size frequency distribution in determining growth rates is only applicable to bivalve species with short reproductive periods however those with extended recruitment period like *Crassostrea tulipa* have their growth rates being variable (Dame, 2012). In relation to shell rings or growth lines, bivalves form stable environments where environmental conditions are uniform (tropics), generally have inconsistent line formation and visible rings and line formation is variable. Hence, the uncertainty in the use of this method lies in the need for a careful check for reliability of rings in each locality.

Given the procedures above, the measurement of individual sizes (particularly the untagged procedure) has been widely used in assessing tropical bivalve fish stocks (Laudien et al., 2003; Mendo & Jurado, 1993). This is because the approach is simple, less time consuming, measures the growth of populations under natural conditions and does not require the sacrifice of specimens. Irrespective of which method is used, growth models are required to relate the age of fish in a population to their length or weight data termed as the final products of growth analyses (Pauly, 1984). With these models on growth, an equation is usually developed to represent the output of the model. The output of population models, relates the estimates of the parameters and growth essential for future comparisons among and within. The most common growth models are von Bertalanffy, Gompertz and Logistic models. To assess growth pattern using these models, length-based procedures which are commonly used in the tropics in fish stock assessment are employed (Pauly, 1984; OforiDanson & Kwarfo-Apegyah, 2008; Osei, 2015). One such example of length-based procedures is the development of the electronic length-frequency analysis (ELEFAN) by FAO. ELEFAN was a separate programme meant for the collection of fishery assessment tools that uses length-frequency data.

It was later implemented in the FiSAT II program of FAO-ICLARM Fish Stock Assessment Tools (Gayanilo et al., 2005) and COMPLEAT ELEFAN (Gayanilo, Soriano & Pauly, 1989). FiSAT II has been extensively used in the analysis of several fisheries around the globe since its publication by Pauly & David (1980). In part, due to the cost effectiveness of length data and the insufficiency of catch data. Lately, Pauly & Greenberg (2013) incorporated ELEFAN I into the R software. This innovation led to the development of R-based packages for fish stock assessment. The relevant ones to the current study are TropFishR (Mildenberger et al., 2017); fish methods (provide functions for the application of fisheries stock assessment methods, Nelson, 2018); devtools

(provide functions that simplify and facilitate commands, Wickham, Hester & Chang, 2018); (kernel smoothing for confidence contours, Duong, 2019) and fishboot (a tool for the study of fish stocks and aquatic resources, Schwamborn et al., 2018). The new optimisation algorithms which are packages built for the R software (R Core Team, 2019), according to Taylor & Mildenberger (2017), have the capability of optimising the search for a combination of four parameters (asymptotic length (L∞), growth coefficient (K), summer point (ts) and strength oscillation (C)) at a reduced computation time, where FiSAT II software fall short. These modern tools were used in this study.

2.1.1 Feeding

The presence of phytoplankton in water constitutes an important component of the diet of suspension feeders (Dupuy et al., 2000). There is high suspension activity of bivalve populations during incidences of high phytoplankton concentration in water. The activities of these suspension feeders, may have profound influences on phytoplankton abundance (Barille et al., 2003).

Studies from gut content analyses and stable isotope carbon analyses have shown that `phytoplankton` particularly benthic diatoms, can be a main food source of oysters (Hsieh et al., 2000; Yokoyama & Ishii, 2003; Kasai et al., 2004). Phytoplankton abundance therefore is indicative of the presence of many benthic species of diatoms (Facca et al., 2002; Perissinotto et al., 2002). The existing gap in gut analyses studies lies on difficulty in identifying the preferred algae during feeding. However, direct observation of gut contents is needed to clarify the feeding preference in various natural food sources of bivalves (Dupuy et al., 2000). Feeding has profound influences on the condition of oysters

thus the volume of the shell cavity that contains the soft body tissue which is also affected by the hydrodynamics of estuaries.

2.2. Hydro Dynamics of Estuaries in Relation to Oysters

2.2.1 Physicochemical Parameters Influencing Oyster Abundance

Quayle (1989) suggested a suite of environmental factors which affect tropical oyster populations both positively and negatively. The positive factors facilitate growth and survival. Conversely, negative factors hinder reproductive capabilities and affect population dynamics. Also, excessive bridging of thresholds of conditions may lead to increases in the incidence of disease reduce fattening ability of oysters and impair growth thereby reducing the productiveness of reefs of oysters and body coverings and increases the incidences of predation. The positive factors are character of the bottom, water movements, salinity, temperature and food.

2.2.2 Character of Bottom

Oysters attach their foot to diverse surfaces. Some of these surfaces ranges from shells of other organisms, compact surfaces and intertidal shores. Ability to attach well provide support to their weight. Silt sand and soft mud are extremely unsuitable bottoms for oyster communities but may be improved by adding dead oyster or clay (Strayer, 2008).

2.2.3 Sediment Particle Size

According to Tait (1981), differences between benthic communities in water can often be correlated with differences in sediment grain size. The rate of circulation of bottom current and size of particles being transported with the wave influences the type of sediment deposited at shore.

Also, the faster the water moves, the coarser is the texture of the substrate, because finely divided materials are easily held in suspension than larger particles of the same density. Sedimentary materials are transported into the estuary from rivers, sea, or are washed in from the land surrounding the estuary (McLusky, 1989). As tidal current enters an estuary, it slackens in speed and deposits first gravel, then sand, and finally silt, which accumulates as mud. Castro & Huber (2005) reported sand and other coarse materials settle out in the upper reaches of the estuary when the river current flows. The fine, muddy particles are carried further down the estuary where many of them settle out when the current slows even more; though the finest particles may be carried far out to sea. The bottoms of most estuaries, therefore, have sand or soft mud substrates (McLusky, 1989).

In a study by Mahu (2015), sediments in the Densu estuary showed mean grain size variation between 49.3 µm and 88.3 µm with modal values ranging from 127.6-185.4 µm. The estuary was dominated by silt (70%), Clay (10% at the top and 30% at the bottom) and sand (27%) at the top section of the cores.

2.2.4 Total Dissolved Solids

The growth of tropical oysters is partly influenced by the amounts of dissolved suspended solids in estuaries. These suspended solids have the ability to clog the gills of oysters as they filter feed. A measure of Total Dissolved Solids (TDS) involves both dissolved and suspended solids. These solids range from silts, clay, soil runoff, plankton, industrial waste to sewage. According to Thommai et al. (2014), total dissolved solids (TDS) in water comprises both inorganic salts and dissolved materials. Salts in natural waters, are made up of chemical compounds of anions and cations such as carbonates, chlorides (Cl^-), sulphates (SO_4^{-2}), nitrates (NO_4^-), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}) and sodium (Na^+).

The design value and design range of TDS for a raw brackish water is 3,394 and 2899-3450 mg/L (WHO, 2007). As filter feeding organisms, oysters tend to have their gills blocked by high amounts of dissolved solids are ingested during feeding. Growth is impaired and aerobic respiration affected during such processes. Prasanna & Ranjan (2010) reported the maximum range of TDS in the months of April and May and the minimum range during January and February at Dhamra Estuary. Likewise, Thommai et al. (2014), observed TDS ranges from 144 to 64600 (mg/L) with explanations to the high values as due to heavy rainfall. In summer, TDS level is usually low probably due to the low inflow of fresh water. The second largest estuary in Ghana, Pra estuary is silted from activities of illegal alluvial gold miners upstream.

2.2.5 Exchange of Water

Among oysters, free exchange of water is crucial for their growth, fattening and reproduction (Angell, 1986). Therefore, an ideal condition for bivalves is that of a steady, non-turbulent flow of water over an oyster bed, capable of providing enough oxygen and food while carrying away the liquid and gaseous metabolites and excreta.

Also, for a suitable expansion of oyster beds, water currents should be able to transport larvae at the required time during spat settlement for adequate contact with clean, hard surfaces (Strayer, 2008). This phenomenon is particularly distinct in estuaries and places these ecosystems at an advantage for the expansion of oyster communities and for the annual rehabilitation of reduced oyster populations . This is so because during the movement, some larvae which are carried back and forth by the oscillating movements of tidal waters, eventually settle beyond the place of their origin.

2.2.6 Tides

Most tropical oyster species like *Crassostrea tulipa*, prefer shallow intertidal waters to avoid desication and less predation. They grow to dense populations along narrow bands or concentrate more at a tidal height of intertidal regions (Angell, 1986). Among the genera Crassostrea, *Crassostrea paraibanensis* is one of the few species which is predominantly or wholly subtidal (Singaraja, 1980). The susceptibility of tropical oysters to heavy fouling and tolerance to desiccation when continuously immersed directly influence culture technology. The interactions between oysters and their physical and chemical environment according to Angell (1986), Pieterse (2013), Lodeiros et al. (2017) and Chumkiew et al. (2018), affect the fauna's distribution and abundance and greatly influence the health and sustainability of aquatic ecosystems.

2.2.6 Temperature

Temperature is among one of the most principal physical factors influencing growth, survival, reproduction and abundance of aquatic life (Landford, 1990). In tropical estuaries, variability in water temperature is mostly attributable to shallow water depth, low water volume and freshwater inflow from land drainage (Fatema et al., 2014). Generally, among shallow estuaries, temperature changes is controlled by atmospheric temperature.

The life of oysters such as rate of water transport, feeding, respiration, gonad formation, and spawning are influenced largely by changes in temperature regime.

Among estuaries, temperature varies between 18.33 °C and -29.44°C (WHO, 2007). Though in other parts of the world, *Crassostrea* is known to thrive between temperatures of 23 °C - 31 °C, there is little documented data on the effects of prolonged temperatures above 32 °C to 34 °C on oyster populations. However, deductions may be drawn from a few physiological observations that long, sustained exposure to high temperature is

unfavorable and impedes the normal rate of water transport by the gills (Quayle, 1989). *Crassostrea tulipa* is known to thrive well in temperatures varying between 25-30°C in estuaries in Ghana (Sutton et al., 2012). In an experimental trial by Yankson (1990) to determine the effects of changing temperature on larval growth, temperature was identified to have intense influence on early stages of *C. tulipa.* However, in an earlier study by Angell (1986) of tropical and subtropical oysters, changes in temperature were posited to have less influence on growth and mortality. The author on the other hand, mentioned that gonad activity coincides with changes in temperature and salinity. Thus, increasing temperature supports gonadal growth whereas maximum shell growth occurs during the months of highest salinity (20-28 ppt) and lowest temperature of 15- 16°C. Similarly, among the population of *Crassostrea virginica* in Louisiana, high temperatures correlate with high growth rate (Lowe et al., 2017). The Butuah estuary according to Okyere et al. (2011), has an extremely higher temperature, averaging 32.9ºC.

In Canada and USA, the works of Cansas et al. (2019) reiterated temperature as a main driver of clearance rate, valve opening duration and oxygen consumption rate. A summary of the temperature requirements by different species of *Crassostrea* are shown in Table 2.1.

Table 2. 1: A Summary of Temperature Requirements for *Crassostrea* spp.

Species/country	Temperature range (º C)	Reference

Crassostrea belcheri		
Malaysia	27 – 31	Chin & Lim, 1975
Crassostrea gasar		
Nigeria	25 – 30	Ajana, 1980
Crassostrea gigas		
Hong kong	11 – 31	Mok, 1973
Israel	12 – 34	Hughes-Grames, 1977
Fiji	24 – 31	Ritchie, 1977
Hawaii	22 – 28	Brick, 1970
Crassostrea gryphoides		
India	19 – 33	Durve, 1965
Crassostrea madarensis		
India	26 – 31	Virabhadra & Nayar, 1956
Crassostrea parabainensis		
Brazil	24 – 30	Singaraja, 1980
Crassostrea rhizophorae		
Cuba	18 – 34	Farfarsie, 1954
Venezuela	27 – 30	Angell, 1973
Puerto Rico	24 – 27	Watters & Prindow, 1975
Colombia	27 – 33	Wedler, 1970
St Croix	25 – 32	Forbes, 1973
Crassostrea tulipa		
Ghana (Benya)	27 – 31.5	Obodai et al., 1997
Ghana (Pra)	27 – 32	
Crassostrea virginica		
Mexico	20 – 30	De Buen, 1957
Hawaii	21 – 27	Sakuda, 1966

Heat is crucial for biochemical reactions. It accelerates the dissolution of chemical substances affecting the pH and conductivity levels of water thus influencing aquatic species diversity and distribution (Gillooly et al., 2002).

2.2.7 pH

According to NERR (1997), most aquatic fauna are known to adapt to pH levels ranging between 5.0 and 9.0. Therefore, knowledge of pH in estuaries is important for sustained growth and wellbeing of brackish life.

The pH in estuaries remain fairly constant. The dissolution of carbonate ions available in the saline water of the sea act to minimize or buffer pH changes by reacting with the ions that alter pH. Biological activities, however, may significantly change the pH concentrations of lagoonal systems. For estuaries, a pH range of 6.5 to 9.4 is required (Wood, 1967). Variations in pH of shallow biologically active tropical marine waters is more pronounced during the daytime especially when pH rises up to 9.5 due to photosynthetic activities where communities in these systems are adapted to such variations (NERR, 1997). In addition, the solubility, toxicity and biological availability of several substances such as trace metals are dependent on pH. For instance, among these metals, lower pH levels enhance their solubility and toxicity or otherwise. In UK, the Tweed estuary has a distinct seasonal variation in alkalinity and pH values within the upstream of the estuary, and these can be largely related to changes in freshwater river flows. Also, during high flows, the pH and alkalinity of the system's water were low whereas at low flows, the pH and alkalinity were high. This is so because of the weathering of rich river bedrock ions thereby affecting the pH and alkalinity of the water (Howland et al., 2000).

2.2.8 Conductivity

Conductivity and salinity are interrelated. Measurement of conductivity of estuarine water for oyster growth is important as it gives a rapid and practical estimate of the dissolved mineral contents of water, usually mainly due to saline water and in part, leaching (Thommai et al., 2014).

Conductivity affects the survival of oyster life and reproduction is effectively favored under higher conductivity levels. Low conductivity and heavy siltation following

monsoonal rains may cause mass mortalities of oysters. Generally, specific conductivity is standardized at 25°C because it is highly correlated with temperature. Standardization is necessary for a fair comparability of data of different aquatic ecosystems with different temperatures (Thommai et al., 2014). At high temperatures, specific conductivity increases due to easy movement of ions from water which becomes less viscous during such conditions. As a result, most reports of

conductivity reference specific conductivity.

The source of regulation of conductivity in estuarine ecosystems could be the rocks' mineral composition, size of the watershed, wastewaters from industries, sewage treatment works, septic tanks, settlements, agriculture and other sources of ions (Okyere, 2019). Determining conductivity is important as it results in high total dissolved solids concentrations and can have adverse effects on aquatic life (Lodeiros et al., 2017). Geology, precipitation, surface runoff, and evaporation are the driving factors of conductivity and salinity.

In the study of the Pra estuary, conductivity and salinity of the estuarine water fluctuated throughout the study indicating similar pattern of changes in these parameters confirming the assertion that conductivity and salinity of water are directly related and has influences on each other (Okyere, 2019).

2.2.9 Salinity

Daily and storm driven tides, one's location in the estuary and volume of freshwater flowing into the estuary are some factors which influences the salinity in an estuary (Chumkiew et al., 2018).

Furthermore, sea and freshwater inflow from tidal action and land drainage as well as a combined effect of the location of the terminal ends of river systems determines the changes in salinity of estuaries. Low salinity levels especially during the rainy season causes mass

mortalities of oysters (Obodai et al., 1997). Among populations in Louisiana, low salinities have been identified as the main cause of reduced mortality. The growth and mortality of *C. virginica* and as well as reproduction is known to be influenced by salinity changes (Shumway, 1996).

Several documented studies along the Gulf of Mexico show evidence of limited or no recruitment at all during low salinity levels of below 10 ppt (Cake, 1983; Chatry et al., 1983; Pollack et al., 2011), This has the tendency to affect oyster size and availability of hard substrate. Also, more so than temperature, higher salinities can be associated with greater instances of disease and predation in *C. virginica* (Ewart & Ford, 1993; Shumway, 1996).

Considering farmed oysters in Brazil, oysters growing close to the ocean experience best growth performance than those farthest from the ocean. Areas close to the ocean have high salinities and less variations Sites farthest from the ocean are influenced by fluvial discharge rendering oysters to be of relatively smaller sizes (Oliveira et al., 2018). The Pra estuary has an average salinity of the sea varying between 30.0‰ and 35.0‰ (Okyere, 2019), except at the peak of the wet season in June 2012 when a low value of 13.5± 1.3‰ was recorded. The average salinity levels of the Densu system according to Biney (1990) ranges between 2 - 28‰ and the mean values are 1.1-39.3‰.

The salinity requirements by different species of the genera, Crassostrea are shown in Table 2.2.

392 **Table 2.2: Salinity Ranges for the Genera *Crassostrea* in Selected Countries**

Species/Country	Salinity range (ppt)	Reference
Crassostrea belcheri		
Malaysia	22 – 28	Chin and Lim, 1975
Crassostrea gasar		
Nigeria	20 – 30	Ajana, 1980
Crassostrea gigas		
Hong Kong	2 – 32	Mok, 1973
Israel	41	Hughes-Grames, 1977
Fiji	26 – 36	Ritchie, 1977
Hawaii	31 – 36	Brick, 1970
Crassostrea gryphoides		
India	3 – 40	Durve 1965
Crassostrea madarensis		
India	0 – 41	Virabhadra and Nayar, 1956
Crassostrea parabainensis		
Brazil	3 – 23	Singaraja, 1980
Crassostrea rhizophorae		
Cuba	22 – 40	Farfarsie, 1954
Venezuela	37 – 39	Angell, 1973
Puerto Rico	11 – 35	Watters & Prindow, 1975
Colombia	15 – 30	Wedler, 1970
St Croix	34 – 37	Forbes, 1973
Crassostrea tulipa		
Ghana (Benya)	30 – 40	Obodai et al., 1996
Ghana (Pra)	0 – 29	
Crassostrea virginica		
Mexico	3 – 12	De Buen, 1957
Hawaii	22 – 32	Sakuda, 1966
Dissolved oxygen		

393

394 Increasing salinity results in a decline in the solubility of oxygen. Unlike in freshwater, the
395 dissolution of oxygen in seawater is far less (20 %) than what occurs in freshwaters under
396 the same condition of temperature (NERR, 1997).

During respiration, aerobic aquatic fauna depend on dissolved oxygen for their sustenance and so a critical determinant factor of abundance (NERR, 1997). Oxygen content in estuarine water influences the distribution of organisms. Diffusion of atmospheric oxygen into water and primary productivity by phytoplankton and aquatic macrophytes are the two natural processes influencing the supply of oxygen to estuarine waters.

Furthermore, according to McLusky (1989) the rate of absorption of atmospheric oxygen into water is driven by the mixing of surface waters by wind and waves. Similarly, fresh and saline waters flowing into estuaries transport large quantity of oxygen which is consumed rapidly by the many organisms living within the estuaries, especially in the bottom deposits. The levels of dissolved oxygen in water are affected by salinity changes which thereby influences chemical conditions within the estuary. The amount of oxygen that can dissolve in water, decreases as salinity increases. The dissolution of oxygen in water also depends on water temperature, and air pressure. Increase in temperature and a decrease in pressure results in a decline in dissolved oxygen. Recycling of nutrients and the removal of organic substances such as dead vegetation from waterways using oxygen is an important natural process. This dissolved oxygen is not only needed by aquatic fauna but also very useful in maintaining a healthy ecosystem. It is therefore essential to balance the sources and sinks of dissolved oxygen for sustainability of aquatic resources.

Biological (e.g., photosynthesis), physical (e.g., wind action, temperature) and chemical (e.g., salinity) interrelated factors all serve as sources of dissolved oxygen which affects its concentration. Spat settlement, growth and survival of oysters are known to be heavily affected during hypoxic conditions in estuaries (Baker & Mann, 2003).

According to Shepard et al. (2019), among bivalves like oysters, a low oxygen event can be classified according to severity: moderate hypoxia (2 mg/ L to 4 mg/ L), severe hypoxia (0.5 mg/L-< 2 mg/ L) and anoxia (< 0.5 mg/L) (Renaud, 1986; Diaz & Rosenberg, 1995; Turner et al., 2005). Among intertidal oysters, low dissolved oxygen is reported to be less likely to be a problem for intertidal oyster reefs. For subtidal oyster reefs, dissolved oxygen levels of > 4mg/L is termed, good (Shepard et al., 2019). Biney (1990) found DO levels in the Densu estuary to be between 3.5-8.4 with mean values ranging between 0 - 8mg/L. In related studies, dissolved oxygen concentration in the Pra estuary was found to be below 5 mg/L. Also, Essei lagoon recorded the least average dissolved oxygen concentration of 0.7 mg/L (Okyere et al., 2011). The dissolution of gases are dependent also on the amount of particulate suspended particles.

2.2.10 Turbidity and Transparency

Another condition of importance in an estuary is turbidity and or transparency. Due to constant mixing of freshwater and saline water from land drainage and tidal action, estuarine waters are more subject to sediment transport which influences the turbidity and transparency of water. Turbidity is the degree to which the water loses its clarity due to the presence of suspended particulate matter while transparency is the ability of light to transmit through the water column. Castro & Huber (2005) has reported large amounts of suspended matter, such as algae, sediment particles, detritus or solid waste, greatly reduce water clarity and prevent light from penetrating through the water column; thus, limiting photosynthesis. Suspended particles clog the feeding apparatus of suspension feeders and eventually may result in their death.

Fincham (1984) noted that higher turbidity with less clarity occurs in estuaries than in adjacent open sea, because suspended materials in estuaries are derived from the river, the sea and from the resuspension of particles by the activity of currents and tides.

Suspended particles in estuarine turbid waters can be removed by flocculation and coagulation induced by the increase in salt concentration seaward in the estuary (Chou & Wollast, 2006). This phenomenon is observed usually at a salinity of 5 ppt associated with a turbidity maximum. In polluted estuaries where there is incessant human activities along the coast, the amount of deposited silt is a controlling factor on the amount of light that may be trapped by surface waters necessary for photosynthetic processes. The amount of light available in estuaries together with other influencing factors like nutrients principally determines primary productivity of the aquatic ecosystems. There is significantly higher turbidity of 180ppm in Butuah estuary than Essei lagoon and Whin estuary (Okyere et al., 2011).

2.2.11 Nutrients

Nutrients content in estuaries influences the growth of filter feeders which are heavily dependent on primary productivity. Phosphates (PO_4^{-2}) and nitrates (NO_3^-) are the two basic but limiting nutrients in aquatic systems required for the sustenance of aquatic primary productivity. Marine waters are nitrates limited and phosphorous rich. This is mainly due to differences in their level of nitrogen fixation and the rate of release of phosphates from sediments. In estuaries, the acceptable limits of nitrates and phosphates are 0.1 mg/L and 1.0 mg/L respectively (EPA, 2001). As such the availability of these nutrients in the required quantities play essential roles in ecosystem sustenance (EPA, 2001; Wetzel, 2001). At elevated concentrations, nitrates and phosphates can enhance eutrophication thereby posing threats to aquatic life (Zuma, 2010).

The availability of these essential inorganic nutrients affect diversity and abundance of shellfish and finfish species (Walker et al., 2007). Nitrates and phosphates in estuarine systems are mostly distributed in the water, fish biomass and the sediments. It is however believed that a large proportion of nutrients end up in the mud as such a crucial role being played by organisms in aquatic ecosystems in nutrient absorption for their sustenance (Walker et al., 2007).

Average and mean phosphate levels of the Densu estuary according to Biney (1990) ranges between 0.02- 0.27 mg/L and 0-0.85mg/L respectively. Similarly, the author found mean nitrates concentration to be between 0.02-1.67 mg/L and average values are found between 0-8.68 mg/L. In Pra estuary, phosphate concentration was higher in the wet season than the dry season (Okyere, 2019). Phosphate content was 0.01 mg/L in the dry season and 0.41±0.04 mg/L in the estuary during the wet season. The highest concentration of phosphate in the estuary was recorded in its riverine reaches. Also, there was seasonal variability in nitrate concentration with the dry season recording the highest (78.2 ±2.3 mg/L) in the estuary than in the wet season (1 to 2 mg/L). The riverine reaches of the estuary had the highest nitrate levels in the dry (78.2 mg/L) and wet (24.4 mg/L) seasons. Concentrations of phosphates and nitrates in the estuary exceeded the optimum values of 0.1 mg/L and 1.0 mg/L respectively in estuaries for prevention of algal bloom (EPA, 2001).

2.2.12 Silicates

Shell bearing organisms like oysters, require silicates for its shell formation during the early life stages. Dissolved silica (DSi) is more concentrated in rivers than in the ocean. Therefore, estuaries which are formed when freshwater mixes with seawater has dissolved silicates (DSi) decreasing rapidly toward the sea (Chou & Wollast, 2006).

Abiotic and biotic processes influence the removal of silicates in estuaries. The biotic processes include, removal of DSi by aquatic siliceous organisms (diatoms, radiolarians and sponges) and removal by phytoplankton (Chou & Wollast, 2006).

DSi losses due to abiotic processes namely reactions of silicates with dissolved substances such as clay, formation of colloidal silica due to increase ionic strength during mixing of seawater and freshwater, low biological activity due to environmental stressors and adsorption of silica on ferrihydrites occur in estuarine systems.

However, these abiotic factors are of little significance in the water column of estuaries as compared to the sediments (Chou & Wollast, 2006). Optimal conditions required for abiotic uptake of silica to occur are; low salinity (0-5ppt), high concentrations of suspended matter and DSi and concurrent rapid increase in salinity. Biney (1990) recorded mean and average silicate levels of 5.12mg/L and 1.7-17.6mg/L respectively. Silicate concentrations were higher in the rainy season than the dry season.

2.2.13 Primary Productivity in Estuaries

Primary productivity of aquatic ecosystems can be estimated from chlorophyll a concentration. It is an indicator of phytoplankton abundance and biomass in coastal and estuarine waters. Many models developed for predicting bivalve growth and carrying capacity has relied on chlorophyll as a proxy for determining food availability (Hofmann et al., 2006). Chlorophyll a has been shown to limit growth when concentrations are too high or too low (Hofmann et al., 2006). The presence or lack of food also have influences on shell variations, the colour and condition of oyster meat. In general, among filter feeding brackish organisms, the quantity of food available can possibly be determined by estimating plankton and nannoplankton samples biomass.

In terms of productivity, nitrate and phosphate concentrations in the Pra estuary far exceeded the optimum levels (nitrate = 1.0 mg/L; phosphate = 0.1 mg/L) for primary productivity in estuaries which is detrimental to aquatic life by inhibiting light penetration and consequently limiting primary productivity in the estuary (Okyere, 2019).

2.2.14 Food Habits of the West African Mangrove Oyster

Trophic ecology of fish stocks is necessary in the development of the aquaculture and sustainable management of aquatic life (Adite et al., 2019). Among natural and wild populations of oysters, one of the factors influencing bivalve growth is the availability and quality of food. Phytoplankton is considered one of the main traditional food sources for bivalves (Gosling, 2003). Meanwhile, recent studies indicates that other food sources such as bacteria, detritus and even zooplankton are also dependent upon by oysters (Davenport et al., 2000; Lehane & Davenport, 2006). Grazing in bivalves has the potential to significantly reduce consequences of eutrophication in shallow low flowing estuaries (Lehane & Davenport, 2006).

Research by Xu &Yang (2007) also confirms the assertion among the many documented dietary forms of energy, phytoplankton is one of the most important food source for the intertidal oyster, *Crassostrea gigas*. Kassim & Mukai (2009) works on *C. gigas* noticed the dominance of benthic diatoms in its diet accounting for 70% in 2003 and 67% in 2004 in the gut contents.

In *C. madrasensis* population of a coastal lake in India, diatoms constituted about 52·8%, detritus 45·7% and animal matter was 1·5% (Thangavelu, 1988). The most predominant algal species fed on were; *Navicula*, *Coscinodiscus*, *Nitzschia*, *Pleurosiqma*, *Rhizosolenia*, *Amphora* and *Peridinium.* Spatial comparison of the algal groups showed high similarity in species obtained from the beds and the guts of the oyster.

Furthermore, the oyster showed preference especially for diatoms like *Pleurosigma*, *Coscinodiscus* and *Peridinium* though the diatoms were in low quantities in the natural bed. With the zooplankton, bivalve veliger was ranked first, followed by ciliate tintinnids. Two peaks of feeding intensities were observed one during December-January and the other during May-June. Oyster fed poorly during monsoon season (October-November) due to prevalence of low saline conditions in the lake.

Adite et al. (2019) observed that the Benin population of *Crassostrea gasar* prefer more of Diatomophycea (33.52%), Chlorophycae (17.19%), Scenedesmacae (13.80%), Dictyosphaeriacae (3.79%), and Pleurococcacae (2.75%). Poly- cystis, *Coelosphaerium*, *Protococcus*, *Botryoccocus*, *Crucigenia*, *Melosira*, *Cyclotella*, and *Gyrosigma* are the eight (8) genuses of phytoplankton which dominated the diet of *C. gasar* with a percentage composition of up to 69.06 % of the diet. Percentage occurrence were high for *Melosira* (n= 263; 41.75%), substrate particles (n = 211; 33.49%), and *Polycystis* (n = 151; 23.97%). Elsewhere in Nigeria, the stomach contents of *C. gasar* consisted mainly of phytoplankton, zooplankton, debris and indeterminate elements. Phytoplankton remained dominant irrespective of the site, the time of year, the size of individuals, sex and sexual maturity. In the findings of Kouakou et al. (2019) in Ivory Coast, the proportion of phytoplankton in Moossou, Bimbresso and Lokodjro sites were 98.91%, 97.23% and 98.86%, respectively. Males had 97.64 phytoplankton and those of females had, 98.22% in their stomachs. Taken into account seasons and sites, the percentage of phytoplankton ranged between 91.13% and 99.2%. Many scientists have found and reported good information on the food fed by oysters from the genera *Crasssotrea* (Kassim & Mukai, 2009; Adite et al., 2019; Kouakou et al., 2019). However, there is limited literature on the food habits of the species *Crassostrea tulipa* in Ghana.

2.2.15 Negative Drivers of Oyster Abundance

Among the negative factors are competition, sedimentation, climate change, contamination from microbial loads and heavy metals. Competition from boring sponges, clams, mud worms, crabs, fouling organisms and predators like birds, man and fish all affect the growth of oysters. Pollution from domestic, industrial and radioactive waste militate against the sustenance of bivalves.

Contaminants have the ability to change the normal environmental conditions of estuaries and render them unsuitable for physiological processes of oysters (Strayer, 2008). To determine the impact of negative factors, scores are assigned to the degree of their harmfulness ranging from 1, for 10 percent effectiveness, to 9, for 90%. excluding 10 (100%) because no oyster population can exist under such a condition. Though all coastal water contain some amount of dissolved organic and inorganic solids, excessive settling of suspended material is considered highly destructive to an oyster community. Interstitially sediment pores and other zones of aquatic systems, are in many cases, accumulated trace metals which can be disastrous to aquatic life.

2.2.16 Trace Metal Accumulation in Estuarine Environments

Among the natural constituents of estuarine ecosystems, are trace metals. In estuaries, traces of all heavy metals are found in their waters, organisms and sediment (Valavanidis & Vlachogianni, 2010). Lead (Pb), Cadmium (Cd), Chromium (Cr), Copper (Cu), Zinc (Zn), Nickel (Ni), Arsenic (As) and Mercury (Hg) are the most common heavy metal pollutants. Within the context of bio accumulation, Hg, Pb, and Cd are of the greatest concern (Stankovic et al., 2014).

584 Seemingly, these elements bio accumulate in the bodies of aquatic organisms and are passed
585 on to other fauna and flora species through the food chain and pose toxic health risks to
586 species higher in the food chain (Stankovic & Stankovic, 2013). Metals such as Cd, As, Hg
587 and Pb have become key concerns in recent years due to their potential to negatively affect
588 aquatic organisms at high concentrations (Valavanidis & Vlachogianni, 2010).

589 The background concentrations of some trace metals from anthropogenic inputs may pose
590 physiological threats on fauna. In relation to marine bivalves such as oysters, the organisms
591 play a role by accumulating trace contaminants in their tissues, revealing essentially that
592 fraction in the environment which may be of direct ecotoxicological relevance. The feeding
593 habits and accumulation gradients of estuaries are key drivers of elemental tissue
594 accumulation (Okyere et al., 2011).

595 *2.2.17 Mercury in Estuarine Environments and its Effects on Oyster Growth*

596 Mercury (Hg) is a relatively non-reactive natural element that exists in elemental volatile
597 form, Hgo. In this form it has a number of toxic mercuric species which comprise Hg^{2+} ,
598 and organic Hg, mainly monomethyl mercury (MeHg), dimethylmercury (Me^2Hg), some
599 ethyl (EtHg) and mercury (Ullrich et al., 2001).

600 The natural sources of mercury in estuarine environments include gradual degassing of soil
601 systems and aerial and sub-aerial volcanism. The man-made emissions of Hg are through
602 small scale gold mining, coal-fired power plants, cement production, pyrometallurgy and
603 the use of Hg in industrial processes (Sonke et al., 2013). The factors which influence the
604 mobility and availability of Hg in brackish environments include thermodynamic solubility
605 of Hg and Hg compounds, temperature, pH, redox potential, activity and structure of
606 bacterial community, speciation, age, and the presence of inorganic and organic complexing
607 agents (Ullrich et al., 2001; Randall & Chattopadhyay, 2013).

In estuarine sediments, one of the key pathways to Hg speciation is its lower oxidation–reduction potential (ORP). This is because a lower ORP promotes microbial- mediated sulfur reduction that results in the promotion of the methylation of Hg (Randall & Chattopadhyay, 2013). The accumulation of dissolved sulfide (reduced sulfur) results in the precipitation of highly insoluble inorganic Hg (HgS mineral) (Randall & Chattopadhyay, 2013). Continual increases in dissolved sulfide concentrations result in decreases in Hg methylation rates (Gilmour et al., 1992). Mercury is a high priority pollutant, persistent in the environment, high toxicity on organisms and has no biological requirement (Jiang et al., 2006).

In laboratory experiments, estuarine organisms have reacted differently to different Hg concentrations. Oysters have shown alterations in larval reproduction, hematological parameters, histopathological changes in liver and kidney, decreasing of enzymatic activities, gonad development deficiencies, reduction of eggs incubation success and survival during embryo-larval stages, decreased locomotor activity, reduction of escape capacity, brain lesions and genotoxic effects (Wiener et al., 2003). Prolonged exposure of oysters to high concentrations of mercury results in haemocyte mortality after 24hours invitro incubation. While aminopeptidase positive cell percentage was enhanced, phenol oxidase like activity is reduced (Sonke et al., 2013). The recommended levels of mercury in fish is 0.001mg/kg (WHO, 2007).

2.2.18 Lead in Estuarine Environments and its Effects on Oyster Growth

Lead (Pb) is a trace constituent in nature and a common anthropogenic pollutant. It occurs in rocks, soils, water, plants, animals, and in the atmospheric air.

Even at low concentrations, when exposed to aquatic and human life has acute and chronic implications on these life forms (UNEP, 2008). Some human sources of Pb to nearshore

and estuarine environments include automobile exhaust emissions, coal-fired power stations, waste from runoff and incineration, batteries, paints and other chemicals (such as those used in photography), and other industrial effluents. Lead has been reported to neither be essential nor beneficial to aquatic organisms. In terms of metabolic effects, Pb is known to affect vascular, renal, hematopoietic, reproductive systems and cause metabolic poison in aquatic organisms (Mielke et al., 2007). In urban areas, water and sediments contaminated is one of the major causes of elevated levels of Pb in humans (Mielke et al., 2007; Kampa & Castanas, 2008; Huang et al., 2012).

In experimental trials, high concentration of lead completely halts shell growth, cessation of biomineralization in pearl oysters. In fish, lead concentrations should not be above 0.0015mg/Kg (WHO, 2007).

2.2.19 Cadmium in Estuarine Environments and its Effects on Oyster Growth

Anthropogenic contributions to trace metals enrichment into near shore and deep-sea ecosystems is of uttermost concern. Trace metals gradually get built up in the sea bed undergo physical, biological and chemical transformations that could have implications for living organisms once introduced into the water column.

Besides trace metals another group of potential impairment to estuarine life are microbial pathogens. Oysters can concentrate high levels of cadmium in their soft tissues. High levels of Cd is known to decrease DNA repair capacity in oysters.

2.2.20 Microbial Contamination in Estuarine Environments and its Effects on Oyster Growth

One prominent cause of impairment of estuarine environments is elevated pathogen levels. There are mainly two sources of pathogens to coastal wetlands; point source and non-point sources. The nonpoint sources are storm water run offs from urban areas, land and industrial discharges, runoffs from vegetated areas, poorly sited septic systems (Pandey et al., 2014). With the point sources, direct discharge of treated and untreated sewage from shoreline outfall of waterfowl feces was a considerable point source of pathogens. Table 2.3 shows a list of microbes frequently found in estuaries

Table 2.3: List of Heterotrophic Bacterial Genera Frequently Found in Estuaries

Gram-negative rods	Gram-positive cocci	Gram-positive rods	Gram-negative cocci
Acinetobacter	*Micrococcus*	*Bacillus*	*Methylococcus*
Aeromonas	*Staphylococcus*	*Clostridium*	*Moraxella*
Alcaligenes	*Enterococcus*	*Desulfotomaculum*	
Alteromonas		*Listeria*	
Aquaspirillum		*Nocardia*	
Bdellovibrio			
Caulobacter			
Chromobacterium			
Cristispira			
Cytophaga			
Desulfovibrio			
Enterobacter			
Flavobacterium			
Hyphomicrobium			
Hyphomonas			
Klebsiella			
Legionella			
Leptospira			
Oceanospirillum			
Pseudomonas			
Spirillum			
Spirochaeta			
Vibrio			

Source:Grimmes (1991)

In estuaries, high levels of water-borne pathogens pose serious danger to aquatic and human life. Anthropogenic activities can affect estuary pathogen levels when they are adjacent to populated areas, and serve as a source of recreation and means of transport to mankind

(Schriewer et al. 2010; Pachepsky & Shelton, 2011). Three decades ago, the least rare pathogens identified in estuaries include *Vibriocholerae*, *Giardia*, *Cryptosporidium*, *Salmonella* and *Campy lobacter* (Rhodes & Kator, 1990). Other pathogens namely *E. coli*, *C. perfringens*, *Clostridium*, *Salmonella* have been reported to be encountered in estuaries in recent times (Desmarais et al. 2002).

Microbial groups may show seasonal variability in coastal systems and this may be as a result of repeatability among years, widely observable spatial variability and differences in hydrological states of the catchment, the time of day, or the state of the tide on the sampling occasions (Hassard et al., 2016). Also, through resuspension processing bed sediments, several studies have shown that estuaries are able to release particle attached (Smith et al., 1978; Desmarais et al., 2002). Pathogen growth and decay are influenced by environmental conditions and this was confirmed by Chandran &Hatha (2005), that sunlight is a major factor that influences survival of pathogens like *E. coli* in estuaries.

Ukwade (1990) reported the proportion of coliform/*Eschericia coli* in *C. gasar* as 56/100g to >1800/100g and 3.10 $\times 10^{2}$ to 10^{2} to 1.99 $\times 10^{6}$/gram of *Salmonella*. Total viable bacteria counts were in the range of 3.18 $\times$ 10^{2}2.20 $\times 10^{6}$ /gram. The author, stated that high temperatures emanating from changes in climate is a contributory favorable condition for the growth of disease-causing pathogens.

2.3. Climate Factors Influencing Oyster Growth

Threats posed by climate variability to fisheries will be similar in the wild as in aquaculture. However, the threats may easily be minimized in aquaculture than the wild.

On the basis of productivity, long term changes in climate will affect less environments with high productivity while lower productivity areas will be more susceptible.

692 Predictions on the effects of climate change on fish and fishery resources can be categorized
693 into three major areas, primary, secondary and tertiary (Koehn et al., 2011). Those threats
694 with direct impact on the physiology of the target organism in the areas of their growth and
695 reproduction are termed primary. The secondary impacts are those that affect the habitat of
696 target species, whereas the tertiary impacts are those that result from a combination of
697 factors (i.e., interactive effects). The impact of the threat is species specific because some
698 drivers can be primary impacts for one species but secondary or tertiary for another. This
699 is due to the inherent link between habitat-forming species and species relying on the habitat
700 they provide (Hoegh-Guldberg & Bruno, 2010).

701 Oysters, for example, being a habitat-forming species, are likely to be influenced (as a
702 primary impact) by increasing estuary acidity and temperature (Parker et al., 2013), which
703 may lead to a reduction in overall abundance and/or distribution. Any species that rely on
704 the habitat created by oysters will then be indirectly affected (i.e. as a secondary impact) by
705 these same influencers.

706 The impacts emanating from primary factors turn to not only weaken the individual but also
707 directly affect its ability to maximally utilize its energy budget, and hence draw energy
708 away from core tasks in growth and reproduction The repercussions are that, the total
709 fishery of any group will be altered by reductions in individuals of the species, population
710 growth and recovery rate from fish lossess from fishery harvest are directly negatively
711 affected.

712 Reductions in fish size can also increase predation risk and hence, the combined primary
713 effects are expected to reduce overall fishery yields (Audzijonyte et al., 2014). Secondary
714 perturbations are among others, the changes in habitat structure and quality. This ultimately
715 influences the connection between habitats and within the food chain affect the abundance,

size, diversity and distribution of organisms at the population level. The effects of climate changes on overall fishery production namely sea-level rise, change in rainfall regimes and increased frequency of extreme weather events can all be categorized as secondary impacts in this context.

In fisheries, climate stress may lead to a reduction in overall catch, decreased number and size of fishery targets, shifts in the distributions of target species. These stressors make catch assessment and predictions challenging. Meanwhile, interactions among the climate effects at multiple scale further heightens forecasting difficulties. Therefore, within the context of predictions, the use of end-to-end models has become one of the recent approaches to understanding the interaction between these effects (Plagányi et al., 2012). These end-to-end models have been implemented in fisheries management through use of the Atlantis (in SE Australia) and inVitro (in NW Australia) models (Fulton, 2011). The difficulty in the use of these models lies in variability at every stage of the process thus from data collection to input of model parameters. This suggests a much clearer understanding of future impacts is necessary though difficult to obtain. The solution lies in the need for requisite research and modelling to improve predictive ability. Therefore, to understand the likely influences of climate changes on key fisheries species within Australia models are being assessed for example, Pecl et al. (2014) developed a rapid assessment model to assist in management efforts. This was achieved partly through assessment of the relative susceptibility of key species to individual climate drivers. This assessment suggests a relatively good understanding around the potential effects of temperature increases, but also points to a paucity of knowledge around most other drivers and their interactions. An example of a secondary threat is Climate driven changes to species distributions (native and invasive).

2.4. Climate Variability and its Impact on Aquatic Life in Ghana

Africa is the least contributor to climate change but highly vulnerable to its impacts due to weak capacity and poverty (WRC,2018) . The signing of the Framework developed by the United Nations on Climate Change was the first attempt by Ghana in providing a legal platform in solving issues related to climate change. Thereafter three climate indices have been identified as highly vulnerable to the effects of climate variability. These are; rainfall, temperature and sea level rise. According to a report by WRC (2018), rainfall pattern has shown concomitant changes from a prolonged dry season to a shorter wet season. Despite concerted efforts by the country at contributing to addressing the subject through the ratification of the convention, Ghana is still challenged in the fisheries sector. Some of these challenges are climate induced disruption of wetland systems, flooding of coastal areas and health problems. These adverse impacts of climate change facing the Ghanaian economy are partly due to the inadequate capacity to undertake adaptive measures to address environmental problems and socio-economic costs of climate change. Several authors have predicted future changes in mainly as temperature and rainfall (Asante & Amuakuah-Mensah, 2015; Owusu et al., 2015). The studies of Asante & Amuakuah-Mensah (2015) shows that Ghana will experience high temperature and low rainfall in the years 2020, 2050 and 2080. Sea-surface temperatures will increase in Ghana's waters and this will have drastic effects on fisheries.

2.5. Local Effects of Climate Change on Oysters

Habitats of oyster populations such as sand flat, mud flat and channel banks will experience changes in duration and frequency of tidal inundation and tidal current velocities.

Storm surges, flooding and coastal erosion will be the resultant effects of these climate impacts on habitat. Furthermore, these detrimental effects are likely to be heightened by other hazards such as cyclones, tsunamis and by anthropogenic activity (IPCC, 2009). Reduction in pH levels will affect shell bearing oysters which have their outer cover made from calcium carbonate. The formation and maintenance of shells of juvenile and adult oysters during growth will be hindered by low pH concentrations of seawater (Barton et al., 2012). Though increasing temperature in eutrophic lakes under climate related changes will result into blooms algae particularly Harmful Algal Blooms (HABs), it may impede on the growth of some calcifying plankton groups which contribute to the overall output of primary productivity under such unfavorable states of water chemistry. Furthermore, high ocean temperature may lead to thawing of glaciers and polar ice which is likely to affect oysters by contributing to Sea Level Rise (SLR). According to United States Environmental Protection Agency (USEPA, 2013), excessive proliferation of coastal waters with algal blooms may pose detrimental effects on these ecosystems by blocking sunlight and depleting the oxygen required by other fauna that are heavily grazed upon directly or indirectly by bivalves particularly oysters and clams (USEPA, 2013). Aquatic life in part to adapt to stressors imposed by the environment, develop mechanisms and physiological resistance or tolerance to perturbations from aquatic environments. This particular feature enables their use to monitor changes in their surroundings for sustainable management purposes in the increasing decline of biodiversity.

2.6 Effects of Climate Change on Shellfish

Shellfishery resources are more vulnerable to the adverse influences of climate change than fin fisheries in many parts of Sub-Saharan Africa, for example Ghana (Allison et al., 2009; WFC, 2009). This will be largely due to high emissions of greenhouse gases which will have implications on habitat resilience and growth of bivalves and gastropods. In terms the effects on habitats, it will lead to habitat alteration, displacement of niches and

disappearance of native species. The changes in habitats will be caused by global warming, sea level rise and ocean acidification. Tidal inundation and velocities along habitats may degrade such ecological niches and reduce fish catch and abundance.

Decreases in fish abundance may occur during periods of high temperature, reduced pH, light and hydrology. Also, physiologically, fauna wellbeing and growth will be impeded upon and lead to a gradual decline in shellfish abundance (Barton et al., 2012). In the light of estuarine acidification, clams, oysters and other organisms which utilize calcium carbonate in building the body coverings will be drastically inhibited (Barton et al., 2012; La Peyre et al., 2009 as cited in Atindana et al., 2019). The formation of frustules of diatoms will be affected by acidified water from estuaries and the plankton filter feeders such as oysters will have their food source depleted. Furthermore, increases in ocean acidification is lethal to shellfish growth as it affects fish recruitment due to reduced sensory responses, predator avoidance and individual behaviours. Sea Surface Temperature (SST) is another threat to fish survival. Increasing SST is predicted to have immediate and greater impact on invertebrates and demersal fishes despite their adaptation to varying diurnal and seasonal temperature cycles. Increasing SST will affect fish ability to reproduce successfully, recruit stocks, grow and survive (Pratchett et al., 2008; Donelson et al., 2010).

2.7 Estuarine Acidification

Estuarine acidification according to Johnson et al. (2018) is a process where increases in atmospheric carbon dioxide enhances dissolution of the gas and results in a corresponding reduction in pH. This phenomenon has adverse negative consequences on estuarine life and communities that depend on the wetlands for their livelihood needs (Johnson et al., 2018). In estuaries, pH changes drastically than in the open marine system.

Also, estuarine inorganic carbon concentrations are highly variable, and the wetland waters acidify not just through exchange with atmospheric carbon dioxide, but also because of many other physical and biogeochemical processes that affect the carbon parameters in disparate ways.

Estuarine chemistry is strongly influenced by seasonal and spatial heterogeneity in mixing between freshwater and oceanic endmembers, which themselves vary seasonally in chemical concentrations that are affected by anthropogenic inputs. Biogeochemical processes such as denitrification, calcification and sulfate reduction reduce pH which have inconsistent impacts on the other carbon system factors. Where acidification has been identified in estuaries, eutrophication, rather than the solubility of anthropogenic carbon dioxide has often been determined to be the primary driver of acidification. Eutrophication emanating from algal blooms, anthropogenic input of nutrients and marine deposit of detrital organic matter play major roles in acidification processes besides climate change (Wallace et al. 2014). Responses of tropical estuaries to climate changes vary widely with some systems showing acidification or a decline in alkalinity; others an increase in alkalinity and others minimal or no acidification.

Four parameters are used to characterise the aquatic inorganic carbon system and any two can be used to calculate the other two if relevant constants and conditions are known.

Dissolved inorganic carbon (DIC) is the sum of bicarbonates ($HC0_3^-$), carbonates ($C0_3^{2-}$) and aqueous carbon dioxide. DIC describes how much carbon dioxide is present in the various forms it takes after reacting with water. Partial pressure of carbon dioxide ($pC0_2$) describes the amount of carbon dioxide in terms of dissolved gas pressure (Wallace et al. 2014).

Total alkalinity (TA) is the total of $HC0_3^-$, $C0_3^{2-}$, $B(0H)^-$, $0H^-$ and sometimes small amounts of other molecules, in the absence of the concentration of protons (written as H^+). Alkalinity

is a complex chemical concept, but can be summarized as the number of bases available to buffer acids. It describes the difference between the negatively charged species and positively charged protons. Most importantly, TA does not change with dissolution of $C0_2$. The number of protons is described by the concept of pH (the negative algorithm of the total concentration of H^+). So, the more protons there are and the less alkalinity to react with and buffer them, the lower the pH of the system. In this way $C0_2$ is an important chemical in regulating aquatic pH (Wallace et al. 2014). Several buffering factors such as revelle factor describes the systems's response to DIC additions. These factors quantify the amount of $C0_2$ that the water can hold.

In estuaries, the point of minimal buffering is usually considered as the state of condition where Dissolved Inorganic Carbon is equivalent to Total Alkalinity. Therefore, the relationship between the two parameters is critical to understanding pH change in estuaries which are frequently near a DIC/TA ratio of 1. Studies by Wallace et al. (2014) indicates that, TA is non conservative in estuaries therefore to understand pH changes, there is the need for consistent measurement of DIC and TA.

2.8 Review of Conventional Water Quality Monitoring Techniques

Within the context of environmental monitoring studies, bio indicators are organisms (or parts of organisms or communities of organisms) that contain information on quality of the environment (or a part of the environment) (Markert et al., 2003).

Gerhart (2011) defines indicators as species or group of species that readily reflects the abiotic or biotic state of an environment, represents the impact of environmental change on a habitat, community or ecosystem or is indicative of the diversity of a subset of taxa or the whole diversity within an area". From the perspective of Holt & Miller (2010), bio indicators include biological processes, species or communities used to assess the quality of the environment and changes which occur over time. These changes may be due to

natural or anthropogenic effects. bio indicators are useful in three situations: 1) where it is impossible to estimate the indicated environmental factor, example in situations like change in climate, paleo-biomonitoring, where environmental factors in the past are reconstructed 2) where the response of indicated factor can be measured but remains difficult to, example pesticides and their residues or complex toxic effluents containing several interacting chemicals and 3) where the interpretation of the environmental factor is challenging, example whether the observed changes have ecological significance.

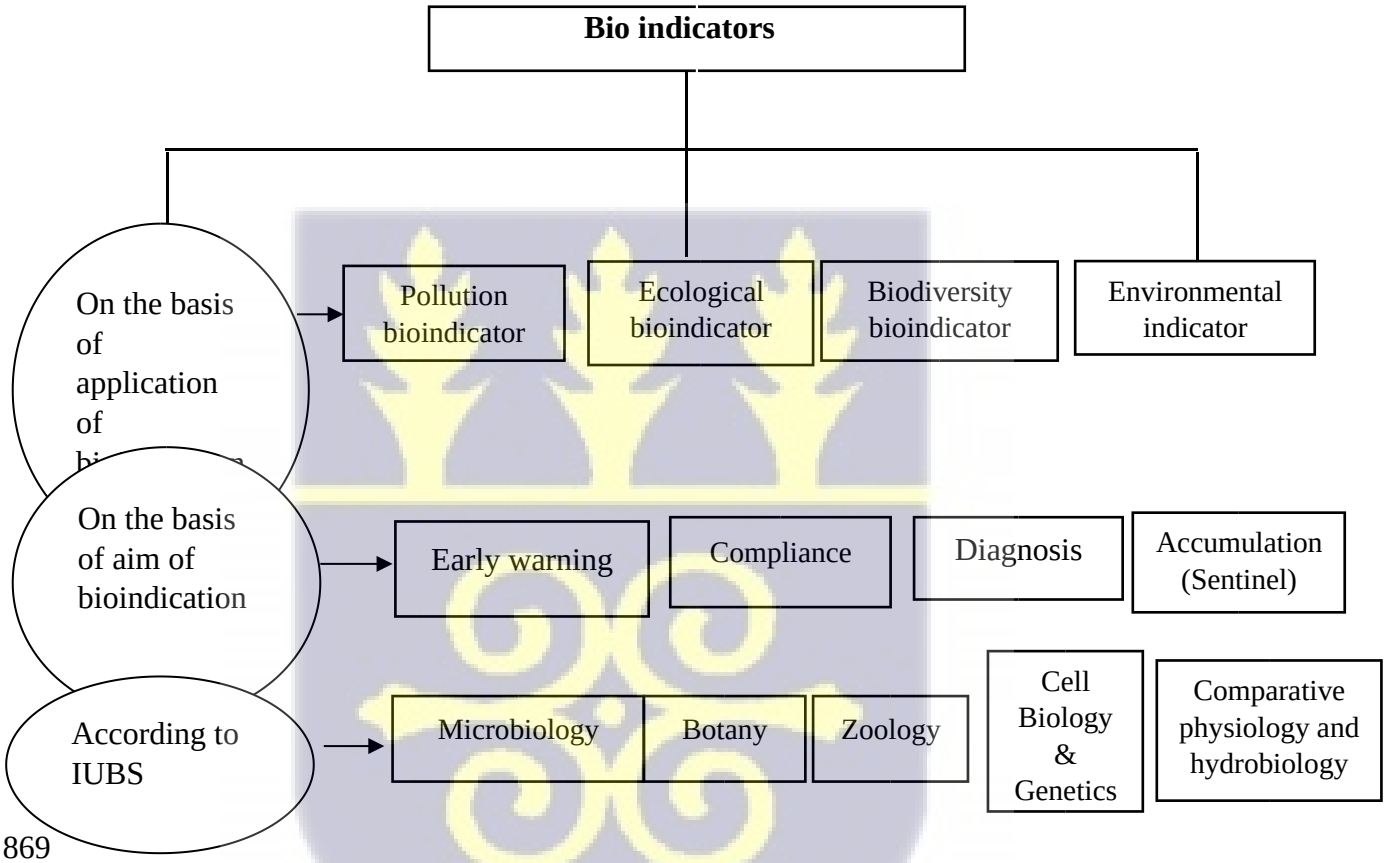


Figure 1: Types of bio indicators in the context of their use in biomonitoring (modified after Gerhart, 2011)

In Figure 1, bio indicators have different applications worldwide. The use of bio indicators is classified according to 1. Aim 2. Applications 3. On the basis of International Union of Biological Sciences (IUBS)

According to Gerhart (2011), there are four major divisions in relation to the different applications of bio indicators;

1. environmental indicator: Environmental indicator are a group of individuals of a species or a species which react predictably to a change in an environment due to stress imposed by the disturbance (example sentinels, detectors, exploiters, accumulators, bioassay organisms).

2. An environmental indicator system is a collection of bio indicators aiming at diagnosing the state of the environment for purposes of policy formulation and implementation,

3. ecological indicator: The trait of interest in ecological bio indicators is their ability to show sensitiveness to a contaminant or any stress imposed by the environment. That response also can be leveraged to the entire community in the case of lichens and plant indicators (Gerhart, 2011),

4. biodiversity indicator: This type of indicator comprises of a collection of measurable species richness parameters of an indicator taxon that is finally used to represent conditions at the community level. In a broader context some of the "measurable parameters of biodiversity", include example species richness, endemism, genetic parameters, population-specific parameters and landscape parameters (Gerhart, 2011),

5. pollution indicator: These are species of organisms which give clues of the presence of pollutants in an area or an ecosystem. Key among these group of organisms are plant and animal indicators.

According to different perspectives and aims, four types of bio indicators are in use (Figure 1).

The first is the compliance indicators, second is a diagnostic indicator, the third is an early warning indicator and the fourth is the accumulation indicator.

Compliance indicators measures the conservativenes of the population or community as a whole. For example, fish population attributes are measured at the population, community or ecosystem level. Diagnostic relies on the measurement of individual or sub organismal level to enable the assessment of an identified aquatic environmental stress.

On the part of the early warning indicators, these organisms give first signs of any form of disturbance and relies on rapid and sensitive responses to environmental changes. Accumulation bio indicators (examples: oysters, mussels, mosses, lichens) are distinguished from toxic effect bio indicators, with the effects being studied on different biological organization levels. Hence, the use of accumulation indicators such as *Crassostrea tulipa is* widely recognized. Therefore, for the purposes of this study, the mangrove oyster is being studied as an environmental sentinel accumulator indicator. The classification on the basis of International Union of Biological Sciences (IUBS), clearly defines microbiology as concerned with the detection of varied types of environmental pollution. Whereas some microbes offer useful information on the decay of some pollutants others are sensitive to the presence of harmful substances.

Changes in the environment is detected when there is a reduction or increment in the population of either the sensitive or tolerant species respectively Examples of such microbes in estuarine ecosystems are *E coli* and *Streptococcus*. The presence of pesticides in soil is indicated by cyanobacteria. In monitoring oil spillage yeast, actinomycetes, filamentous algae and bacteria are used.

Botany involves studying two categories of plants; higher and lower plants. Lower plants such as algae, lichens and fungi help in the identification of short- and long-term effects

using the appropriate choice of organisms. Higher plants are used to detect the presence of heavy metals such as Cd, Pb, Cu, Ag etc. Similarly in Zoology, individual or whole communities of fauna are studied for accumulation of pollutants in different organs of their bodies. Some examples of these animals as indicators include;silver carp and daphnia for assessing heavy metals, rotifers and cladocerans for monitoring freshwater quality and the use of earthworms as indicators of radioactive pollution. Hydrobiology, refers to the use of organisms such as macrobenthos to indicate the quality of water.In using the sense organs in various organisms to show behavioral responses on exposure to any kind of environmental stress or disturbance, it is termed the comparative physiology approach. The measuring of physicochemical parameters as a water chemistry indicator provides a rapid response transport model exposure concentration. However, there is high variability with time and space when using water (Stankovic, 2014). The adoption of sediments use integrates over time easily sampled high levels. Invariably, the difficulty with the use of sediments is low availability to biota whereas the survival limits interspecific differences (Holt & Miller, 2010). The use of aquatic organisms particularly integrates over time high levels direct availability.

2.9 Review of Conventional Bio Indicators

Bio indicator use in water quality assessment has been in existence for some time. A wide range of aquatic fauna, flora, sediments and water have been experimented with and suggested for use.

Among some of these organisms are the use of plankton (*Euglena clastica, Phacus tortus, Trachelon anas, Alona guttata, Mesocyclops edox*) fish, crabs, seaweeds (Rhodophyta), macrophytes (*Wolffia globosa*) water birds, sea turtles, cetaceans, snails, mussels, lichens, corals, diatoms, microbes (*Vogesella indigifera, Escherichia coli*) and invertebrate species

(Serfor-Armah, 2001; Fierro et al., 2017; Beric et al., 2017). In recent times the use of bio indicators is being encouraged by ecologists. However, this technique requires the organism intended for use be able to meet a criterion outlined by Holt & Miller (2010) in Table 2.4.

Table 2.4: Criteria for Selection of Aquatic Bio indicator

Criteria	Response
Good indicator ability	Proportionate response to the degree of contamination
	Susceptible to the disturbance while recording no losses
Copious	Adequate local population density with minimal rare species
	Widely distributed and abundant
	Relatively stable despite erratic environmental conditions
Well investigated	Ecology and life history well understood
	Taxonomically well documented and stable
	Easy and cheap to survey
Commercial usage	Species already being harvested for economic purposes
	Public awareness of the species

Adopted after: Holt & Miller (2010)

2.10 Challenges in Using Aquatic Bio indicators

Bio indicators are not without challenges in their usage. Generally, bio indicators are limited by their inapplicability to heterogeneous environments because of their inability to differentiate between variability due to nature from changes due to anthropogenic impacts. Also, bio indicator species have their habitat requirements which differ from that of other organisms within the ecosystem and so management of the system with reference to the habitat requirements of a single bio indicator species, may be problematic as this may not be successful in protecting rare species of different habitat requirements.

Furthermore, the proxy ability of bio indicators is scale dependent for example a large vertebrate species may be challenged with its ability to indicate the biodiversity of the local insect community (Holt & Miller, 2010; Stankovic et al., 2014).

Despite these challenges, the benefits of bio indicators outweigh their limitations. For instance, the lifespan and residence time of a bio indicator in a particular system add a temporal component to the ecosystem by integrating present, past and future environmental conditions. Conversely, many chemical and physical assays are appropriate for characterising present conditions at the time of sampling. Bio indicators are able to indicate indirect biotic effects of pollutants whereas chemical and physical measurements are inept. Contaminant bioaccumulation levels at higher trophic levels may be under presented by physical and chemical measurements *(http://www.aquaticlifelab.eu/3-1-bio indicators/).*

The advantages associated with using bio indicators according to Parmar et al. (2016) are as follows:

1. Ease in determining biological impacts,
2. Ability to assess synergetic and antagonistic impacts of various pollutants on living things,
3. Timely diagnoses from early-stage through to adult while assessing harmful impacts on flora and humans stage diagnosis as well as harmful effects of toxins to plants, and mankind,
4. Highly prevalent hence can be easily counted,
5. Economically viable alternative when compared with other specialized measuring systems.

The use of bio indicators is widespread globally (DeGroot et al., 1995; Kirby et al.,1998; Harper et al., 2000; Brander 2007; Barbour et al., 2010; Mekawy & Madkour, 2013. Crampton et al., 2016). In most parts of Africa, aquatic bio indicators have been in existence for decades.

Conventionally, water, sediments and fish have been studied and developed for use in monitoring the health of water bodies in Africa. In Ghana, water birds, plankton, macroinvertebrates, fish and sediments of waterbodies have been used for predicting the health of these systems (Ndanu, 1998; Essuman & Nortsu, 2008; Amoah et al., 2011; Debrah et al., 2011; Apau et al., 2012; Osei et al., 2013; Anim Gyampoh et al., 2013; Agyemang, 2013; Mahu, 2015; Atindana et al., 2016; Ansah et al., 2018; Asare et al., 2018; Botwe, 2018; Okyere & Nortey, 2019).Existing studies on the use of oysters as bio indicators is shallow in Ghana (Otchere, 2003; Ansah & Bashir, 2007; Dodoo et al., 2012; Obodai et al., 2010; Obodai et al., 2011). Otchere (2003) investigated the mercury levels in

oyster in the wet season using the AAS cold vapor analyser. Similarly, Okyere et al. (2012) used the cold vapor technique to determine the levels of metals in oyster and sediments. The PCB levels in three populations of oysters were studied by Dodoo et al. (2012). The effects of depuration and boiling on removal rates of heavy metals in *Crassostrea tulipa* population in Benya lagoon was reported by Obodai et al. (2010).

In all these studies, there is no related work done on the Densu estuary system. The scientists investigated few of the metals and in some cases excluded metals that have the potential to be bio accumulated in the oyster species. Furthermore, there was no comparison with metal concentrations in the meat and water.The authors used conventional methods which are not without challenges.

Therefore, this study is an attempt to investigate metals that bio accumulates in oyster meat and their levels in water. Concentrations in water and microbial organisms of potential human health risks in meat and water to establish the interactions between these contaminants and the West African oyster for use as a bio indicator of system status in the Densu estuary.

2.11 Overview of the Physico-Chemical Conditions of the Densu estuary

Biney (1990), showed that the Densu estuary estuary has a temperature of 27-33^{OC}, pH of 6 – 8.2, salinity of 2 – 28 ppt, dissolved oxygen content of 3.5 – 8.4 mg/L, a depth of 0.4 – 4.8 m and phosphates and nitrates concentration of 0.021 – 0.27 mg/L and 0.02- 1.67 mg/L respectively.

A study by Entsua Mensah (1998) showed that the Densu estuary has a temperature range of 26-33°C, pH of 6.3 to 7.8, dissolved oxygen levels of 3.0 – 8.4 mg/L, Depth of 0.8 – 3.8 m, phosphates 0.01 – 0.4 mg/L, nitrates level of 0.02 – 1.67 mg/L and silicates content of 1.7- 17.6 mg/L.

Osei et al. (2020) recorded pH values of 6.2-9.5. Monthly conductivity levels ranged from 235-60000 µS/cm. The concentrations of nitrates (>0.0009 mg/l) and phosphates (>0.0009 mg/l), is indicative of organic contamination and high nutrient levels. Similarly, according to Denuitsui et al. (2011) the surface water in Densu estuary has high conductivity of 150-3412µS/cm, is slightly alkaline (pH of 7.5) and has a TDS of 801750 mg/L.

Addo (2017) explored the levels of copper, zinc, cadmium, arsenic and mercury in Densu estuary estuary. From the study, the dominant trace metals assessed in water and sediments were copper and zinc. In the sediments, copper and zinc were 6.68 ± 0.24 mg/kg and 28.99 ± 0.95 mg/kg respectively.

For the dry season, the average concentrations of copper and zinc in sediments were 6.01 ± 0.21 mg/kg and 30.02 ± 0.99 mg/kg respectively.

The concentration of copper and zinc in the water was 1.54 ± 0.11 mg/kg and 2.98 ± 0.38 mg/kg respectively during the wet season while in the dry season, the mean concentration of copper and zinc was 1.11 ± 0.07 mg/kg and 13.04 ± 0.4 mg/kg correspondingly.

The physicochemical features of the Densu basin of Ghana studied by Karikari & Ansa Asare (2006) between July 2003 and March 2004, showed that pH of the water was neutral (pH range 7.20 –7.48) and the river waters moderately soft to slightly hard (range of hardness 91.2–111 mg/l $CaCO_3$). Turbidity values ranged from 21.5 to 49.4 NTU. Water temperatures ranged from 26.8 to 27.5^{o}C. Electrical conductivity values varied between 237 and 402 µS/cm.

Nitrate's level ranged between 5.4 – 371 kg/day and phosphates were 11.3 -181 kg/day. Fe in the water ranged from 0.614 - 1.19 mg/L. Levels of Cu in the river water varied between 0.028 and 0.220 mg/L. Pb levels ranged from < 0.005 to 0.014 mg/L. The total cocunts of

total coliforms ranged between 1136 and 1880 CFU/100 ml while the faecal coliforms ranged between 336 and 739 CFU/100 ml suggesting high microbial quality of the river water. In the study of Fianko et al. (2010), the Densu river was found to be circumneutral and fresh with pH ranging between 6.54 and 7.84 and high concentrations of nutrients.

The levels of ammonium nitrates ranged between 0.21 and 2.1 mg/ L with mean concentration of 1.19 ± 0.02 mg/ L while that of nitrate is between 0.13 and 5.21 mg/L with a mean concentration of 2.07 ± 0.01 mg/L. The levels of phosphates phosphorous fluctuated within the range 0.54 and 1.04 mg/L with a mean of 0.84 ± 0.01 mg/L.

2.12 Review of Studies on the Ecology and Biology of Brackish water Oyster Populations in Ghana

Yankson (1990) successfully reared *C. tulipa* from artificially-fertilized eggs through to settled spat in laboratory cultures as part of studies on ways of producing this oyster on a large scale. The study focused on combined effects of temperature and salinity on fertilization success and larval yields from a closed lagoon population. The results showed that combined temperature and salinity ranges of 25-30 °C and 20-30‰ respectively, supported satisfactory fertilization and larval development. However, this precluded studies on settlement success and factors likely to affect oyster settlement rate. It is documented that temperature and salinity has little effects on settlement because as long as these factors are satisfactory for growth and survival of larvae, they directly will be suitable for settlement. However preliminary studies on the environmental factors influencing successful settlement and growth of spats on the field is lacking.

Obodai et al. (1996), investigated seasonal changes in breeding pattern of two populations of oysters. Estuarine populations showed a discontinuity in breeding while the lagoon oysters bred throughout the year. All hydrographic factors namely dissolved oxygen,

temperature and pH were similar in pattern in both wetlands except salinity and transparency. Conversely many other environmental stressors such as chlorophyll a content, microbial load and heavy metals likely to impact breeding were not monitored. Extending this study further Yankson (1996), investigated the sexual differentiation of *Crassostrea tulipa* in an estuary and an open lagoon and concluded that both populations exhibit protandric sexual development like other oviparous oysters.

Sutton et al. (2012), in an attempt to determine the food habits, of oysters, assessed the filtration rates of oysters from two populations; closed and open lagoon and attributed the differences in filtration rates to turbidity and salinity.

However, the authors could not explain if this adaptation was due to environmental or genetic variation. The study however was limited as filtration rates in oysters may not necessarily be the best measure of feeding and it's defective in explaining why oysters from closed suspended culture systems do better than open bottom culture methods. Food ingested may not necessarily be utilized. However, information from the fish itself is the best approach to explaining a proper utilization of the food. Information on the annual cycle of growth and fatness of oysters reflects best the annual cycle in the availability and consumption of food. In the light of all these gaps, the SFMP, FAO and the Fisheries Commission of Ghana have also expressed interest in obtaining ecological data on the oyster population in Ghana.

The available work (unpublished) on the West African oyster in the Densu estuary is determination of oyster larvae sites, culture trials using different culture methods, biomass determination, reproductive biology, socio-economics, bacterial and heavy metal contamination of meat and water.

None of these works have attempted to model the interactions between *C. tulipa* and the natural environment for use as a proxy of climatic and environmental variability. The findings of this novel research will be useful for commercial culture of oysters and for its use as a proxy of environmental changes in coastal wetlands for sustainable management of oyster habitats in Ghana.

CHAPTERTHREE

ASPECTS OF THE ECOLOGY OF THE WEST AFRICAN MANGROVE OYSTER (*Crassostrea tulipa*) IN THE DENSU ESTUARY RELEVANT FOR CONSERVATION

This chapter entails information on relative abundance of experimental and commercial fishing, growth pattern, condition index and food habits, of *C. tulipa* in the Densu estuary.

Oyster abundance data gives important information about the trophic structure and overall reproductive output of the oyster reef. The information on growth pattern and condition index will give clues on the health of the oyster population and environmental favorability respectively. This data is necessary for forecasting future populations to enable adaptation and planning of increases or decreases in oyster abundance. Assessment of catch and feeding regimes of the species is vital in contributing to knowledge and informing the

adoption of sustainable management interventions particularly as the fishery is open and unregulated by any specific legislation.

3.1 Introduction

The average Ghanaian relies on fin and shell fishes obtained from coastal and freshwater wetland systems for about 60 % of animal protein consumed (Nunoo et al., 2013; Nunoo et al. 2014; USAID-BC, 2016).

The Densu estuary is one of the systems currently supporting commercial oyster fishery in Ghana (Yankson, 2004). The fishery has over the years been operating a community based management system resulting in the formation of institutions such as Development Action Association under the Sustainable Fisheries Management Project (SFMP) and the Densu Oyster Pickers Association (DOPA).

Despite these efforts, the overarching rise in human population, commercial nature of the fishery, decline in marine catches particularly small pelagics and the popularity of the fishery render oysters vulnerable to overexploitation. Recent studies on the Densu estuary by Chuku (2019) and Osei (2019) focused on determining viable strategies for optimising seed collection and oyster culture and socioeconomics of the West African Mangrove Oyster. Osei (2019) assessed the growth pattern of *C. tulipa* under different culturing techniques using the von Bertalannfy growth model. Although this model has been largely used in describing growth patterns of finfishes, it is not certain if the model is the best fit model for describing the growth pattern of *C. tulipa* due to wide application on finfishes. This research therefore seeks to fit growth data of *C. tulipa* using von Bertalannfy, logistic and Gompertz growth models to determine which of them best fits the growth pattern of the shellfish. In this study, the height data of the shell of *C. tulipa* which is widely used in literature was used to represent the length for the estimation of growth parameters.

In depth studies have been conducted on bivalve biology and ecology (Angell, 1986; Ofori-Danson & Amoah, 2013). Some of these studies in Ghana were on *C. tulipa* (Obodai, 1990; Yankson, 1996), *Perna perna* (Krampah et al., 2016), *Etheria elliptica* (Ampofo-Yeboah, et al., 2009) and *Galatea paradoxa* (Adjei Boateng & Wilson, 2011; Adjei Boateng & Wilson, 2012; Ofori-Danson & Amoah, 2013). However, variability in environmental conditions of these organisms and peculiarity at the species level present an opportunity to evaluate the growth, condition index and feeding of the oyster population in the Densu estuary to enhance their management and conservation. In furtherance to this, the natural food, state of condition of the mangrove oyster and relative abundance of oyster catch in the Densu fishery is lacking.

Meanwhile, this information could be useful in estimating if experimental catches in the Densu estuary may reflect trends in commercial fish catches for culture purposes and to inform management decisions. The main objective of this study is to determine the relationship between the West African Mangrove Oyster and the natural environment to ascertain the environmental factors which influences its growth while establishing its use as a bio-indicator in the system.

3.2. Materials and Methods

3.2.1 Study Area

The study was conducted in the Densu estuary located between latitudes $5^{o}30^{1}$N and $5^{o}31^{1}$N and longitudes $0^{o}17^{1}$W and $0^{o}18^{1}$W (Figure 1). The Densu estuary takes its source from the River Densu. The Atewa-Atwiredu mountain range near Kibi in the East Akyem District of the Eastern Region of Ghana is the source of the river Densu (Hagan et al., 2011). The Densu basin is drained by river Adeiso, Nsakyi, Dobro and Kuia. There are nine administrative districts bordering the Densu river. The riverine system is about 116 km long with a catchment area of 2564 km^2 and drains through the Old and New Tafo Townships

through to Bepowase (Debrah, 1999). These areas are all underlain by Birimian and Dahomeyan basement rocks which comprises granites, biotite and muscovite granites, granodiorites, pegmatites, aplites with biotite schist pendants (Hagan et al., 2011). The Pokuase, Weija, Bortianor, Kokrobite and Nyanyanu townships are made of Togo series rocks (Debrah, 1999).

3.2.2. Site Description

The Densu estuary is located 11km west of Accra. It is a complex open lagoon that is found in the river valley between the Aplaku-Takuse and Weija McCarthy hills (Figure 3.1). Besides Songor, Keta, Muni near Winneba and Sakumo lagoon near Tema, the Densu estuary is one of the unique RAMSAR sites in Ghana. A Ramsar site is a wetland site designated of international importance and protected under strict guidelines of the Ramsar Convention. The Ramsar convention also known ass Convention on Wetlands of International Importance, `is an international agreement (1971) to protect wetlands

The Densu estuary wetland is made of saltpans, sand-dunes, freshwater marsh and scrub. A large proportion of the land area where the Densu estuary is located is owned by the Panbros Salt Company (MOFAD, 2020). The upstream section of the River Densu (from which the Densu estuary is fed) is dammed forming the Weija dam, which is a main source of water supply to the city of Accra (MOFAD, 2020). There are numerous significant effects emanating from the creation of the Weija dam. Among some of these effects is the varying hydrology of the wetland due to human control of freshwater inflow into the wetland from the management of Ghana Water Works in Weija. Ecologically, the Densu estuary is strongly influenced by freshwater inflow from the Densu River and water from the reservoir during the annual opening of the Weija dam. The flow of water from the Weija system results into the formation of small tributaries downstream and into the sea which have the tendency to affect the oyster fisheries through dilution of freshwater which affects

the growth of the bivalve group. This is so because apart of precipitation the amount of freshwater in the delta is also mainly controlled by the spilling and closing of the dam during and after the wet season respectively. Therefore, there is usually large variability in water depth which reaches over 2 m in some parts, during the rainy season. A prominent phenomenon that occurs in the Densu estuary is its frequent overflows into the sea after heavy rains.

There is little vegetation on the dunes and in the saltpans; some coconut palms *Cocos nucifera* fringe the dunes, while the banks of some of the pans are colonized by *Sesuvium portulacastrum*.

Scattered stands of mangrove are found in some areas around the lagoon, while the freshwater parts of the wetland support stand for mainly *Imperata sp., Typha sp. and Cyperus sp*. Scrub vegetation grows on other parts of the wetland.

Forty one species of water birds have been recorded at this site, with estimated maximum numbers of 35,000 birds (MOFAD, 2020). The site is particularly important for roosting terns and is the second most important site for the rare *Sterna dougallii*. In addition, the site supports large numbers of *Egretta garzetta, Charadrius hiaticula, Calidris ferruginea* and *C. minuta*. Three species, *Glareola pratincola, Himantopus himantopus* and *Sterna albifrons* breed regularly at the site. Its proximity to Accra and easy access around the site as result of the saltpan construction, make the site attractive for birdwatching (Oteng-Yeboah, 1999; GSS, 2012). Some of the sea turtle species are *Lepidochelys olivacea, Chelonia mydas* and *Dermochelys coriacea*. Shellfishes exploited in the estuary are crabs (*Uca tangeri, Cardiosoma armatum* and *Callinectes amnicola*), mud flat periwinkle, *Tympanotonus fuscatus* and shrimps, Penaeus spp. Finfish comprising fresh, marine and estuarine finfish (flat sardinella, *Sardinella maderensis* and blackchin tilapia, *Sarotherodon*

melanotheron (MOFAD, 2020). Aside serving as feeding and nesting grounds for migratory birds, crabs and fish, the Densu estuary, with its sandy mud bottom, provides suitable habitat for a significant population of *C. tulipa.* The fishing methods common in the area are the atidza fishing (open water culture using branches), basket and hand fishing with cast and set nets gears predominating.

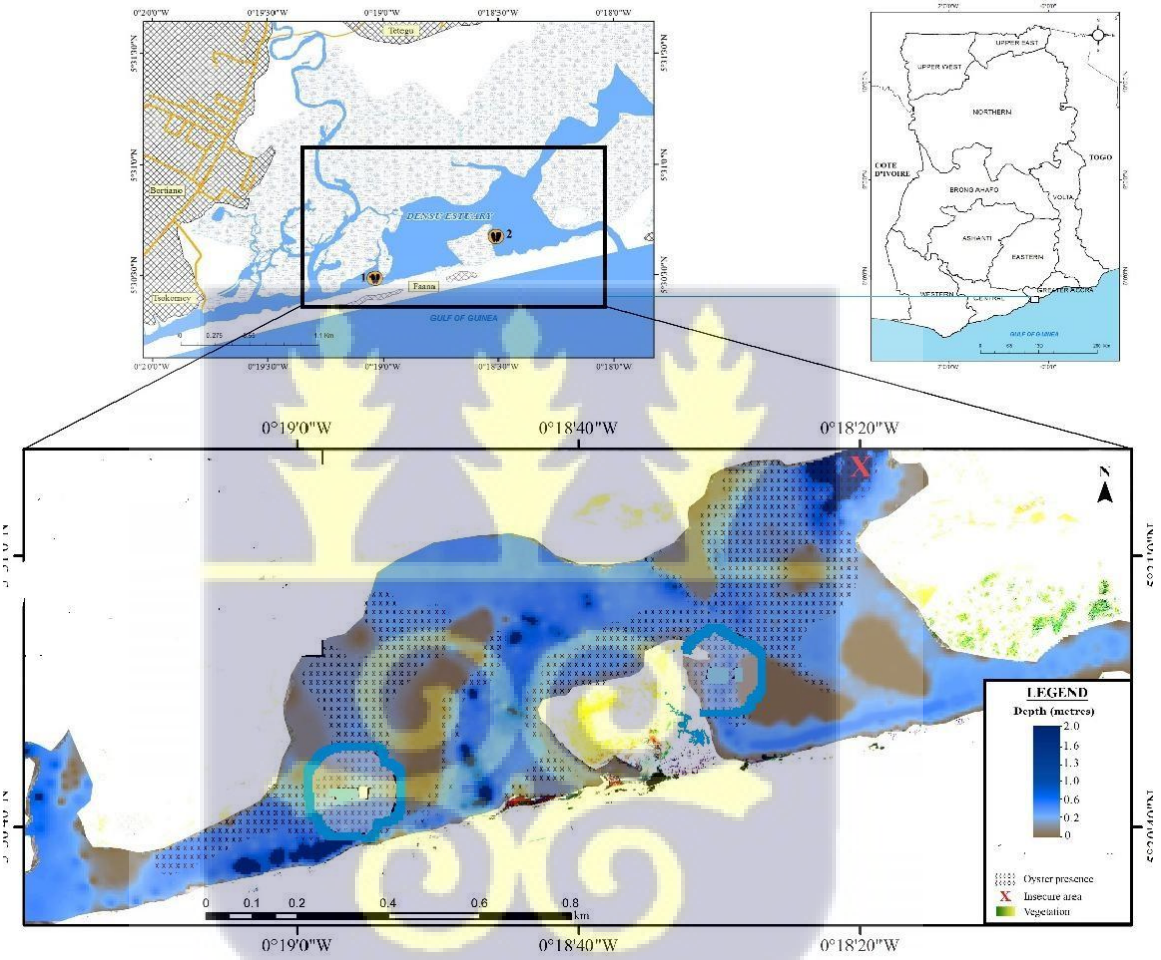


Figure 3.1: Map of Ghana Showing the Densu Estuary and Areas of Oyster Presence and Spat Availability (Adopted from Chuku, 2019)

3.2.3. Sampling Design

The study was conducted for a period of 18 months from March 2019 to August 2020 normally between the hours of 6:00 and 16:00 GMT on sampling days. First, following the approach of King (1995), the distribution of the oysters were mapped and measured into an

area of 5200 m^2 (Figure 3.2) using Grid tool in QGIS (Remote sensing Laboratory, DMAFS). The area was subsequently divided into a total of fifty-two (52) grids of equal size (100 ×100)m.

On each monthly visit, a sub sample of 10 grids was randomly selected from randomly generated numbers in Microsoft excel (Version 12) and oysters collected and measured. Collection of the samples were made at low and high tide.

According to data from Ghana Meteorological Service, (Greater Accra) in 2019, the dry season span through mid-November to 20th April and the rainy season, from 21st April to October. Therefore, oyster samples were collected throughout the year.

Figure 3.2: Map of Densu Estuary showing grids where Sampling for Estimation of Catch Per Unit Effort (kg/hr/fisher/day) were done

3.2.4. Relative Abundance of Oyster

3.2.4.1 Commercial Catches

The Densu oyster fishery has a closed season management practice which commences from November to April annually. All oyster collectors are prohibited from harvesting around

this period but the fishery in 2019 and 2020 was opened to the collectors on the 14th April to November.

Therefore, due to the seasonal nature of the fishery, sampling surveys for the commercial fishery were done from April to November every year. During the survey, a sampling unit was considered as an oyster collector who wears hand worn gloves, collects oysters into a basket/basin and utilizes a canoe. Individuals of oysters were weighed in grams.

Oyster collection was done at low tide every day except for period when the Weija dam was opened (June to August). There were about 2000 oyster collectors in the fishery. Two collectors per canoe, harvest for a duration of 6 hours a day until high tide. Each person collects within the 6 hours 4 baskets of oyster. A basket of unshucked oysters cost ten Ghana cedis (GH¢10.00). The crafts used in the fishery are non-motorized canoes, hand gloves improvised protective foot ware (trouser material cut and worn on their legs) with few using wellington boots.

3.2.4.2 Experimental Catches

Experimental fishing was also undertaken to ascertain whether experimental catches could be a good indicator of trends in commercial fish catches (Vanderpuye, 1984). Sampling was also done at low and high tide to determine the influence of tidal changes on catch. The gears used consisted of a basket, gloves and wellington boots. A 29-yearold skilled oyster male collector with a motorized canoe was hired to collect oysters by hand for a duration of one hour each month. The criteria for the choice of the fisher was on the basis of his expertise and active involvement in the oyster business. Catch Per Unit

Effort (CPUE) was estimated as number collected in kg per hour per fisher per day thus, the time, duration and CPUE were standardised. The total number of oysters collected every month was weighed in kilograms whereas each individual was weighed in grams.

3.3 Data Analyses

The catch per unit effort (CPUE) for commercial fishing was determined as catch per active canoe per day (kg/canoe/day). The monthly oyster catches (C) were estimated using the relation: C = Mean CPUE × Fishing days.

The total catch (kg) per day was determined as:

Total catch = Mean CPUE × No. of active canoes/No. of individuals/day.

The catch per unit effort (CPUE) for experimental fishing was determined as catch kg per hour per fisher (kg/hr/fisher).

Full days of the active months were used in the estimation because during the active months oyster collectors work all seven (7) days in a week. Monthly length-frequency (Length (L) cm) data were compiled from the sampled oyster length measurements and the distribution was determined at 1.0 cm length intervals. Shell or Total Height (TH) was measured as the distance between the anterior and posterior of the oyster, Width (W), distance between the left and the right side of the oyster and Shell or total length (TL), the distance measured between the top and bottom of the oyster.

ShellWeight(SWt) (cm)

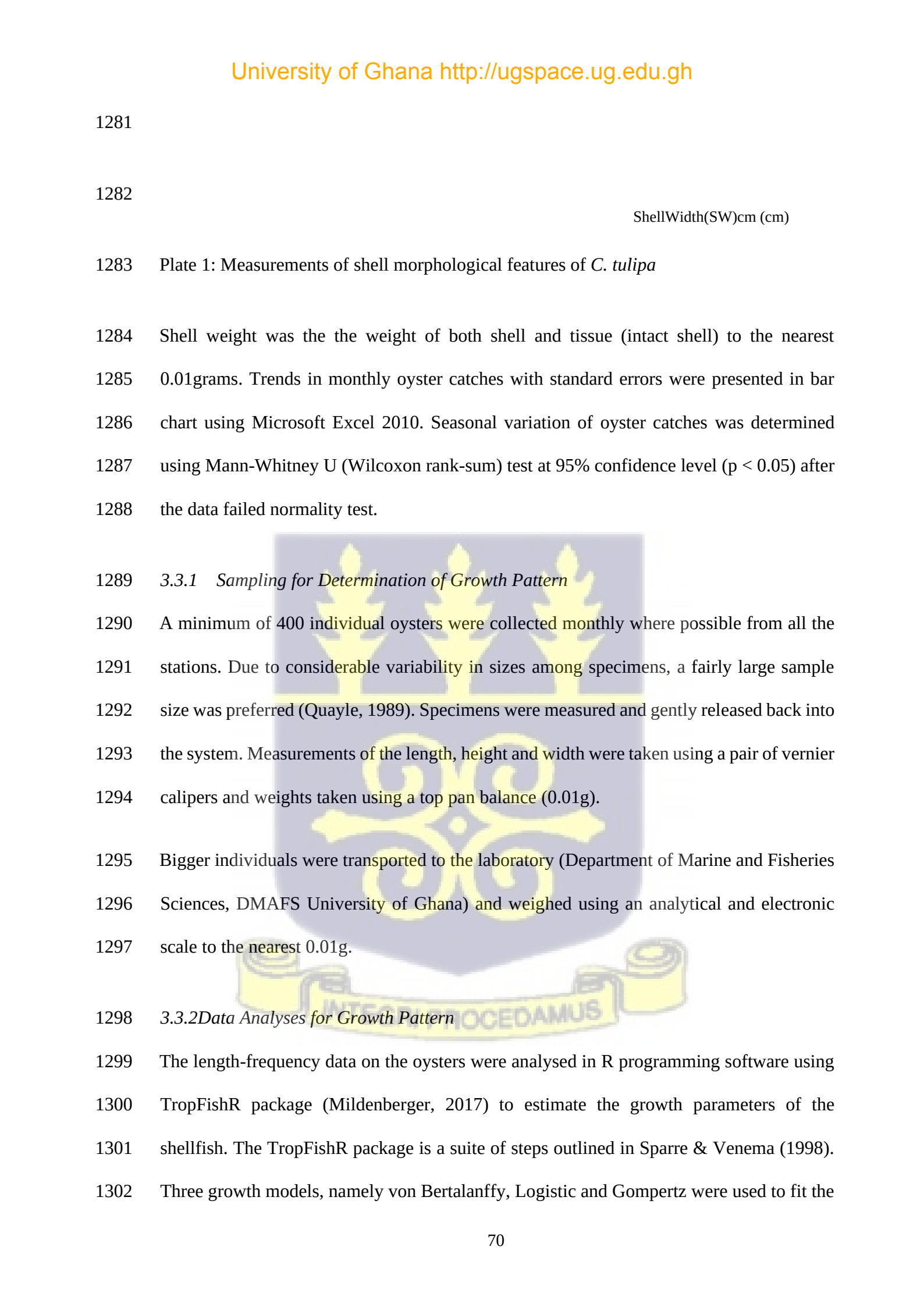


Plate 1: Measurements of shell morphological features of *C. tulipa*

Shell weight was the the weight of both shell and tissue (intact shell) to the nearest 0.01grams. Trends in monthly oyster catches with standard errors were presented in bar chart using Microsoft Excel 2010. Seasonal variation of oyster catches was determined using Mann-Whitney U (Wilcoxon rank-sum) test at 95% confidence level ($p < 0.05$) after the data failed normality test.

3.3.1 Sampling for Determination of Growth Pattern

A minimum of 400 individual oysters were collected monthly where possible from all the stations. Due to considerable variability in sizes among specimens, a fairly large sample size was preferred (Quayle, 1989). Specimens were measured and gently released back into the system. Measurements of the length, height and width were taken using a pair of vernier calipers and weights taken using a top pan balance (0.01g).

Bigger individuals were transported to the laboratory (Department of Marine and Fisheries Sciences, DMAFS University of Ghana) and weighed using an analytical and electronic scale to the nearest 0.01g.

3.3.2Data Analyses for Growth Pattern

The length-frequency data on the oysters were analysed in R programming software using TropFishR package (Mildenberger, 2017) to estimate the growth parameters of the shellfish. The TropFishR package is a suite of steps outlined in Sparre & Venema (1998). Three growth models, namely von Bertalanffy, Logistic and Gompertz were used to fit the

data using the growth parameters to determine the best fit model for the growth pattern of the shellfish. The von Bertalanffy was chosen because of its wide use in stock assessment studies. However, the Logistic and Gompertz models which are relatively rarely used were chosen to test their applicability in oyster fisheries in Ghana.

The von Bertalanffy growth function states that the growth rate of fish is linearly related to its length by a growth coefficient (K). The von Bertalanffy growth model assumes that fish grows rapidly at a young age but slowly at an adult age until growth becomes asymptotic.

The assumption of the logistic and the Gompertz (a special case of the logistic model) models however assume that growth of an organism is slow at the early (tender) ages but becomes rapid at a point in time and then becomes slow again until it becomes asymptotic.(Bertalannfy, 1938)

The growth equation of von Bertalannfy growth model used in this study is given as:

$$Lt = L\infty\ (1+e\text{-}k(t\text{-}t0))$$ (Bertalannfy, 1938)

Where L_t= length of fish at time, t, L_∞ = asymptotic length (length at which growth is constant), k = von Bertalannfy growth constant, t = age of fish and t_o=theoretical age of fish at which length is zero.However, the logistic growth function is given as:

$$L_t = \frac{L\infty}{1+e^{-k(t-t_0)}}$$ (Brown et al., 1976)

Where L_t, t, t_0 and L_∞ have already been explained and *G* is the instantaneous growth rate at the origin of the curve.

The Gompertz growth model which is a special case of the simple logistic model is described by this equation:

$$L_t = L\infty e^{-K(t-I)}$$ (Brown et al.,1976)

Where L_t, t and L_∞ have already been described, *G* is the instantaneous rate of growth at age t_0 and t_0 is the inflection point of the curve and the age at which absolute growth rate begins to decline.

The Electronic Length Frequency Analysis (ELEFAN) method incorporated in the "TropFishR" package was used to estimate the asymptotic height (H_∞) and the growth coefficient (k) for the West African oyster population in the Densu estuary of Ghana using height-frequency data of the shellfish. However, the time at zero height (t_0) of the shellfish was estimated using this equation:

Log (-to) = -0.392-0.275LogL∞ -1.038LogK (Pauly, 1979)

The age of the shellfish was estimated from the von Bertalanffy growth function (VBGF). Subsequently, age-height data were compiled and collectively fitted to three growth models (VBGF, logistic and Gompertz) in the "Fish methods" package to determine the best fit.

3.3.3 Determination of Condition Factor

Oyster samples of not less than 60 individuals were randomly collected monthly from the field and transported to the laboratory for detailed analyses. In the laboratory the weights of individuals were measured to the nearest 0.01g using a weighing balance whereas length and height were taken using a pair of vernier calipers (to the nearest 0.1cm). Diseased and empty shells were excluded. Oysters were shucked to obtain tissues and weight of fresh flesh taken. The total fresh weight: (Pt) was the body weight of the individual after withdrawal of the foreign bodies of the shell; the weight of the fresh flesh (Pch): fresh visceral weight, drained during at least 30 minutes on filter paper and the weight of the empty shells (Pc): weight of the two valves after insulation of the visceral mass.

The weight of wet oyster tissue was taken and the tissue oven dried to constant weights at temperatures of 95-98 °C. Condition factor was determined using the Hopkins' formula (Quayle, 1989)

$$\text{Condition Index} = \frac{(Dry\ tissue\ weight\ in\ g) * 1000}{(Internal\ cavity\ volume\ in\ \text{cm}^3)} \quad \text{(Quayle, 1989)}$$

In determining cavity volumes, the relation suggested by Lawrence and Scott (1982) was followed.

Cavity volume $= Weight\ of\ \ valve - weight\ of\ \ intact\ oyster\ (both\ in\ g)$

This method is valid because the effective density of the cavity of the contents is close to 1 g per cm^3 (Lawrence & Scott, 1982).

A condition factor value of up to 150 indicates a high condition while a low value of about 75 and below indicates a very poor condition (Quayle, 1989).

3.4 Data Analyses

3.4.1 Data Collection for Analysis of Food Habits,

Monthly oyster samples were obtained from an artisanal oyster collector who handpicks into a wooden basket throughout the sampling period. Oyster samples were immediately preserved in 10 % formaldehyde solution to reduce post mortem digestion immediately after capture and sent to the laboratory. At the laboratory, morphometric parameters (weight to the nearest 1.0, length, height and width to the nearest 0.1 cm) of specimens were measured and recorded. Oysters were shucked and the tissues removed using a pair of forceps. The guts were carefully removed and the content emptied into petri dishes.

A 10 ml volume of distilled water was added to the content and a sub sample of 5 ml taken and placed on a slide covered with slide cover and observed and identified under either a dissecting or compound microscope depending on the size of the food item at varying magnifications. Food items were identified up to the genus level wherever possible using identification keys by Shiel (1995) for zooplankton and Bellinger & Sigee (2015) for phytoplankton. Stomach contents were analyzed using the frequency of occurrence and numerical composition methods (Bagenal & Braum, 1978; Hyslop, 1980; Lima Junior & Goitein, 2001). The frequency of occurrence method estimates the percentage of stomachs in a sample containing a given food item whereas the numerical composition method determines the total number of a particular food item recorded and expressed as a percentage of total number of all food items:

$$\text{Frequency of Occurrence} = \frac{\text{Total number of stomachs with a particular food item}}{\text{Total number of stomachs with food}} \times 100$$

$$\text{Numerical} = \frac{\textit{Total number of a particular food item}}{\textit{Total number of food items}} \times 100$$

The measures of frequency of occurrence (F) and number of food items (N) recorded in this study were integrated into an 'index of relative importance' (IRI) as described by Clark (1985) to determine the principal food item of *C. tulipa*:

$$IRI = F \times N \text{ (Clark, 1985)}$$

Where N = Numerical percentage, F = Frequency of occurrence percentage and IRI = Index of relative importance.

Checklist of species in the gut content and water medium, was generated from identification of monthly samples. Diversity indices were used to describe and compare the diversity of the species of food items in the estuary and the oyster. These were:

(i) Margalef's Index (D) for species richness (Margalef, 1968),

$$D = S - 1/\ln N$$

where S = number of species and N = number of individuals (ii) The Shannon Wiener's Index (H') of species evenness (Shannon & Wiener, 1963),

(ii) The degree of similarity between gut contents and food items in water was determined as,

$$Cs = \frac{2j}{a+b} \text{ (Krebs, 1999)}$$

where Cs is Sorensen's index which ranges from 0 (dissimilar) to 1 (completely similar), *j* is the number of species common to a given pair of stations, and a and b are the number of species occurring in either of the pairs.

(iii) Species richness and equitability were assessed using Shannon -wiener diversity index

$$H' = -\sum Pi \ln Pi$$

where Pi is the proportion of the total number of individuals occurring in species i. Pi = ni/N; ni = Number of individuals of each species in the sample. N = Total number of individuals of all species in the sample. Range from 0 to 5.

3.5 Results

The results are presented under thematic areas.

3.5.1 Oyster Catch

Results on tidal, monthly and seasonal relative abundance in the commercial and experimental oyster fishing are illustrated in Figures 3.3, 3.4 and 3.5.

3.5.2 Experimental Catches

In Figure 3.3, the monthly CPUE of experimental fishing at low and high tide are shown. Generally, catch was significantly higher during low tide (p =0.0161) than high tide with mean monthly values ranging between 15 ± 0.11 – 500 ± 15.0 kg/hr/fisher and 6 ± 3.01 – 200 ± 5.30 kg/hr/fisher respectively. CPUE in the year 2020 was highest in the months of May to August (Low tide;16.8-500kg, High tide: 32-132.5kg) during the study and lowest in September and October (Low tide;15-18kg, High tide: 16-10kg).

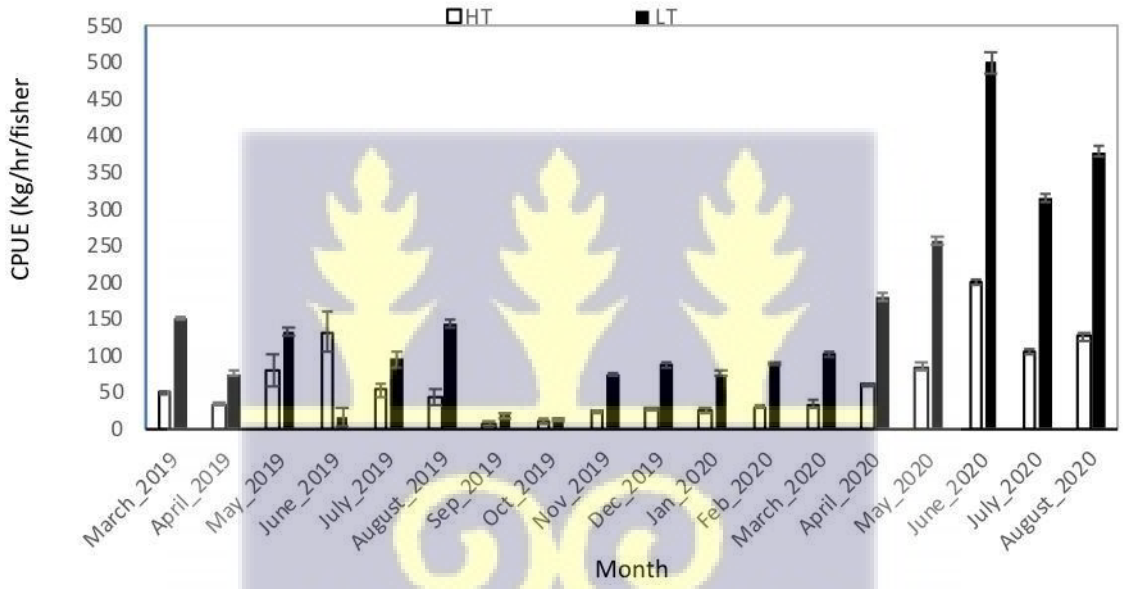


Figure 3.3 Tidal Variations in CPUE of Experimental Fishing of the Densu Oyster Fishery, 2019-2020

Figure 3.4, shows the CPUE of the commercial and experimental oyster fishing in Densu. Catches from experimental fishing was higher (6.00-200kg/hr/fisher) than commercial fishing (3-100kg/hr/fisher). Catch peaked in June in 2019 and 2020 with mean CPUE in experimental fishing being 132.50±10 5 kg/hr/fisher/day while that of the commercial fishing was 397.50±9.33 kg/hr/fisher/day.

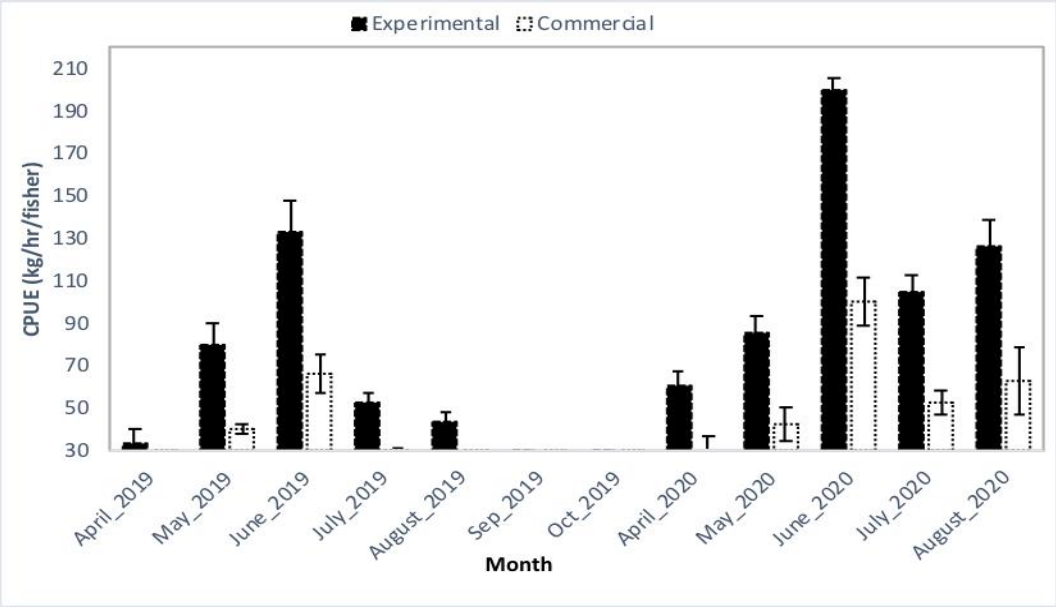


Figure 3.4: Monthly Variations in CPUE of Commercial and Experimental Oyster Fishing in Densu estuary in 2019 and 2020.

The results of Mann-Whitney U test showed that experimental catches were significantly higher (p= 0.0005) than that obtained in commercial fishing. The estimated monthly catch of the commercial oyster fishery is illustrated in figure 3.4.

Seasonal variations in CPUE (kg/hr/fisher/day) levels were studied (Figure 3.5). Mann Whitney U test shows that oyster catch was higher (p = 0.023) in the dry season (50± 3.4102.95± 11.35 kg/hr/fisher/day) than the rainy season (23 ± 0.5- 57.45 ± 8.62 kg/hr/fisher/day). Dry season catches ranged between 50 ± 3.4 – 102.95 ±11.35 kg/hr/fisher/day. Conversely, rainy season recorded values varying from 23 ± 0.5 to 57.45± 8.62 kg/hr/fisher/day.

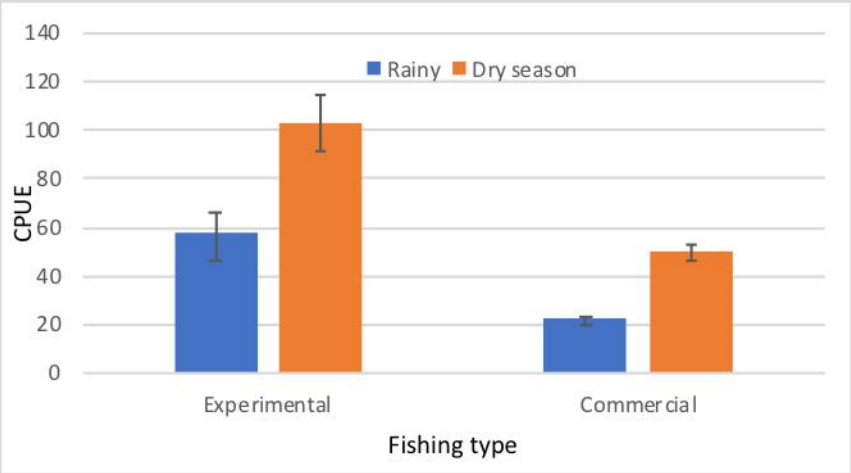


Figure 3.5 Seasonal Trends in Catch for Experimental and Commercial Oyster Fishing 2019-2020

3.5.3 Growth Pattern

The estimates for the parameters of the von Bertalanffy, logistic & Gompertz growth models fitted to the age-height data are presented in Table 3.1 and the fitted curves of these models are illustrated in Fgures 3.6 and 3.7. The height data of *C. tulipa* which is widely used in literature were used to connote length for the estimation of growth parameters. The results on length of shell connotes the shell height of the mangrove oyster. The lowest sum of squared residuals (SSR) and Akaike information criterion (AIC) estimated for the von Bertalanffy growth model indicate that the model is the best among the three growth models. Hence, asymptotic height (∞), growth coefficient (k) and time at zero height (t_0) of the West African oyster population in the Densu estuary were estimated at 13.24 cm, 0.81 y^{-1} and -0.13 years, respectively.

Table 3.1: Parameter Estimates of SSR and AIC Generated from Fitting Three Growth Models to Age-Height Data on *C. tulipa* in Densu estuary

Type of Information	Model	Estimates	Sum of squared residuals (SSR)	Akaike growth criterion (AIC)
von Bertalanffy	$= [1 + ^{-(-0)}]$	$H_\infty = 13.24$ $^{\infty}$ k = 0.81 $t_0 = -0.13$	0.007	-18605.46
Logistic	$\frac{\infty}{[1 + =1(0.53)]}$ $_{--(-0)}$	$H\infty =$ $k = 2.55\ t_0 = 0.52$	63.94	-1083.33
Gompertz	$= \infty$	$H\infty = 11.24\ k = 1.67$ $t_0 = 0.34$	20.92	-3234.22

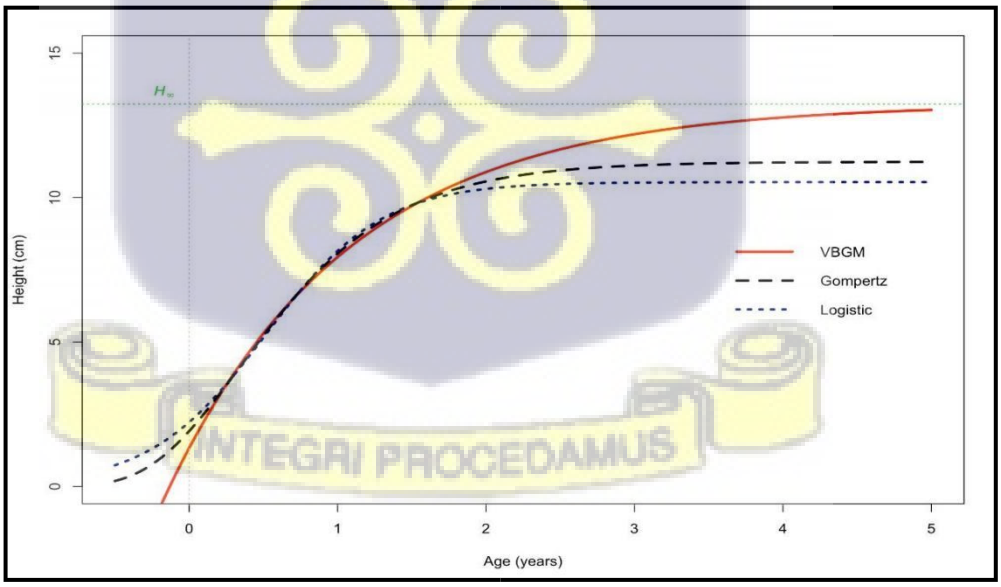


Figure 3.6 Resultant Growth Curves Fitted to the Monthly Length-Frequency Distribution of West African Oyster in the Densu estuary in 2019 and 2020.

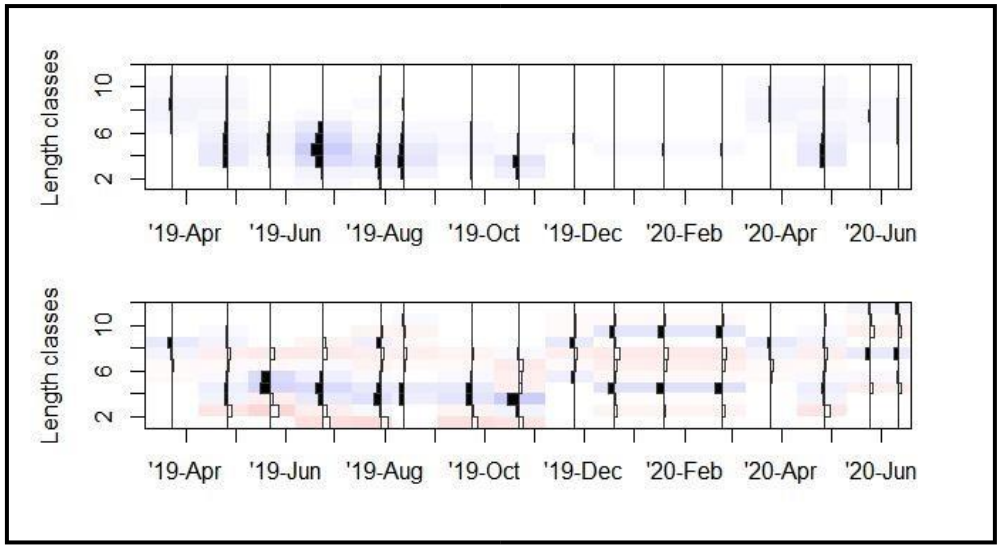


Figure 3.7 Monthly Length-Frequency Distribution of Crassostrea tulipa Visualized in Terms of Catches (Top) and Restructured Distribution (Bottom) Fitted with Growth Curves with a Moving Average (MA) Set to 5 (n = 1926) (2019,2020).

3.5.4 Condition Index

Details of the relationship between the environmental parameters and biological parameters are discussed in chapter IV.

Figures 3.8 and 3.9 show monthly and seasonal variations in the mean CI of *C. tulipa* in Densu estuary respectively. Generally, condition indices followed a similar pattern in 2019 and 2020. Low values were recorded in March, September, October, January and February with mean values varying from 20.10 ± 0.13 – 60.00 ±.1.2. Higher values (150 ± 3.33 – 287.87± 0.79) were recorded from April to August, November and December in 2019 and 2020. The highest index (297.87 ± 7.00) was recorded in July of 2019 and 2020.

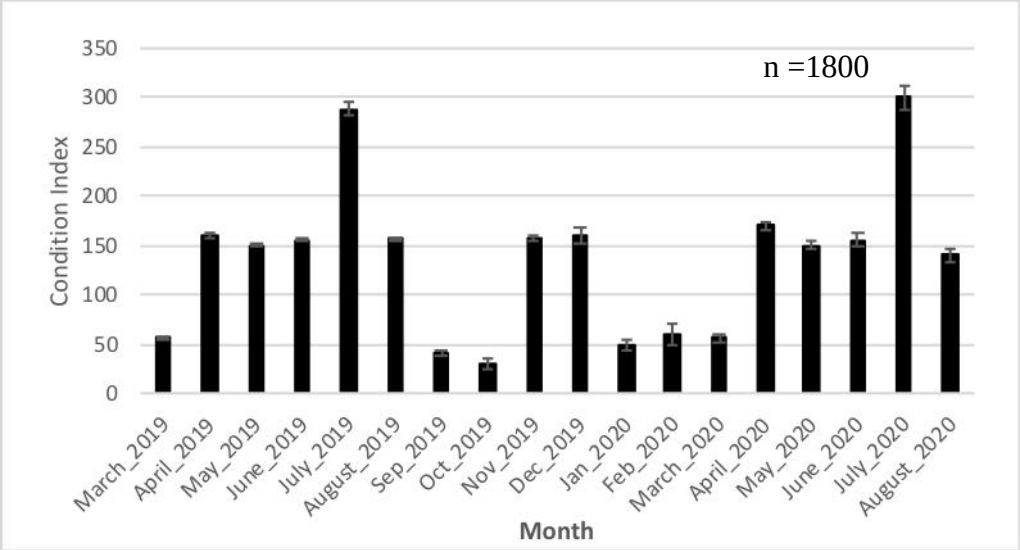


Figure 3.8 Monthly Variations in Condition Index of C. tulipa in Densu estuary, 2019 and 2020 (n = Numerical Counts of Individual Specimens Examined)

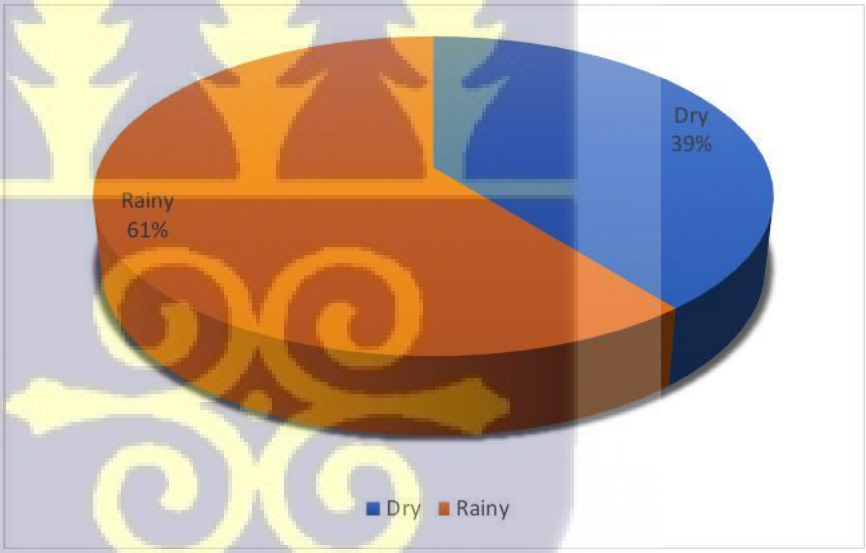


Figure 3.9 Seasonal Variation in Condition Index of C. tulipa in Densu estuary (2019-2020)

The rainy season (April to October) recorded high values (60 %) of condition index. The dry season (November to April) showed low condition index (39 %). The results of the Mann-Whitney U (Wilcoxon rank-sum) test revealed significant difference (p = 0.032) in general wellbeing of the oyster during the dry and wet seasons for 2019 and 2020.

3.5.5Food Habits

The occurrence and abundance of food items identified in the guts of the West African Mangrove Oyster and in the estuary are presented in Tables 3.2 and 3.3 respectively.

In Table 3.2, species occurrence in the gut of the mangrove oyster are shown. A total of 43 species from 8 phyla and 33 families were identified in the gut contents of the species. Out of this number, except for the larvae of stonefly and the protozoan, *Vorticella sp*., all other food items recorded in the study were found in the guts of *C. tulipa*. (Table 3.2). All the 43 species were found in the water samples examined for food items (Table 3.2).

In Table 3.3, golden algae, comprising five (5) species was the predominant (Occurrence =35 %, IRI= 595 %) food items filtered by the shellfish. The phylum Rhodophyta comprising one species, was the second abundant (Occurrence =20.9 %, IRI= 209 %, n = 1080) group of food ingested by *C. tulipa*. Green algae occurred in 13.4 % of the guts examined and composed of 9.8% of the food ingested. Out of the 1080 stomachs examined, blue green algae were found in 10.8 % of *C. tulipa* diet making up a composition of about 3.9%.

The larvae of amphipods and damselfly made up less than 3% (IRI= 16.20) of the gut contents of the mangrove oyster.

Table 3.2: Species Occurrence in the Guts of *C. tulipa* and Water of Densu estuary (2019 and 2020)

Family	Food item (phylum/species)	Gut	Water
	Bacillariophyta (Diatom)		
Hemidiscaceae	*Azpeitia neocrenulata*	+	+
	Aspeita sp.	+	+
Achnanthidiaceae	*Achnanthidium minustissmum*	+	+
	Achanthidium sp.	+	+
Fragilaraciaceae	*Aesterionella formosa Hassall*	+	+
Aulacoseiraceae	*Aulacoseira granulate*	+	+
	Aulacoseira sp.	+	+
Cocconeidaceae	*Cocconeis pediculus*	+	+
Tabellariaceae	*Meridion* sp.	+	+
	Unidentified sp.	+	+
Melosiraceae	*Melosira sp.*	+	+
Naviculaceae	*Nanoneis hasleae*	+	+
	Nanoneis sp.	+	+
Bacillariaceae	*Pseudo-nitzschia inflatula*	+	+
Stephanodiscaceae	*Stephanodiscus* sp.	+	+
	Unidentified sp.	+	+
Thalassionemataceae	*Thalassionema bacillare*	+	+
	Thalassionema javanicum	+	+
	Cyanophyta (Blue green algae)		
Nostocaceae	*Anabaena sp.*	+	+
		+	+
Chroococcaceae	*Anacystis sp.*		
Oscillatoriaceae	*Lyngbya sp.*	+	+

Table 3.2 cont'd: Species Occurrence in the Guts of *C. tulipa* and Water, Densu(2019,2020)	**Food item (phylum/species)**	**Gut**	**Water**
Family			
	Cyanophyta (Blue green algae)		
Microcystaceae	*Microcystis viridis*	+	+
	Microcystis sp.	+	+
Microcoleaceae	*Planktotrix agardhiii*	+	+
	Oscillatoria sp.	+	+
Oscillatoriaceae	Unidentified sp. 1	+	+
	Unidentified sp. 2	+	+
Rivulariaceae	*Rivularia sp.*	+	+
	Unidentified sp.	+	+
Microleaceae	*Trichodesmium sp.*	+	+
Chlorellaceae	*Nannochloris* sp.	+	+
Oedogoniaceae	*Oedogonition* sp.	+	+
	Ochrophyta (Golden algae)		
Mallomonadaceae	*Synura petersenii*	+	+
	Synura uvella	+	+
Tabellariaceae	*Tabellaria flocculosa*	+	+
Toxariaceae	*Toxarium undulatum*	+	+
	Unidentified sp (Amphipod)	+	‡
	Rhodophyta (Red algae)		
Solieriaceae	*Agardhiella* sp.	–	+ ‡
	Unidentified species (stonefly larvae)		
	Arthropoda		
	Ciliophora (protozoan)		
Vorticellidae	*Vorticella* sp.	–	+
	Odonata (Damselfly)		
	Bradinopyga alpogastra		+

Table 3.3: Frequency of Occurrence and Numerical Percentages of Gut Contents of *C. tulipa* in Densu estuary

Food item (phylum/species)	**Frequency of occurrence (%)**	**Numerical percentage (%)**	**IRI (n = 1080)**
Bacillariophyta (Diatom)	**17.2**	10	172
Azpeitia neocrenulata			
Achnanthidium minustissmum			
Aesterionella formosa hassall			
Aulacoseira granulata			
Cocconeis pediculus Meridion sp.			
Melosira sp.			
Nanoneis hasleae			
Pseudo-nitzschia inflatula			
Stephanodiscus sp.			
Thalassionema bacillare			
Cyanophyta (Blue green algae)			
Anabaena sp.			
Anacystis sp.			
Lyngbya sp.			
Microcystis viridis			
Planktotrix agardhiii			
Oscillatoria sp.			
Rivularia sp.			
Trichodesmium sp.			
	10.8	3.9	42.12

*n= number of stomachs examined

Table 3.3 contd: Frequency of Occurrence and Numerical Percentages of Gut Contents of *C. Tulipa* of the Densu estuary.

Food item (phylum/species)	Frequency of occurrence (%)	Numerical percentage (%)	IRI (n = 1080)
Chlorohyta (Blue green algae)	13.4	9.8	33.32
Chlamydomonas caudata			
Coelastrum sp.			
Cylindros permopsis			
Gonatozygon sp.			
Nannochloris sp.			
Oedogonition sp.			
Ochrophyta (Golden algae)	35	17	595
Synura petersenii			
Synura uvella			
Tabellaria flocculosa			
Thalassionema javanicum			
Toxarium undulatum			
Rhodophyta (Red algae) *Agardhiella sp.*	20.9	10	209
Arthropoda	1.8	7.3	13.14
Amphipod			
Odonata (Damselfly)			
Bradinopyga alpogastra	0.9	4	3.6

*n= number of stomachs examined

In Figure 3.10 the abundant taxa examined in surface water (per 500 ml) of Densu were Ochrophyta, Rhodophyta, Bacillariophyta, Chlorophyta and Cyanophyta. They occurred in 32 %, 15.2 %, 17 %, 11 % and10.8 % of sampled water respectively.

The damselflies were the least abundant group (IRI= 4) (Figure 3.10).

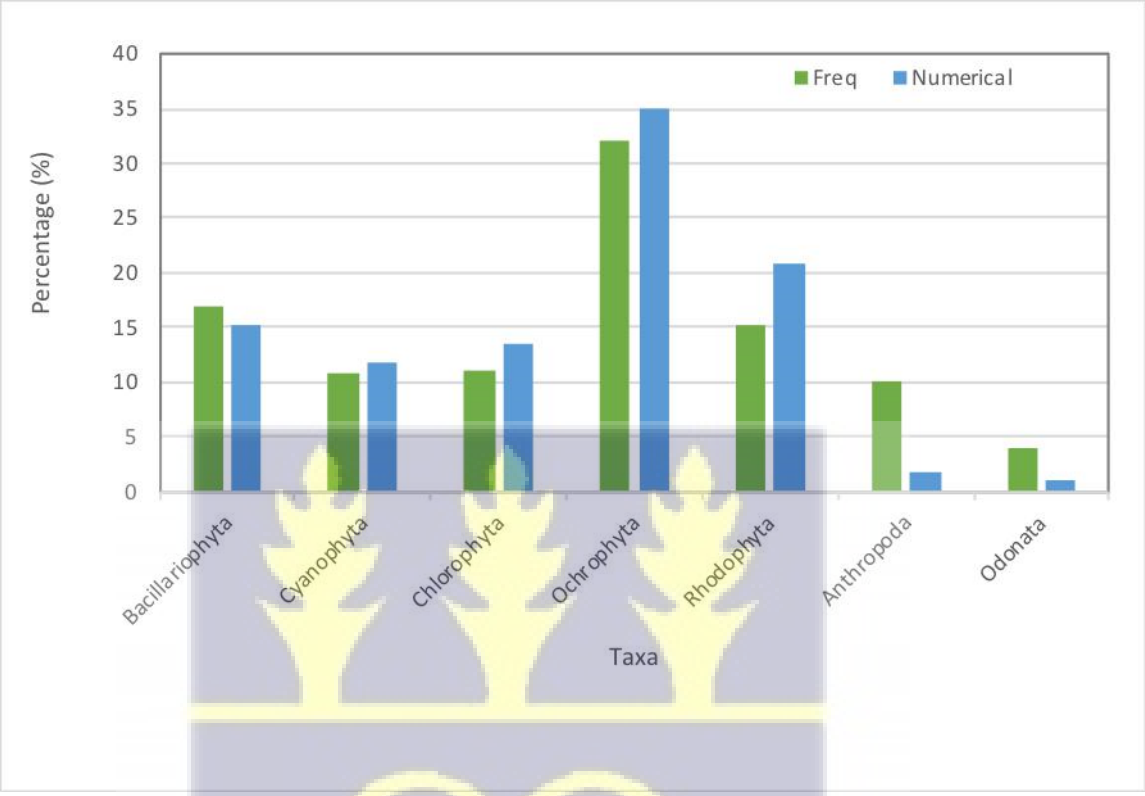


Figure 3.10 Percentage Abundance and Occurrence of Food Items in Water of Densu estuary

Figure 3.11, gives further illustration on the IRI of all groups of food items fed on by *C. tulipa*). While the least group was the Odonata (IRI=0 %), the most important groups were the Ochropyhyta (IRI = 56 %), Rhodophyta (IRI =16 %) and Bacillariophyta (IRI = 13 %) and the remaining were distributed among the Chlorophyta (IRI= 8 %), Cynophyta (IRI = 6 %) and Arthropoda (IRI = 1 %).

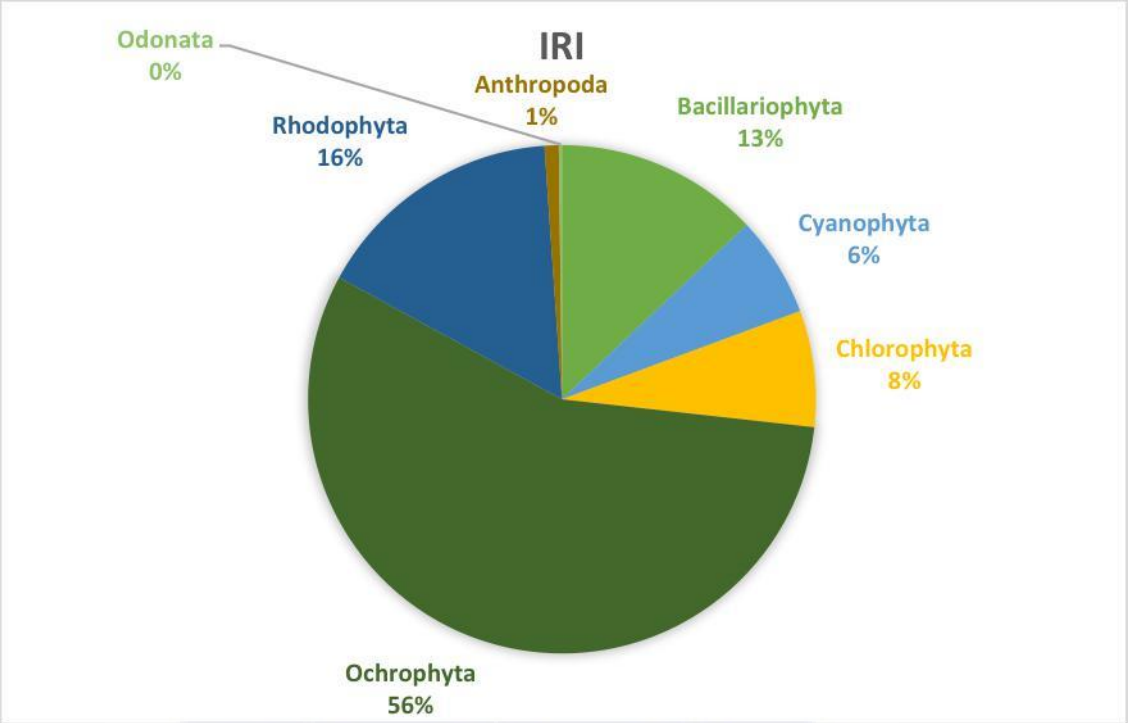


Figure 3.11: Index of Relative Importance of Food Items in Water of Densu estuary

3.5.6 Species Richness, Diversity, Evenness and Similarity

The number of species, genera, families, species richness, diversity and evenness for the plankton and insect communities recorded in the stomach contents and water samples of the Densu estuary are presented in Table 3.4.

Among the 43 species belonging to 33 genera and 33 families identified in the guts and water samples of the estuary, species diversity was not significantly different ($p < 0.05$) between gut contents ($H' = 0.30 \pm 0.12$) and contents in water medium ($H' = 0.32 \pm 0.05$) ($t = 2.16$, $p < 0.05$) (Table 3.). Similarly, 40 species were found in the guts and 43 in water samples implying higher number of species in water than in the guts. A Mann Whitney U - test performed on results obtained from Margalef's index analysis indicated no significant difference in species richness between the food items in guts (D = 6.60 ±

0.10) and water (^{D} = 7.01 ± 0.03) (t = 0.15, p > 0.05). Individuals were evenly distributed among species in the guts (J' = 0.60) and water (J' = 0.68) communities (Table 3.4).

3.5.7 Similarity of Food Items in Guts and Water

Most of the species found were represented in the guts and water of the estuary (Table 3.4). In comparing similarity between the two, a Sorensen's similarity index value of 0.970 was obtained suggesting a high similarity among food items found in the guts and surface water of the Densu estuary.

Table 3.4: Diversity Indices of Gut Content of *C. tulipa* and Water in Densu estuary (2019 and 2020)

Biotic index	Gut	Water
No. of phyla	7	8
No. of families	31	33
No. of genera	31	33
No. of species	40	43
D	6.60 ± 0.10	7.01 ± 0.03
H'	0.30 ± 0.12	0.32 ± 0.05
J'	0.60 ± 0.02	0.68 ± 0.15

3.6 Discussion

3.6.1 Oyster Catch

The relative abundance of fish populations is assumed to be directly linearly related with Catch Per Unit Effort (CPUE) (Harley et al., 2001). In the experimental fishing of the Densu oyster, CPUE (kg/hr/fisher/day) was significantly higher during low tide (p = 0.0161) than high tide with mean monthly values ranging between 15 ± 0.11 – 500 ± 15.0 and 6 ± 3.01 – 200 ± 5.30 respectively. Tidal action is known to have profound effects on effort. According to Angell (1986), Pieterse (2013), Lodeiros et al. (2017) & Chumkiew et al. (2018), tides influence the abundance of sedentary species and effort of fishers.

In the commercial oyster fishery at Densu, oysters are exposed at low tides and water levels are lower and so suitable for oyster collection. At high tides, water levels are high and a danger to lives as such collectors seldom harvest at high tides.

CPUE was highest from May to August (Low tide;16.8-500kg, High tide: 32132.5kg) during the study and lowest in September and October (Low tide;15-18kg, High tide: 16-10kg). The period of high catches coincided with the open season as well as breeding season of the West African mangrove oyster. The Densu population breeds continuously as such might explain the observed pattern (Osei, 2019), The low catches in September and October may be due to the occurrences of heavy rainfall in 2019. The results of the Mann Whitney U test shows that oyster catch was higher ($p = 0.023$) in the dry season (50± 3.4-102.95± 11.35) than the rainy season (23 ± 0.5- 57.45 ± 8.62).

Catches from experimental fishing was higher (6.00-200kg/hr/fisher) than commercial fishing (3-100kg/hr/fisher). According to King (1995), fishing effort is influenced by an interplay of factors such as age, fishing duration, skill and experience. The highly skilled fisher coupled with the use of a motorized canoe might have facilitated fishing activities.

Effort will be maximized in the commercial oyster fishery of Densu estuary if oyster collectors are supported with motorized canoes in replacement of man power canoes. The institution of low technologically advanced gears according to Cobbina (2018) does not necessarily reduce catch but reduces efficiency. Hence it is vital to promote the use of highly efficient methods of harvesting oysters in Densu while reducing catch quotas as a means of regulating overexploitation. The findings of this study on catches obtained in the experimental fishing (6-200kg) is similar to the study of Entsua-Mensah, (1998) at the Densu estuary (6.19kg) artisanal fisheries.

The higher catches in this study probably indicates less depletion of the resource over the years and the employment of more improved methods of harvestingsuch as the use of motorised canoe,. Ofori-Danson & Amoah (2013) estimated a monthly catch of clams from lower Volta to be 5,400 kg of clam per month per aqualung diving fisher which is relatively higher than *C. tulipa* in Densu. The differences in catch could be as a result of variability in abundance, environmental perturbations and fishing effort.

Catch peaked from the months of April to August in 2019 and 2020 with mean CPUE in experimental fishing ranging from 33.57±6 - 200±5 kg while that of the commercial fishing ranged between 16.79±3 – 100±11 kg. The Densu oyster fishery operates a close season management system where the fishery is closed from Mid-November to early April for the mangrove oyster to recruit. The period of high catches in this study coincided with the open season where oyster catches are high. Catch was highest in the month of July in both commercial (66.25±9.33 -100±11 kg) and experimental catches (132.5±15 - 200± 5kg).

The works of Arendse (2007) and van Overzee (2014) further reiterates the effectiveness of closure of fishing on catch during the breeding period on aggregating groups like oysters. The authors emphasized the need to combine closure with reduced effort in artisanal fishery activities.

In the Densu commercial oyster fishery collectors are restrained from harvesting small-sized oysters (below 5 cm) during the open season and huge oysters within the range laid down as spawning sizes in the month of July.

The Mann Whitney U test showed that oyster catch was significantly higher ($p = 0.023$) in the dry season (50± 3.4-102.95± 11.35) than the rainy season (23 ± 0.5- 57.45 ± 8.62). The

dry season is a period of reduction in water levels and collectors easily wade through the water for collection of oysters. The rainy seasons is characterised by high water levels from the occurrences of rains and therefore presents a danger to the lives of oyster collectors which affects fishing effort and therefore catches.

3.6.2 Growth Pattern

The estimated asymptotic length (L∞) (10.53 – 13.24 cm) of mangrove oyster suggest that its capable of growing to a much larger size if fishing pressure is reduced and they are allowed to grow indefinitely. Osei (2019) reported relatively high value of asymptotic length (L∞ = 14.78-16.97 cm) for the *C. tulipa* in Densu. These variations in asymptotic length are likely due to the fact that the author measured growth from cultured experiments where exploitation was controlled.

The growth coefficient of fish is influenced by habitat quality. A habitat with high productivity is expected to support a faster growth rate (Osei, 2015).

The growth coefficient (K) of 0.81 obtained in this study shows that the mangrove oyster grows at a faster rate. Comparatively, Osei (2019) reported k values ranging from 0.30-0.47 implying a slower growth rate for the cultured Densu population. These differences in the K value of the same population is probably due to differences in sample size.

This current study was conducted with a minimum of 400 specimens per month while Osei (2019) used a monthly range of between 40 and 100.

Other researchers reported the growth performance of *C. virginica* and *C.madrasensis* in Bangladesh as 2.07 and 2.18, respectively (Amin et al. 2006; Amin et al. 2008).

The K value of 0.81 in this study implies *C. tulipa* of Densu estuary has a lifespan of approximately 4 years (from the relation: t_{max}= 3/k).

The results on logistic and Gompertz models should be treated with caution because the age data were generated from the von Bertalannfy growth function.

3.6.3 Condition Index

The mean monthly (CI) of *C. tulipa* in Densu was 139.50 ± 0.11 which corroborates with the wild population of *C. madrasensis* in India where a mean CI of 181.5 ±2.81 was recorded (Suja, 2020). The low values recorded in some months of the year and high values (150 ± 3.33 – 287.87± 0.79) in other months (April to August, November and December) could be explained by the variability in environmental conditions suitable for the growth and general wellbeing of the shellfish. Variations in condition indices of the genera *Crassotrea* have been reported by several authors (Obodai, 1990; Obodai, 1997; Pogoda et al. 2011; Osei, 2020). Also, according to Pogoda et al (2011), a high condition index among oysters is indicative of the accumulation of glycogen and or gonads, whereas a low condition factor value implies the onset of spawning and preparedness to accumulate glycogen, which may later be utilized for gonad development.

In this study, high condition index (60 %) was recorded during the rainy season (April to October) than the dry (39 %) season (November to April).

The results of the Mann-Whitney U (Wilcoxon rank-sum) test revealed significantly (p = 0.032) higher CI during the rainy season than the dry seasons in 2019 and 2020.

The rainy season coincides with the open harvest period where oysters are allowed to breed, recruit and grow to optimum sizes other than the dry season where the resource is already

thoroughly exploited before closure and recruitment, beginning.The higher condition index during that season may be also as a result of abundance of its food during the rains.

The findings in this work contradicts the observations of Quayle (1989) & Angell (1986) where condition of oysters was high during the dry season and low during period of rains. The observed trend in this study can be attributed to the unique complexity of the Densu estuary in regulating itself. The frequent opening of the Weija dam and the creation of two inlets with the aim of flushing out saline water from the estuary leaves the system inundated with freshwater in most months of the year. Condition factor of oysters is influenced by reproduction and growth (Quayle, 1989) and the Densu population reproduce under high salinity levels and grow better when salinity is low. Therefore, this practice of frequent inundation of the Densu estuary estuary by freshwater could be an influencing factor for the observed pattern in condition indices of *C. tulipa* in the Densu estuary thereby, contradicting that reported in literature (Gosling 2015). Apparently, the findings of this research is similar to the inferences drawn by Osei (2019) on the species where a low index (< 30 %) was observed from January to April 2018 and high mean CI values (> 35%) in November and December 2017 and July to October 2018. During the open season, big (recruiting) oysters are left to grow and harvesting restrained in the month of July as part of the community management strategies. The month of July also marks the peak of the breeding period of the West African oyster where there is the accumulation of glycogen and gonads as such might explain the highest condition index in Densu estuary.

3.6.4 Food Habits

The predominance of the diet of *C. tulipa* in Densu by golden algae (IRI=595), red algae (IRI=209), green algae (IRI= 131.37) and diatoms (IRI =172) is similar to reports on other species of the genera *Crassostrea.* The research of Dupuy et al. (2016) in France and Kasim & Mukai (2009) in Japan showed that lagoon population of *C. gigas* preferred micro phytoplanktonic benthic diatoms.

However, the preponderance of the golden and red algae in guts of *C. tulipa* and the water column implies their possible abundance and proliferation in the Densu estuary estuary. Conversely, the Densu mangrove oyster ingested less of the blue green algae, arthropods, protozoans and damselflies which is similar to that reported on the lagoon pearl oyster population in France by Loret (2000). In Densu, a high similarity was observed among food items found in the guts and surface water of the Densu estuary which did not conform with the findings of Kasim & Mukai (2009). The authors stated no significant correlations between diet items in gut of the oyster and water column (Kasim & Mukai, 2009). Also, in the study of Densu population, species diversity and richness were not significantly different between contents in the gut and water medium with individuals evenly distributed among species in the guts (J' = 0.60) and water (J' = 0.68) communities (Table 3.6c). However more species were found in the water column than that found in the guts. Kassim & Mukai (2009) encountered low algal species diversity and abundance in water column of the Akkheshi-Ko estuary in Japan in comparison with species found in the guts which is dissimilar to this report on the Densu estuary in Ghana.

However, in the study of Kassim & Mukai (2009), some groups of algae (diatoms) were found concurrently in high concentrations in the guts and water column. Rouillon et al. (2005) also identified abundance of phytoplankton (dinoflagellates) in the stomach contents

relative to water samples. Conclusively, probably the pattern of continual presence of some taxa of food items in both water and gut of *C. tulipa* in Densu may be an indication of their abundance in the water column and benthic regions of the system. In literature, a suit of factors for example cell size, ontogeny, capture rate, selection and consumption influences feeding habits among wild bivalve oysters (Metian et al., 2020; Rosa & Padilla, 2020).

In furtherance to that, the authors explained that bivalves do not feed what is filtered but that they have the ability to sort the cleared particles and reject them prior to ingestion in the form of pseudofeces, depending on various factors such as the concentration of particles filtered from suspension, the surface properties of the trapped particles, low nutritional value, or particle chemical properties (Metian et al., 2020; Rosa & Padilla, 2020) Another study by Galimany (2020) established in an experiment that filtered and cleared algae species in diet of *Crassostrea* were also assimilated by the bivalves. Therefore, the Densu population may not be ingesting high quantities of diatoms, golden and red algae but rather probably selected, consumed and retained these preferred groups. Low retention of food particles have been reported by Loret (2000) where the research found low counts of cyanobacteria in the gut of pearl oyster.The presence of some species of Cyanobacteria is of potential danger to the fishery. This is because some species of cynaobacteria produce toxins which may bio-accumulate in *C. tulipa* posing threats to aquatic and human life.

3.7 Conclusions

The high catch registered in this current study implies that the Densu commercial oyster fishery resource is viable enough to support livelihood. *C. tulipa* has a fast growth rate a potential for restocking of the population. Therefore the existing regulations on size limits should be enforced for conservation purposes. The species is of good condition during the

open season however the existing drainage and sewage outlets is a threat to the fishery and the wellbeing and sustainability of the wetland resource.

The mangrove oyster feeds on a wide range of food items of plant material which categorises it as a planktivore omnivore. This implies in the development of the oyster culture industry in the Densu estuary, feeding cost could be minimized by relying on feed sources from the wild and supplementing with artificial feeds. Therefore, this information is important for development of feed types for aquaculture purposes among stakeholders.

CHAPTERFOUR

4.0 ASSESSMENT OF THE POTENTIAL USE OF THE WEST AFRICAN OYSTER AS A BIO-INDICATOR OF ENVIRONMENTAL VARIABILITY

This chapter investigates the relationship between Physicochemical Parameters, relative abundance and the morphometric parameters of the West African Mangrove Oyster as bio indicator of changes in the aquatic environment.

4.1 Introduction

In Ghana, the West African Mangrove Oyster is widely distributed in mangroves, sediments and compact substrates of coastal water bodies (Obodai, 1999; Ampofo-Yeboah, 2014). These substrates are also home for a large group of organisms such as macrophytes, foraminifera, fish, benthic invertebrates and algae.

Water quality parameters, invertebrates, algae, foraminefera, birds, macrophytes and fish have been the conventional proxies in use in Ghana for assessing environmental health and managing aquatic systems (Ndanu, 1998; Essuman & Nortsu, 2008; Amoah et al., 2011;Debrah et al., 2011; Apau et al., 2012; Osei et al., 2012; Anim-Gyampoh et al., 2013; Agyemang, 2013; Mahu, 2015; Atindana et al., 2016; Debrah et al.,2011; Ansah et al., 2018; Asare et al., 2018; Botwe, 2018; Okyere & Nortey, 2019).

The high mobility of birds, fin fish, short life span of algae, frequent changes in water quality requiring a longer period of monitoring, presents a challenge to their sustainable usage. However, oysters are sedentary bivalves that are cosmopolitan in nature and has the ability to filter pollutants.

Therefore, oysters are capable of regulating the health of estuarine environments better than other aquatic bio indicators (Kirby et al., 1998; Harper et al., 2000; Brander, 2007; Barbour et al., 2010; Whitfield & Harrison, 2014). In many parts of the world, extensive studies have been carried out on oysters and mussels as ecological indicators of environmental variability (Rudolf et al., 1995; Kirby et al., 1998; Harper et al., 2000; Brander, 2007; Barbour et al., 2010; Whitfield & Harrison, 2014). However, in Ghana scanty scientific studies have been done on oysters (Katikiro & Macusi, 2012; Parker et al., 2013; Zougmore et al., 2016). Therefore, this study seeks to fill knowledge gap and use the information

obtained from this baseline study in establishing the use of the West African oyster as an early warning signal of changes in the natural environment of the Densu estuary for the development of the commercial oyster fishery.

4.2 Materials and Methods

The study was conducted for a period of 18 months from March 2019 to August, 2020 in the Densu estuary estuary. The estuary is located at 0°16′43″ W, 5°34′07″ N and 0°20′02″ W, 5°30′21″ N – west of Dansoman, south of Mallam, McCarthy Hill and Aplaku, and east of Bortianor.

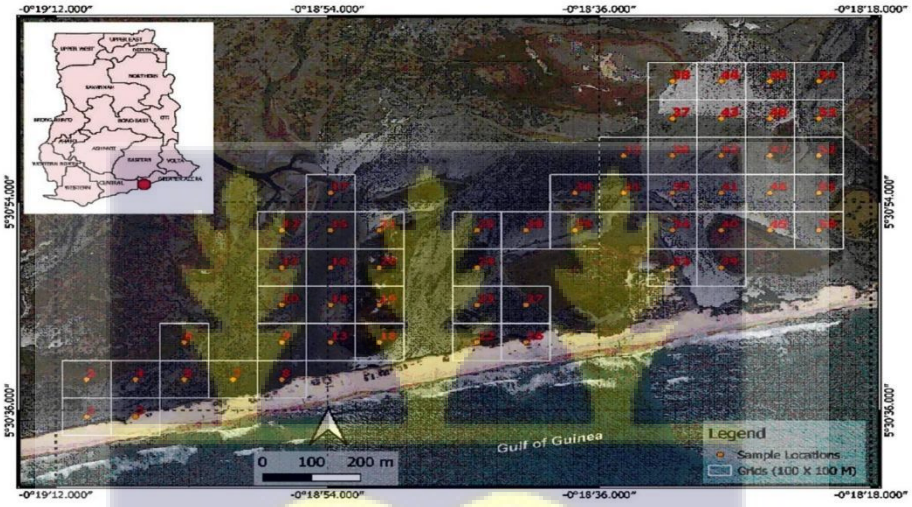


Figure 4.1 Map of Ghana showing the location of the DensuEstuary in Ghana and Study Grids

4.2.1 Study Design

Sampling for measurement of physicochemical parameters was done at low and high tide and for the two designated hydrological seasons defined from data from the Ghana Meteorological Agency (GMet) as dry season from Mid-November to 20th April and rainy season spanning 21st April to October.

4.2.2 Measurement of Physicochemical Parameters

Physicochemical parameters namely: Temperature (^{O}C), Dissolved Oxygen (mg/L), pH, Total Dissolved Substances (mg/L), Conductivity(µS/cm) and Salinity ($^{0}/_{00}$) were measured

in situ at the predetermined sites (denoted as grids) in triplicate groups between the hours of 0600 and 0700 GMT using a multiparametric water quality checker (TOADK -22 A).

The probe of the metre was released into the water to a depth of 1m at every sampling station. Depth (m) readings were taken by using a measuring tape, attached to a stick. For every parameter, monthly mean values were determined by calculating the means of the measurements. Silicates, Total Alkalinity, Chlorophyll a, microbes and heavy metals were measured *ex situ*.

4.2.3 Sampling and Determination of Silicates

In measuring silicates level, water samples were collected into 500 ml plastic bottles from predetermined sites. Sampling bottles were rinsed with water from the site and the bottles slowly immersed to the bottom to reach oyster beds and water allowed to flow slowly in and corked. Samples were immediately preserved on ice and transported to the laboratory. Where possible, samples were analysed within 24 hours of collection. Alternatively, samples were stored at a temperature of 4 °C for about 7 days before analyses.

In the laboratory silicate concentration were determined within 24 hours of sample collection using Silicomolybdate method (range 1 - 100 mg/L SiO_2) (any reference?). The program number was selected by pressing 3350 on a DR 2800 mass spectrophotometer and the wavelength (λ) of 452 nm selected. Samples were allowed to attain room temperature of between 15–25 °C. A

10 ml sample cell was filled with the sample and the contents of one Molybdate Reagent Powder Pillow added to the prepared sample and swirled to mix. The contents of one Acid Reagent Powder Pillow were added and swirled and allowed to stand for 10 minutes. The appearance of a yellow coloration indicated the presence of silica. The Citric Acid Powder Pillow was poured to the treated sample and mixed for 2 minutes. A blank was

prepared to zero the mass spectrophotometer. The prepared sample was placed in the cell holder, closed and the results in mg/L silica (SiO_2) read.

4.2.4 Sampling and Measurement of Primary Productivity (Chlorophyll a)

Water samples were collected into 1000 ml dark bottles placed in an ice chest containing ice to the laboratory. For determination of chlorophyll *a* concentration samples were allowed to attain room temperature. To avoid degradation of chlorophyll *a*, three to five drops of aqueous solution of 50 % magnesium carbonate were added and the sample centrifuged at 448 *g* for 15 min. The filtrate was transferred into dark bottle and capped tightly. It was then placed in a refrigerator for 14 hr to allow complete extraction of chlorophyll. The content of bottle was again centrifuged at 1008 *g* for about 15 min. The supernatant was transferred to a volumetric flask of 10 ml, and the volume of the content raised to 10 ml by adding 90% acetone. The optical density of the extract was recorded in mg/ L on a spectrophotometer at 630, 663 and 750 nm following the methods described in APHA (1998).

In estimating the chlorophyll a content of the water the algorithm ;

C= 116(E655)-13.1(E 633) (Strickland & Parsons, 1972) was followed

Where c = chlorophyll a concentration (mg/L) was used to calculate for C and subsequently divided by V as C/V; where V is the volume of the water filtered in litres (Strickland & Parsons, 1972).

4.2.5 Field Data Collection and Measurement of Microbial Loads

Sample bottles were pretreated with 70% ethanol prior to field collection. In the field bottles were rinsed with water from the estuary. Clean oyster samples and filtrates from the water

samples were collected into aseptic containers, bottled and preserved on ice in preparation for laboratory analyses. In the field, oysters were first sorted into different size classes; Large sized (L)- 4.5-5.4g and Small sized(S)- 2.5-3.4g following the criteria set by FAO (1998). The Pour Plate Technique was followed in determining Total count of aerobic mesophiles (TVC), faecal coliform bacteria and *Escherichia coli* in water and oyster tissues (APHA, 2015). The growth media (Plate count agar for TVC, Luria broth for *E coli* and Macconkey agar for total coliform) for each microbe was weighed into a conical flask and distilled water added and covered with aluminium foil. Growth media were autoclaved at 121^{p}C for 15 minutes at a pressure of 15 millibars in an inoculation chamber.

The innoculum was prepared by serially diluting into 6 sterilised plates (6 for each microbe) containing the stock sample and then, thoroughly mixed by rotating the plates and allowing them to solidify. The mixture was allowed to settle at 37 °C for 24hrs for all bacteria.

After incubation, the plates were examined for the presence of individual colonies growing throughout the medium and counted using a colony plate counter APHA (2015) .

4.2.6 Sampling for Heavy Metals Determination

The procedure adopted followed the standard method established by APHA (2015) for heavy metal determination.

Different size classes of oyster and water samples were collected in the field into sampling bottles pre washed with 0.01 % nitric acid. The nitric acid was added to water samples to ensure dissolution of metals, minimize oxidation and microbial degradation, avoid precipitation (in container) and adsorption on the surface of the walls of sample bottles. Four metals namely Lead (Pb), Cadmium (Cd) and Mercury (Hg) of toxic effects and having the ability to interfere with metabolic processes (As) in humans and oyster growth

were studied. Samples were prepared by washing them with deionized water in plastic bowls and freeze dried in a christ freeze dryer. Small and large oyster samples were shucked and tissues removed into separate containers. Each group was pulverized using Retch Zm 200 pulverizer and stored in clean washed plastic containers. The samples were rigorously shaken in their containers to ensure uniformity before weighing. After mixing, 1g of each sample were weighed into Teflon bumbs. For water samples, 5 ml were taken for digestion. Samples were treated with 6 ml of 65% nitric acid and 1 ml of 30% hydrogen peroxide, allowed to cool and made up to 50mls and then stored in clean containers. They were then read on Spectra AAS for concentrations of Lead (pb), Cadmium (Cd) and Mercury (Hg) in milligram per kilogram for tissues and milligram per litre for water. The reference materials used are shown in Table 4.1

Table 4.1: Standard Reference Material (1566b Oyster Tissue) Used for Validation

Element	Reported(mg/kg)	Literature (Yesudhason et al. 2013)	Current study(mg/kg)
Lead (Pb)	0.308 ± 0.009	0.001-0.02	0.312 ± 0.009
Cadmium (Cd)	2.48 ± 0.08	1.58-5.74	1.98 ± 0.06
Mercury (Hg)	0.0371 ± 0.0013	0.01-0.03	0.402 ± 0.05
Arsenic (As)	197.2 ± 6.0	-	0.05 ± 0.01

4.2.6.1 Preparation of Standard Reference Materials

Standard Reference Materials (1566b oyster tissue, blanks and single standard elements) for Pb, Cd and Hg were equally prepared as the samples and loaded on to a rotor in an industrial microwave and digested. The recovery rates for all the metals was 98.9 %.

4.2.6.2 Washing of Teflon Bombs and Negative Controls

After each round of digestion, the Teflon bombs were washed in dilute detergent, rinsed in copious volumes of doubly distilled water (ddH_20) and soaked in 10% HNO_3 for 30 minutes. The acid was decanted and 5 ml of fresh 10% HNO_3 reintroduced into each Teflon bomb and digested to wash as described above. The bombs were then rinsed in copious volumes of doubly distilled water and dried in an oven.

To test the integrity of washing and to confirm the absence of our interest elements in the doubly distilled water used routinely in the laboratory, 10 ml of the doubly distilled water were used as negative control.

Each negative control was treated as a sample as described above and the analyte assayed for the presence of elements using the AAS. These are referred to as Blanks which help to check contamination during sample preparation.

4.2.6.3 Positive Control

Sample element (Cd, Hg and Pb) reference standard samples (SPECTRA CAN, SWEDEN standard reference material) included in the analysis were treated as a sample as described above. These served as internal positive control samples.

4.2.6.4 Determination of Arsenic Concentration in Water and Oyster

After collection of samples from the field, 50 mls of samples, blanks and standards were measured in measuring cylinders and transferred into conical flasks designed for the arsenator. An A1 powder is each poured into the conical flask. A2 tablet is added into each flask and covered quickly, one after another with the bung and allowed to wait for 20 minutes for complete reaction. The black paper slide from the bung device is removed and treated samples read on the arsenometer in µg/L.

4.2.6.5 Data Analyses

4.2.6.6 Intake Rate Limits

To estimate daily intake (EDI), the equation by Miri et al. (2017) was followed

$$EDI = \frac{EF \times ED \times FIR \times CF \times C}{WAB \times TA} \times Cm$$

where ED = exposure duration (60 years), EF = exposure frequency (365 days/year), CF = the conversion factor (0.208) to convert dry weight of oyster to wet weight, WAB = average body weight for adult (70 kg), FIR = ingestion rate (25.2 g/day), C = heavy metal concentrations in muscle tissues of oyster and TA = average exposure time (Miri et al., 2017 as cited in Kwaansa-Ansah et al., 2019).

To determine the toxicity or otherwise of contaminants in oyster following standard doses, a target hazard coefficient was estimated using the relation:

$$\text{Target hazard quoefficient (THQ)} = \frac{\sum(F \times ED \times D1 \times HC)}{RFD \times BW \times ET}$$

Where EF = Exposure frequency, ED = Exposure duration/average lifetime, D1= Average daily intake of fish in Ghana, HC = Heavy metal concentration, BW= Average body weight

of an adult in Ghana, ET= Average exposure time for non-carcinogenic (Miri et al., 2017 as cited in Kwaansa-Ansah et al., 2019).

If the THQ or HI is < 1 it implies no threat to health, while THQ >1, indicate a higher risk associated with fish intake (USEPA, 2011).

The hazard index (HI) was evaluated as; $=HI = \sum(THQ)$

If the THQ or HI is below one, it implies no threat to health, while THQ or HI above 1, indicate a higher risk associated with fish intake (USEPA, 2011).

4.2.6.7 Daily Intake Limit

The daily consumption rate limit (CRlim) of fish species in order to determine the carcinogenic effects of contaminants, was evaluated using the equation of Miri et al. (2017):

$$CRlim \frac{ARL \times WAB}{CSF \times Cm}$$

where ARL = maximum acceptable lifetime risk level (10-5) and CSF = cancer slope factor, (Yu et al., 2014 as cited in Kwaansa-Ansah et al., 2019). CSF of Pb = 0.0085 mg/kg day-1

The maximum acceptable daily intake of fish for non-carcinogenic risk of heavy metals (pb) contaminants was determined using the relation;

$$CRlim \frac{RfD \times WAB}{CSCF \times Cm}$$

where RfD is the oral reference dose (Alipour et al., 2014). The RfD values for Cd, Pb, Hg and As are 0.001, 0.0035, 0.00016 and 0.0003 in mg/kg-day respectively (USEPA, 2011 as cited in Kwaansa-Ansah et al., 2019).

Cancer risks (CR) was estimated as: $CR = EDI \times CSF$

To establish the difference in bioaccumulation of metals in water and oyster, a bioaccumulation factor was calculated following the protocol of EPA.

$$\text{BAF} = \frac{Mean\ metal\ concentration\ in\ \ oyster}{\text{Mean metal concentration in estuarine water}} \text{ (EPA, 2013)}$$

BAF values > 1 indicate that the accumulation in the organism is > the medium

4.2.7 Sampling for Measurement of Estuarine Acidification Factors

The photometry approach (palintest photometer) (APHA, 2015) was employed in determining total alkalinity. Monthly water samples were collected, preserved in ice and transported to ISO 2083 Envaserve laboratory in Greater Accra Region. In the laboratory, samples were allowed to attain room temperature and a test tube filled with sample to the 10 ml mark. An alphabot tablet was added, crushed and mixed until all the particles dissolved. Samples were allowed to stand for a minute and remixed.

The photometer was set to Phot 2 and samples poured into cuvette and readings of $CaCO_3$ taken in mg/L. Total alkalinity as $CaCO_3$ was converted to Total alkalinity as HCO_3^- by multiplying the result by 1.22 .

4.2.7.1 Data Analyses for Estuarine Acidification Factors

Seawater carbonate chemistry parameters (Seawater partial pressure of carbon dioxide (pC02), Dissolved Inorganic Carbon (DIC), carbon dioxide concentration ($C0_2$), mineral saturation states for calcite (ῼcalcite) and revele factor were calculated using $C0_2$ calculator software (Dickson, 2010; Nunoo et al., 2016).

To calculate the carbonate system parameters, total alkalinity (µmol/kg SW) and pH were entered and CO_2calc software calculated the concentrations (µmol/kg SW) of the two

remaining CO_2 system parameters (total carbon dioxide (TCO_2), partial pressure of carbon dioxide (pCO_2), the Revelle factor, and the saturation states (Ω) for aragonite and calcite (Dickson, 2010). An output temperature and pressure were specified to calculate system parameters at in situ conditions. Salinity (psu), input temperature (^{O}C) and pressure or depth (dbars), concentrations of silicate (µmol/kg SW**)**, two known CO_2 system parameters (Total alkalinity; TA and pH) at the input conditions and output temperature and pressure were accepted by the CO_2calc as input data. By specifying output temperature and pressure, CO_2calc provided the following at input conditions as well as a set adjusted for the specified output temperature and pressure. The Constants for Estuarine Waters K1 and K2 of carbonic acid were determined following the procedure suggested by Millero (2010). To achieve this, the CO_2calc was opened and the Millero constants, seawater scale, gas transfer velocity, wind speed units, and pH scale was chosen. After this, all other input data were entered into a single point mode. Data was processed and the results recorded to three digits after the decimal point.

As a result, the CO_2calc provided values for the remaining CO_2 system parameters, the degree of saturation for calcite and for aragonite and the Revelle, or homogeneous buffer factor (Robbin et al., 2010).

4.2.7.2 Data Analyses of Physicochemical Parameters

Microsoft excel (Version 2005) was used to calculate descriptive statistics (means, standard errors). The twenty-nine physicochemical parameters were first tested for normality using Shapiro-Wilk test in R studio. After the test, normality was assumed

($p > 0.05$) for Water temperature, Salinity, Dissolved Oxygen, silicates, chlorophyll a, Total Viable Counts, faecal coliform, *E coli*, Cadmium, Total Alkalinity, Revelle factor, carbonates ($C0_3$), bicarbonates ($HC0_3$), Aragonite, saturated Calcite and Total Carbon

dioxide (Appendix. Table 5). A normality probability test was carried out on the remaining 13 parameters. Hydroxyl ions (OH), Buffer alkalinity (Balk), Silica Alkalinity (Si Alk) and $XC0_2$ were found to be normally distributed. Eight parameters namely depth, conductivity, TDS, Mercury, pH, Lead, partial Pressure of carbon dioxide and Carbon dioxide were log transformed to assume normality or otherwise. Except for depth, conductivity, TDS and Mercury which were not normally distributed, the other four parameters (pH, Lead, partial Pressure of carbon dioxide and $C0_2$) obtained normality.

4.2.7.3 Analysis of Species-Environmental Driver Relationship

Canonical correspondence analysis (CCA) using the Vegan package (version 2.5-4.) in R studio software (version 1.3.1056) was performed to examine the relationship between oyster abundance, shell morphometric parameters and the distribution of associated environmental factors or gradients (ter Braak et al.,1995; Pally & Shankar, 2016).

CCA is a direct constrained multivariate ordination method that incorporate correlation and regression between morphometric, abundance data and environmental factors within the analysis (ter Braak et al.,1995), and extract the most important environmental factors and biological data sets (ter Braak &Verdonschot1995). There were different entities namely sites, response variables (abundance, shell width, height, length and weight) and explanatory variables (environmental data). Multicollinearity (i.e. perfect correlation with other predictive factors, which tend to inflate variances of the parameter estimates), was removed using the stepwise model (ordistep function in R). Biological data was log transformed to normalize the data before the CCA analysis to prevent extreme values (outliers) from unduly influencing the ordination. A total of twenty-nine (29) environmental variables were correlated with biological data on relative abundance (CPUE), shell width, height, length and weight. This is by an initial examination of the variance inflation factor

(VIF) and tolerance. Environmental variables with VIF>10, presents collinearity with another or other variables.

Highly collineated or redundant variables are automatically removed from initial dataset and this process goes forward and backward for the selection of variables not highly correlated with each other. Trip lots relating to species, predictive factors and plots among the four sites, were created to visually interpret the outcomes of the CCA ordination.

Permutation tests of the CCA model, CCA axes and CCA terms for the significance of constraints was performed in vegan using the function anova.cca (where R automatically chooses the correct anova variant for the result of constrained ordination).

The test mimics standard analysis of variance function (anova), and the default test analyses all constraints simultaneously: The permutation tests shows whether the whole CCA model, the CCA terms (environmental variables), and CCA axes explain more variance of morphometric and abundance (observations) matrix than expected by chance.
The test of ANOVA suggests significant or non significant differences between variables. To determine which of the predictor variables contributed significantly in oyster data, eigen values were generated for both biological and environmental data, and inferences drawn using CANOCO (Version 5).

Multiple linear Regression and Assumptions

To determine the linear relationship between oyster data, climate sensitive parameters, Physicochemical Parameters and contaminants, multiple linear regression modelling approach was used. The assumptions of the model were; there is a linear relationship

between variables, the independent variables are not highly correlated with each other, variance of the residuals is constant, independence of observation and residuals are normally distributed (Multivariate normality). To test the model, a one year data on oyster size and water parameters was collected and used.

4.3. Results

4.3.1 Monthly Variations in Physicochemical Parameters

Table 4. 2 is a presentation of monthly changes in physico-chemical parameters of the Densu estuary. Monthly water temperature ranged between 24.04 and 34.74 ^{O}C with a mean value of 28.83 ± 6.43 ^{O}C. The mean depth of the oyster reefs sections of the Densu estuary was 0.61 ± 0.07 m deep and ranged between 0.54 and 1.00 m deep monthly. Total dissolved substances were between 51.40-8801 mg/L. The DO content varied between 1.85 to 24.27 mg/L with a mean value of 6.09 ± 1.36 mg/L. The water was neutral to basic (7.43-9.47) with a mean value of 8.07 ± 1. 80. Salinity varied between 0.36-35.11 ppt. The monthly variations in silicate ions concentration in the water varied from 3mg/L to 19.90 mg/L. Chlorophyll a concentration ranged between1.26 and 11.49 and recorded a mean value of 4.45± 1.04. Total count of aerobic mesophiles (TVC), coliforms (faecal coliforms and *Escherichia coli*) were 19.00-99.00 CFU/ml, 0.00-55.0 OCFU/ml and 0.00-50.0OCFU/ml respectively. Similarly, the trace metals of Arsenic, Lead, Cadmium and Mercury ranged from 0.001-0.088 mg/L< 0.0001-
0.068 mg/L, 0.043-0.088 mg/L and <0.0001 mg/L respectively.

Monthly ranges and mean levels in concentration (µmol/kgSW) of Total alkalinity**,** Total carbon dioxide, carbon dioxide, bicarbonates, carbonates, buffer alkalinity and hydroxyl ions ranged from 99.91-1511.01(936.42 ± 104.61), 67.53-2052.73 (834.62 ± 111.57), -

0.34-585.23 (140.90 ± 32.23), -54.45-1440.56 (430.32 ± 98.00), -12.75-183.55 (70.62 ±16.20),0.14-742.92(161.90 ± 37.15) and 0.32-322.69 (7.18 ± 1.64) respectively (Table 4.2). The Carbon dioxide fugacity and Seawater partial pressure of carbon dioxide concentration (µatm) were 0.08-18894.27 (1657 ± 948.23) and -14.50-10612.63 (4746.72 ± 88.01) correspondingly.

The monthly ranges and mean levels of homogenous buffer (Revelle factor) was 0.28.0016.36 (3.50 ± 0.80) while the mineral saturation states for calcite (ΏΩcalcite) and aragonite (ΏΩAr) were -0.23-4.61 (1.39 ± 0.32) and -0.144 -4.61 (0.90 ± 0.21) respectively.

Table 4.2: Range and Mean (± Standard Error) Values of Physicochemical Parameters of Densu Estuary (2019,2020)

Parameter	**Range**	**Mean ± S.E.**
Temperature (^{O}C)	24.04-34.74	28.83 ± 6.43
Depth (m)	0.54-1.00	0.61 ± 0.07
Total Dissolved Substances(mg/L)	51.40-8801	3550.58 ± 790.24
Salinity (ppt)	0.36-35.11	16.41 ± 3.65
Dissolved Oxygen (mg/L)	1.85-24.27	6.09 ± 1.36
pH	7.43-9.47	8.07 ± 1.80
Conductivity (µs/cm)	1.92-2867.67	453.14 ± 94.27
Silicates (mg/L)	3.00-19.90	11.79 ± 3.65

Chlorophyll a	1.26-11.49	4.45 ± 1.04
Total Viable Counts (CFU/ml)	19.00-99.00	64.36 ± 10.58
Faecal coliform bacteria (CFC/ml)	0.00-55.00	22.89 ± 3.76
Escherichia coli (CFC/ml)	0.00-50.00	17.08 ± 2.81
Arsenic (mg/L)	0.001-0.088	0.05 ± 0.01
Lead (mg/L)	< 0.0001-0.068	0.03 ± 0.01
Cadmium (mg/L)	0.043-0.088	0.05 ± 0.01
Mercury (mg/L)	<0.0001	< 0.001
Total alkalinity (µmol/kgSW)	99.91 -1511.01	936.42 ± 104.61
Total carbon dioxide (TCO_2) (µmol/kg SW)	67.53 – 2052.73	834.62 ± 111.57
Carbon dioxide fugacity ($fC0_2$) (µatm)	0.08-18894.27	1657.67 ± 948.23
Mineral saturation states for aragonite (ΩAr)	-0.144-4.61	0.90 ± 0.21
Revelle factor	0.28-16.36	3.50 ± 0.80
Bicarbonates ($HC0_3$) (µmol/kgSW)	-54.45-1440.56	430.32 ± 98.00

4.3.2 Seasonal Changes in Physicochemical Parameters

The seasonal changes in Physicochemical Parameters are shown in Tale 4.3. From the Welch *t* test, mean water depth, cadmium, total alkalinity, pH, carbon dioxide, lead, TCO_2, $fC0_2$, chlorophyll a and $xc0_2$ were significantly higher ($p<0.05$) in the wet season than the dry season (Table 4.3). During the wet season mean depth was 5.29 ± 0.25, cadmium (0.05 ± 0.01), total alkalinity (1115.32 ± 104.69), pH (7.94± 0.04), carbon dioxide (6.70 ± 1.37), TCO_2 (1080.00 ± 118.45), $fC0_2$ (2956.37 ± 72.97), chlorophyll a (3.66 ± 0.40) and $xc0_2$ was 220. ± 33.73 (Table 4.3).

The dry season values were; depth (4.32 ± 0.03m), cadmium (0.04 ± 0.01mg/L), total alkalinity (911.79 ± 27.80), pH (7.82 ± 0.12), carbon dioxide (4.55 ± 1.89), total viable counts (83.25 ± 5.96 CFU/ml), total carbon dioxide (753.27 ± 44.00), carbon dioxide fugacity (178.47 ± 11.23), chlorophyll a (3.12 ± 0.58) and $xC0_2$ (187.70 ± 76.40) (Table 4.3). Surface water temperature, total viable counts, total dissolved substances, lead and buffer alkalinity were significantly higher ($p < 0.05$) in the dry season than the wet season (Table 4.3). The mean values of water temperature, Total viable counts, total dissolved substances, lead and buffer alkalinity were 30.78 ± 0.83 ^{o}C, 83.25 ± 5.95 CFU/ml, 3083 ± 12.25 mg/L, 0.05 ± 0.01mg/L and 68.91 ± 10.85 respectively in the dry season.

Wet season values were, water temperature (27.49 ± 0.25 ^{o}C), Total viable counts (65.59 ± 10.90 CFU/ml), total dissolved substances (17386 ± 15.90 mg/L), lead (0.03 ± 0.01 mg/L) and buffer alkalinity (36.46 ± 3.73).

Salinity, dissolved oxygen, faecal coliform, *E coli*, conductivity, aragonite, calcite and arsenic did not differ significantly ($p < 0.05$) from the dry season to the wet season (Table 4.3). During the wet season mean dissolved oxygen was 17.16 ± 6.46mg/L, faecal coliform (32.75 ± 8.70 CFU/ml), *E coli* (25.28 ± 6.81 CFU/ml), conductivity (939.10 ± 14.3 µs/cm), arsenic (0.06 ± 0.01mg/L), salinity (11.02 ± 1.05ppt) and that of aragonite was 1.17 ± 0.22. In the dry season, dissolved oxygen level was 4.74 ± 0.60mg/L; faecal coliform 0.88 ± 0.22 CFU/ml, pH 7.82 ± 0.12, *E coli* 1.00 ± 6.81 CFU/ml, conductivity 307.80 ± 1.33 µs/cm, arsenic 0.04 ± 0.0mg/L, salinity 19.27 ± 2.00ppt and the concentration of aragonite was 79.98 ± 30.74.

Table 4.3: Seasonal Variations in Physicochemical Parameters in The Densu Estuary, 2019-2020

Parameter	**Dry season**	**Wet season**	***t* value**	***P* value**
Temperature (^{O}C)	30.78 ± 0.83	27.49 ± 0.25	-7.90	4.23e-12*
Depth (m)	4.34 ± 0.03	5.29 ± 0.25	3.48	6.75 e-4 *
Total Dissolved Substances(mg/L)	30837.45 ± 12.25	17386± 15.90	-2.31	0.02*
Salinity (ppt)	19.27 ± 2.00	11.02 ± 1.05	1.19	0.24
Dissolved Oxygen (mg/L)	4.74 ± 0.60	17.16 ± 6.46	1.04	0.30
pH	7.82 ± 0.12	7.94 ± 0.04	-4.01	1.05 e-04*
Conductivity (µs/cm)	307.80 ± 1.33	939.10 ± 14.3	-1.82	0.07
Silicates (mg/L)	8.21 ± 2.50	14.47 ± 2.77	5.23	1.2e-03*
Chlorophyll a	3.12 ± 0.58	3.66 ± 0.40	5.09	2.98e-05*
Total Viable Counts (CFU/ml)	83.25 ± 5.96	65.59 ± 10.90	13.96	7.9e-04*
Fecal coliform (CFC/ml)	0.88 ± 0.22	32.75 ± 8.70	2.05	0.14
Escherichia coli (CFC/ml)	1.00 ± 0.05	25.28 ± 6.81	1.41	0.25
Arsenic (mg/L)	0.04 ± 0.01	0.06 ± 0.01	1.77	0.38
Lead (mg/L)	0.05 ± 0.01	0.03 ± 0.01	2.50	0.05*
Cadmium (mg/L)	0.04 ± 0.01	0.05 ± 0.01	2.92	0.04*
Mercury (mg/L)	<0.001	0.001 ± 5.27E-05	13.17	9.4e-04*
Total alkalinity (TA) (µmol/kg)	911.79 ± 27.80	1115.32 ± 104.69	3.27	0.05*

Total carbon dioxide (TCO_2),	753.27 ± 44.00	1080.00 ± 118.45	1.09	0.01*
Carbon dioxide fugacity ($fC0_2$)	178.47 ± 11.23	2956.37 ± 72.97	2.11	0.04*
Bicarbonates ($HC0_3$) (µmol/kgSW)	668.74 ± 234.85	926.82 ± 27.25	2.85	0.07
Revelle factor	2.19 ± 0.86	3.27 ± 2.29	1.70	0.11
Carbonates ($C0_3$) (µmol/kg SW)	79.98 ± 30.74	65.11 ± 12.94	2.85	0.06
Hydroxyl ions (OH) (µmol/kgSW)	4.55 ± 1.89	6.70 ± 1.37	2.41	0.10
Buffer alkalinity (BalK) (µmol/kg SW)	68.91 ± 10.85	36.46 ± 3.73	6.34	7.91e-03
Mineral saturation states for aragonite (ΏAr)	1.41 ± 0.55	1.17 ± 0.22	2.56	0.08
Mineral saturation states for calcite (Ώcalcite)	2.19 ± 0.86	2.01 ± 848.03	2.55	0.08

Lead (mg/L)	0.05 ± 0.01	0.03 ± 0.01	2.50	0.05*
Cadmium (mg/L)	0.04 ± 0.01	0.05 ± 0.01	2.92	0.04*
Mercury (mg/L)	<0.001	0.001 ± 5.27E-05	13.17	9.4e-04*
Total alkalinity (TA) (µmol/kg)	911.79 ± 27.80	1115.32 ± 104.69	3.27	0.05*
Total carbon dioxide (TCO_2),	753.27 ± 44.00	1080.00 ± 118.45	1.09	0.01*
Carbon dioxide fugacity ($fC0_2$)	178.47 ± 11.23	2956.37 ± 72.97	2.11	0.04*
Bicarbonates ($HC0_3$) (µmol/kgSW)	668.74 ± 234.85	926.82 ± 27.25	2.85	0.07
Revelle factor	2.19 ± 0.86	3.27 ± 2.29	1.70	0.11
Carbonates ($C0_3$) (µmol/kg SW)	79.98 ± 30.74	65.11 ± 12.94	2.85	0.06
Hydroxyl ions (OH) (µmol/kgSW)	4.55 ± 1.89	6.70 ± 1.37	2.41	0.10
Buffer alkalinity (BalK) (µmol/kg SW)	68.91 ± 10.85	36.46 ± 3.73	6.34	7.91e-03
Mineral saturation states for aragonite (ΏAr)	1.41 ± 0.55	1.17 ± 0.22	2.56	0.08

Mineral saturation states for calcite	2.19 ± 0.86	2.01 ± 848.03	2.55	0.08

± Shows standard error of means; '*t*' is the t value of Wilcoxon rank sum test and p is the significant level of 0.05 Asterix on the p value shows p < 0.05 thus significant difference from one another.

4.3.3 Tidal Influences on Physicochemical Parameters

Table 4.4 shows the results of the Welch *t* test on variations in water quality parameters at low and high tides. Water depth, *E coli* and revelle factor were significantly higher ($p < 0.05$) at high tide than low tide. Mean water depth was 0.71 ± 0.05 m at high tide and 0.14 ± 0.06 m at low tide. The levels of *E coli* at high and low tide were 22.23 ± 3.43CFU/ ml and 11.83 ± 1.81CFU/ ml respectively. Revelle factor was 11.79 ± 1.13 at high tide and 9.07 ± 1.28 at low tide. Conversely, mean silicates level was significantly higher ($p < 0.05$) at low tide (15.37 ± 3.08 mg/L) than at high tide (8.21 ± 2.00 mg/L).

Mean water temperature, dissolved oxygen, Chlorophyll a, conductivity, salinity, total dissolved substances, pH, total viable counts, faecal coliform, arsenic, lead, cadmium, mercury, aragonite, calcite, total alkalinity, total carbon dioxide, fugacity carbon dioxide, bicarbonates, carbonates, carbon dioxide, buffer alkalinity, silica alkalinity and hydroxyl ions did not show any significant differences ($p > 0.05$) during tidal changes.

At hightide, mean water temperature was 28.61 ± 0.72^{O}C, Total Dissolved Substances 63003.66 ± 3.21 mg/L, Salinity 20.81 ± 3.70ppt, dissolved oxygen 4.95 ± 2.23mg/L, pH 8.15 ± 0.17, conductivity 363.79 ± 100.01 µs/cm, chlorophyll a 5.82 ± 2.00, total viable counts 75.56 ± 3.42CFU/ ml, and faecal coliform 17.22 ± 2.42CFU/ ml. Among the metals, arsenic was 0.05 ± 0.03 mg/L, lead 0.04 ± 0.01 mg/L, cadmium 0.05 ± 0.01mg/L and mercury <0.001mg/L.

The values of the estuarine acidification factors were, total alkalinity 955.25 ± 116.95 µmol/kg, total carbon dioxide 846.73 ± 111.57, carbon dioxide fugacity 1657.67 ± 98.23, bicarbonates 931.89 ± 119.77 µmol/kgSW, carbonates 84.69 ± 12.69 µmol/kgSW, carbon dioxide 6.30 ± 0.93, aragonite 1.51 ±0.32, calcite 2.47 ± 0.48, buffer alkalinity 32.57 ± 10.60, $XC0_2$ 226.99 ± 34.87, silica alkalinity 4.69 ± 1.01, revelle factor 11.79 ± 1.13 and hydroxyl ions 7.13 ± 1.99.

Table 4.4: Tidal Variations in Physicochemical Parameters of Densu estuary for the Study Period 2019-2020

	Range		Mean ± S. E				
Parameter	**High Tide**	**Low Tide**	**Overall mean**	**High Tide**	**Low Tide**	***tt***	***p***
Temperature (^{O}C)	24.04-30.96	26.00-34.74	28.83 ± 6.43	28.61 ± 072	29.05 ± 0.95	-0.37	0.71
Depth (m)	0.54-1.00	0.17-0.65	0.61 ± 0.07	0.71 ± 0.05	0.14 ± 0.06	2.97	0.01*
Total Dissolved Substances(mg/L)	468.00-8801.00	51.40-3080.00	3550.58 ± 790.24	63003.66± 321.00	4461.20 ± 211.00	-0.16	0.88
Salinity (ppt)	0.510-35.11	0.36-23.50	16.41 ± 3.65	20.81 ±3.70	12.01± 2.79	1.89	0.08
Dissolved Oxygen (mg/L)	2.19-8.94	1.85-24.27	6.09 ± 1.36	4.95 ± 2.23	7.23± 2.23	-0.98	0.35
pH	7.50-9.47	7.43-9.18	8.07 ± 1.80	8.15 ± 0.53	7.98 ± 0.17	0.66	0.52
Conductivity (µs/cm)	18.75-1666.72	1.92-2867.67	453.14 ± 94.27	363.79 ± 101.21	542.49 ± 112.01	-0.49	0.64
Silicates (mg/L)	3.00-17.70	8.00-19.90	11.79 ± 3.65	8.21 ± 2.00	15.37 ± 3.08	-2.29	0.04*
Chlorophyll a	1.26-11.49	2.19-3.78	4.45 ± 1.04	5.82 ± 1.83	3.07 ± 0.38	1.46	0.18

Total Viable Counts (CFU/ml)	41.00-98.00	19.00-99.00	64.36 ± 10.58	75.56 ± 3.42	53.17 ± 3.62	1.87	0.08

Table 4.4 cont'd: Tidal variation in Physicochemical Parameters of the Densu estuary

Parameter	Range		Mean			*t*	*p*
	High Tide	Low Tide	Overall mean	High Tide	Low Tide		
Escherichia coli (CFU/ml)	0.00-50.00	0.00-28.00	17.08 ± 2.81	22.33 ± 3.43	11.83 ± 1.81	3.39	0.01*
Arsenic (mg/L)	0.001-0.083	0.001-0.088	0.05 ± 0.01	0.05 ± 0.03	0.04 ± 0.02		
Lead (mg/L)	< 0.0001-0.068	<0.0001-0.032	0.03 ± 0.01	0.04 ± 0.01	0.01 ± 0.009	1.69	0.12
Cadmium (mg/L)	0.051-0.062	0.043-0.088	0.05 ± 0.01	0.042 ± 0.01	0.06 ± 0.02	-1.20	0.26
Mercury (mg/L)	<0.001	< 0.001	< 0.001	< 0.001	< 0.001		
Total alkalinity (µmol/kg)	99.91 -1508	509.54-1511.01	936.42 ± 104.61	955.25 ± 116.95	527.82 ± 26.3	-0.06	0.95
Total carbon dioxide (TCO_2),	67.53 – 2052.73	305.94-1334.51	834.62 ± 111.57	846.73 ± 128.70	471.72 ± 19.90		
Carbon dioxide fugacity ($fC0_2$)	-14.46-18894.27	57.92-528.27	1657.67 ± 948.23	2003.59 ± 115.08	195.77 ± 21.88		
Bicarbonates	-2.59-98353	447.47-1297.32	749.69 ± 155.59	931.89 ± 119.77	840.79 ± 104.75	-0.93	0.38
Carbonates	-0.37-117.35	22.26-147.78	63.59 ± 21.26	84.69 ± 17.59	74.14 ± 12.69	-0.76	0.46
Carbon dioxide	-0.01-613.93	3.14-8.57	106.71 ± 101.45	6.30 ± 0.93	56.50 ± 7.24	0.99	0.37
Buffer alkalinity	0.96-90.22	2.26-8.07	61.98 ± 14.58	32.57 ± 10.60	47.28 ± 9.04	1.64	0.14

Aragonite	-0.01-2.01	0.39-2.65	1.07 ± 0.36	1.51 ± 0.32	1.29 ± 0.22	-0.91	0.39
Calcite	-0.01-2.75	0.68-4.11	1.63 ± 0.53	2.47 ± 0.48	2.05 ± 0.34		
Hyxroxyl ions	0.07-13.02	3.31-16.69	7.59 ± 1.88	7.13 ± 1.99	7.35 ± 1.24	0.17	0.87

± Implies standard error of means; '*t*' is Wilcoxon rank sum **t** test value, p is the significant level of 0.05, Asterix on the p value shows $p < 0.05$ thus significant difference from one another.

At low tide, mean water temperature was 29.05 ± 0.95, total dissolved substances, salinity, dissolved oxygen, pH, conductivity, chlorophyll a, total viable counts, and faecal coliform were 4461.20 ± 211 mg/L, 12.01± 2.79ppt, 7.23± 2.23 mg/L, 7.98 ± 0.17, 542.49 ± 112.01 µs/cm, 3.07 ± 0.38, 53.17 ± 3.62 CFU/ml, and 28.56 ± 3.46 CFU/ml respectively.

Among the metals, the monthly concentrations of arsenic was 0.04 ± 0.02 mg/L, Lead 0.01± 0.009 mg/L, cadmium 0.06 ± 0.02 mg/L and mercury was <0.001 mg/L. The variations in estuarine acidification factors were, total alkalinity 527.82 ± 26.3 µmol/kg, total carbon dioxide 471.72 ± 19.90, carbon dioxide fugacity 195.77 ± 21.88, bicarbonates 840.79 ± 104.75 µmol/kgSW, carbonates 74.14 ± 12.69 µmol/kgSW, carbon dioxide 56.50 ± 7.24, aragonite 1.29 ± 0.22, calcite 2.05 ± 0.34, buffer alkalinity 47.28 ± 9.04 µmol/kgSW, $XC0_2$ 2111.18 ± 76.45, silica alkalinity 3.85 ± 0.84 µmol/kgSW, revelle factor 9.07 ± 1.28 and hydroxyl ions 7.35 ± 1.24.

4.4.4 Relationship between Physico-Chemical Factors, Relative Abundance and Morphological Characteristics of the West African Mangrove Oyster

The focus of the CCA was to relate environmental data with biological data with no emphasis on stations (Fig 4.2).

The output of the canonical correspondence analysis is shown in Table 4.5. The overall inertia or variance (in abundance and size) in data set, was 0.17007. The variance explained by the environmental variables (gradients matrix) was 0.14836 (87.2%). The variance in unexplained (unconstrained) was 0.02172 (%) .

The "Proportion" values represent the percentages of variance in biological data explained by Constrained (environmental) and Unconstrained variables.

Table 4.5: Constrained and Unconstrained Variance Output

	Inertia	Proportion	Rank
Total	0.17007	1.00000	
Constrained	0.14836	0.87231	5
Unconstrained	0.02172	0.12769	3
Inertia is scaled Chi-square			

In Table 4.6 the first two axes (CCA1 = 0.12007; 80.9% and CCA2 = 0.02486;16.75%) of the CCA ordination analysis accounted for 97.5% variances in oyster size and abundance in relation to the predictive variables.

Table 4.6: Eigenvalues for Constrained and Unconstrained Axes

Axes/Eigen values	Constrained					Unconstrained		
Axes	CCA1	CCA2	CCA3	CCA4	CCA5	CA1	CA2	CA3
Eigen	0.12007	0.02486	0.00318	0.00017	0.00007	0.013394	0.007496	0.000827

Table 4 .6 shows result of the permutation tests (ANOVA) for determining significant differences in CCA model, the CCA terms (environmental variables), and CCA axes in explaining more variance of size and abundance (observations) matrix than expected by chance is shown in Table 4.7. There was significant difference in the model (p = 0.05). Among the terms, the influence of total alkalinity in the total variance in oyster size and abundance was significant (p = 0.004). The first axes

(CCA1) significantly (p = 0.0048) contributed to the variance in biological data.

Table 4.7: ANOVA Summary of the CCA Model

Df	Chi Square	F	Pr (>F)	
Model	6	0.148356	3.4157	0.051
Residual	3	0.021717		
Signif. codes:	0 '***'	0.001 '**'	0.01 '*'	0.05 '.' 0.1 ' ' 1

Model: cca (formula = spe ~ Temp + Fc + Ta + Tco + Fco + Ar, data = env)

Table 4.8: ANOVA summary of the Canonical Correspondence Analysis (CCA)

Terms	Df	ChiSquare	F	Pr (>F)
Temperature (Temp)	1	0.024412	3.3723	0.103
Faecal coliform (fc)	1	0.002739	0.3783	0.679
Total alkalinity (Ta)	1	0.093444	12.9085	0.004 **
Total carbon dioxide (Tco)	1	0.004498	0.6214	0.535
Fugacity carbon dioxide (Fco)	1	0.014114	1.9497	0.208
Aragonite (Ar)	1	0.009150	1.2640	0.305
Residual	3	0.021717		
Number of permutations:		999		

* Denote significant difference at p<0.05; where fc=faecal coliform, Ta=Total alkalinity, Tc0= Total carbon dioxide, carbon dioxide fugacity and Ar= saturation state of aragonite

Table 4.9: ANOVA Summary of the Canonical Correspondence Analysis Axes

Axis	Df	ChiSquare	F	Pr(>F)
CCA1	1	0.120074	22.1164	0.048 *
CCA2	1	0.024865	4.5798	0.570
CCA3	1	0.003179	0.5856	0.999
CCA4	1	0.000171	0.0314	1.000
CCA5	1	0.000067	0.0124	1.000
Residual	4	0.021717		

From Figure 4.2, faecal coliform, carbon dioxidefugacity and Temperature collectively influenced Shell width and Shell length. Total alakalinity of the Densu estuarine water influenced shell height, condition factor and shell width whereas, total carbon dioxide and Aragonite affected CPUE.

Using CCA 1, the coefficient of total alkalinity (ta), faecal coliform (Fc), Carbon dioxide Fugacity (Fco) and Temperature (Temp) were -0.656, -0.344, -0.138 and -0.246 respectively, While, the coefficients of total carbon dioxide (Tco) and aragonite (Ar) were 0.654 and 0.210 (Table 4.10). Similarly, Shell weight, condition factor, shell height, shell length and shell width recorded coefficient values of -0.174g, 0.150, -0.172cm, -0.107cm and -0.042cm respectively. The coefficient value of relative abundance (CPUE) was 0.234. The positive coefficient value indicates an increasing gradient while a negative coefficient shows a declining gradient (Table 4.10). This implies that decreases in faecal coliform, carbon dioxide fugacity and temperature resulted in declining shell width and shell length.

A decline in total alkalinity yielded a reduction in shell height, condition factor and shell width. However, increasing total carbon dioxide and aragonite leads to an increase in Catch Per Unit Effort.

Table 4.10: Eigen Values of Variables and Axis Generated from CCA

Variables	Axis 1	Axis 2	Axis 3	Axis 4	Axis 5
Sw	-0.174	-0.153	0.107	-0.012	0.038
Sh	-0.172	0.020	0.076	-0.050	-0.017
Sl	-0.107	-0.098	0.070	0.056	-0.020
Swt	-0.042	0.144	0.044	0.018	0.008
Cf	-0.150	-0.007	-0.046	0.000	0.001
Cpue	0.234	-0.012	-0.004	-0.003	0.000
denst1	0.826	-1.330	3.567	0.248	-5.977
denst2	-1.356	-1.039	-3.248	-0.339	-1.381
denst3	-0.155	-0.847	-0.582	-1.692	-5.825
denst4	-2.333	0.787	1.059	-0.761	1.768
denst5	0.268	4.246	1.549	4.129	7.337
denst6	1.674	-0.651	-1.188	-2.493	-2.122
denst7	0.088	1.196	-2.098	0.526	2.528
denst8	0.326	-2.156	0.381	0.141	2.804
denst9	0.087	-0.837	0.099	1.678	1.054
denst10	-0.432	-0.376	2.306	-2.091	-2.840
Temp	-0.246	-0.346	-0.380	-0.374	-0.185
Fc	-0.344	-0.265	0.058	-0.413	-0.140
Ta	-0.656	0.286	-0.260	0.126	0.072
Tco	0.054	0.092	0.049	-0.428	-0.345
Fco	-0.138	-0.305	-0.247	0.029	-0.269
Ar	0.210	0.179	-0.375	-0.169	-0.181

Where sw = shellwidth, sh = shell height, sl = shell length, swt=shell weight, cf = condition index, cpue = catch per unit effort, denst = Densu stations; Temp = temperature, Fc = faecal coliform, Ta=total alkalinity, Tc0=total carbon dioxide, carbon dioxide fugacity, ar= saturation state of aragonite.

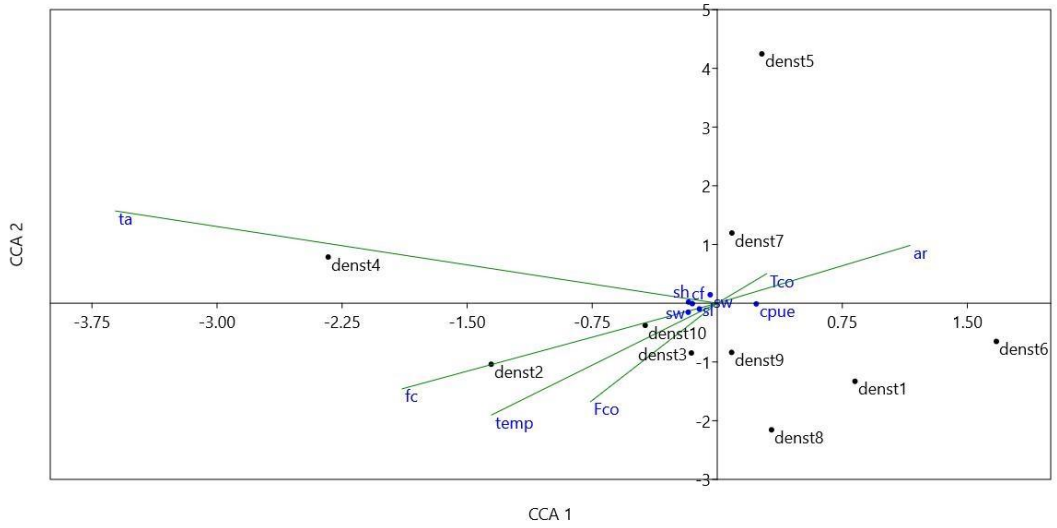


Figure 4.2: Canonical Correspondence Analysis Ordination Plot Relating Oyster Abundance and Morphological Features with Physico-Chemical Factors of the Densu estuary Estuary, Ghana (2019-2020)

4.4.5 Results on Multiple Linear Regression Models on Factors Influencing *C. tulipa* Size and Abundance

Models were developed to ascertain the influence of predictor variables obtained from the CCA model on size and relative abundance of the West African Oyster in Densu estuary.

Variations in size, abundance and condition index of C. *tulipa* is shown in Table 4.11.

Table 4.11: Descriptive Statistics of Biological Parameters of the Mangrove Oyster in Densu

Biological parameter	Range	Mean ± S. E
Shell Width (cm)	1.00-3.00	3.53 ± 0.178
Shell Height (cm)	3.44-8.24	6.11 ± 0.28
Shell Weight (g)	7.70 -66.70	19.17 ± 4.16
Shell Length (cm)	2.24-5.13	2.24 ± 5.13
Relative Abundance (CPUE)	15.00-500.00	15.00-500.00
Condition factor	30.00-300.00	30.00-300.00

SE denotes standard error of means

4.4.5.1 Predictive Shell Height Model

The selection approach to determine the relationship between shell height and Physicochemical Parameters were done using the AIC method in R (Table 4.12 & 4.13). The predictor variables that significantly explained shell height were total carbon dioxide and carbon dioxide fugacity (Table 4.14).

Table 4.12: Model Selection from the Akaike Information Criterion (AIC) for Predicting Shell Height of *C. tulipa* In Densu estuary (2019,2020)

Model Identifier	Models	AIC
Mod1	lm(h~temp+ta+fc+tc02+fc02+ar)	71.35277
Mod2	lm(h~temp+fc+tc02+fc02)	69.66195
Mod3	lm(h~temp+fc)	77.32984
Mod4	lm(h~temp)	80.17471

*Definition of abbreviations: h=shell height, temp= Temperature, FC=faecal coliform, $tc0_2$= Total carbon dioxide, AIC= Akaike Information Criterion

Table 4.13: Model Summary Relating Shell Height and Physicochemical Parameters of the Densu estuary(2019,2020)

Model	R	R square	Adjusted R squared	Std Error of the estimates	*P* value
2		0.5226	0.465	0.4102	0.01015

Table 4.14: Regression between Predictor Variables and Shell Height in Densu (2019, 2020)

Model	Coefficients Estimate	Std error	*t*	significant	95% Confidence Interval	
					Lower Bound	Upper Bound
Intercept	-1.106e+01	4.223e+00	2.618	0.0342	1.9975	0.02024
Temperature	-1.893e-01	1.394e-01	-1.358	0.1921	-0.4880	0.1141
faecal coliform	-6.673e-02	7.378e-04	-3.308	0.004159*	-0.1094	-0.02026
Total carbon dioxide	2.933e-03	7.378e-04	3.976	0.000978*	0.0014	0.0050
Carbon dioxide fugacity	-2.556e-04	8.343e-05	-3.063	0.007042*	-0.00048	-8.0281e05

*Indicates significant at $p < 0.05$

In Table 4.13, model 2 significantly ($p = 0.01015$) best describes the relationship from the AIC (69.66). As faecal coliform increases by one coliform forming unit, shell height of the West African Mangrove Oyster decreases by 0.006.673 cm.

For every one unit rise in total carbon dioxide and carbon dioxide fugacity, shell height increases by 0.0029933 cm and decreases by 0.0002556 cm respectively (Table 4.14).

The coefficient of determination, R^2, of the predictor variables, faecal coliform, total carbon dioxide and carbon dioxide fugacity against shell height was 0.5226 indicates that 52.26% of the variations in shell height was explained by faecal coliform bacteria, total carbon dioxide and carbon dioxide fugacity (Table 4.13). Thus, knowing faecal coliform, total carbon dioxide and carbon dioxide fugacity, shell height of the West African oyster of the Densu population in Ghana could be predicted. The regression model to ascertain shell height was represented as follows:

Shell Height = -0.006.673 Faecal coliform - 0.002933 Total carbon dioxide - 0.0002556 carbon dioxide fugacity

The model could best be generalised from the adjusted R^2 value of 0.4102, which is close to the R^2 value of 0.5226. Therefore, if the model were derived from the population rather than a sample it would account for approximately 11.24% less variance in the outcome.

4.4.5.2 Predictive Shell Width Model

Table 4.15 shows the AIC selection of the model that best describes the relationship between shell width with Physicochemical Parameters.

Model 2 significantly (p = 0.024) best describes the relationship from the AIC (28.78). The significant predictor variables of shell width are faecal coliform, total carbon dioxide and carbon dioxide fugacity (Table 4.16). As faecal coliform increases by one coliform forming unit, shell width of *C. tulipa* decreases by 0.02cm.

For every one unit rise in total carbon dioxide and carbon dioxide fugacity, shell width increases by 0.00089 cm and decreases by 7.221e-05 cm respectively (Table 4.17).

The coefficient of determination, R^2, of the predictor variables, faecal coliform, total carbon dioxide and carbon dioxide fugacity against shell width was 0.4102 which shows that 41.02% of the variations in shell width was explained by faecal coliform bacteria, total carbon dioxide and carbon dioxide fugacity (Table 4.16).

The best, most prudent simple regression model for prediction of shell width was represented as follows:

Shell Width = -0.02262 faecal coliform + 0.00089 Total carbon dioxide - 0.0000722 Carbon dioxide fugacity (Table 4.17).

Table 4.15: Model Selection from the Akaike Information Criterion (AIC) for Predicting Shell Width of *C. tulipa* in Densu estuary (2019, 2020)

Model Identifier	Models	AIC
Mod1	lm(swd~temp+ta+fc+tc02+ar)	30.77034
Mod2	lm(swd~temp+fc+tc02)	28.78512
Mod3	lm(swd~temp+fc)	32.25880
Mod4	lm(swd~temp)	34.63023

Table 4.16: Model Summary of Shell Width and Physicochemical Parameters

Model	R Square	Adjusted R squared	Std Error of the estimates	*P* value
2	0.4102	0.3225	0.4031	0.02476

Table 4.17: Regression Analyses

Model	Coefficients Estimate	Std Error	Std	T	significant
Intercept	-4.586	e-01	1.668e+00	-0.275	0.78668
Temperature	6.608	e-02	5.504e-02	1.201	0.24637
Faecal coliform	-2.262	e-02	7.967e-03	-2.840	0.01132*
Total carbon dioxide	8.911	e-04	2.914e-04	3.058	0.00711*
Carbon dioxide fugacity	-7.221	e-05	3.295e-05	-2.191	0.0426 *

The model could best be generalised from the adjusted R^2 value of 0.3225, which is close to the R^2 value of 0.4102. Therefore, if the model were derived from the population rather than a sample it would account for approximately 8.77% less variance in the outcome (Table 4.16).

4.4.5.3 Predictive Condition Factor (CF) Model

Table 4.17 shows the AIC selection of the suitable model describing the relationship between condition factor with Physicochemical Parameters. The appropriate Model which significantly (p = 0.0112; AIC =248.0812) describes the relationship is model 1 (Table 4.17). The significant (p = 0.0198) predictor variable of condition factor is saturation state of aragonite (Table 4.8). As aragonite content increases by one unit, the tissue fatness of *C. tulipa* increases by 65.646 cm.

The coefficient of determination, R^2, of the predictor variable, aragonite against condition factor was 0.5743. This implies, 57.43% of the variations in condition factor was explained by aragonite content.

The best, simple regression model to predict condition factor was shown as follows:

Condition Factor = 65.646 Aragonite

The model could best be generalised from the adjusted R^2 value of 0.4412 which is close to the R^2 value of 0.5743. Therefore, if the model were derived from the population rather than a sample it would account for approximately 13.31% less variance in the outcome (Table 4.19).

Table 4.18: Model Selection from the Akaike Information Criterion (AIC) for Predicting Condition Factor of *C. tulipa* in Densu estuary (2019, 2020)

Model Identifier	Models	AIC
Mod1	lm(cf~temp+fc+ta+tc02+ar)	248.0812
Mod2	lm(cf~temp+fc+tc02)	253.7784
Mod3	lm(cf~temp+fc)	252.3816
Mod4	lm(cf~temp)	253.2515

Table 4.19: Model Summary of the Relationship between Condition Factor and Physicochemical Parameters

Model	R	R square	Adjusted R squared	Std Error of the estimates	*P* value
1		0.5743	0.4412	57.99	0.0112

		squared	the estimates	
1	0.5743	0.4412	57.99	0.0112

Table 4.20: Regression between Predictor Variables and Condition Index of *C.tulipa* in Densu (2019-2020)

Model	Estimate Std error	efficients	*T*	significant	95% confidence interval Lower	Upper
Intercept	446.98806	296.11	1.510	0.1507	-1.807302e+02	1.074706e+03
Temperature	-11.897362	9.01336	-1.218	0.2409	-3.507936e+01	8.8124e+00
faecal coliform	-0.995789	1.185028	-0.840	0.4131	-3.50796e+00	8.652665e-02
Total carbon dioxide	-0.041766	0.060518	--0.690	0.5000	-1.700584e-01	8.652665e-02
Carbon dioxide fugacity	0.010500	0.007269	1.445	0.1679	-4.909338e-03	2.590994e-02
Aragonite	65.645480	25.357016	25.36	0.0198 *	1.189101e+01	1.194000e+02

*indicates significant at p<0.05

4.4.5.4 Predictive Relative Abundance (Catch Per Unit Effort) Model

The AIC selection of Model 3 describing the relationship between relative abundance with Physicochemical Parameters is illustrated in Table 4.10.

The relationship between relative abundance with Physicochemical Parameters is insignificant (p = 0.1342) (Table 4.21). The significant (p = 0.0345) predictor variable of CPUE is temperature (Table 4.22). As surface water temperature increases by one unit, the CPUE of *C. tulipa* decreases by 35.5197 (Kg/hr/fisher/day). The coefficient of determination, R^2, of temperature as a predictor variable against relative abundance was 0.2605. This signifies that 26.05% of the variations in abundance was explained by temperature. And the remaining 73.05% not accounted for (Table 4.21).

The simple regression predictive model for CPUE was described as follows:

Catch Per Unit Effort = - 35.51973 Surface Water Temperature

The model can best be generalised from the adjusted R^2 value of 0.1372 which is close to the R^2 value of 0.2605. Therefore, if the model were derived from the population rather than a sample it would account for approximately 12.33% less variance in the outcome (Table 4.21).

Table 4.21: Model Selection Using the Akaike Information Criterion

Model Identifier	Models	AIC
Mod1	lm(cpue~temp+ta+fc+tc02+ar)	278.6818
Mod2	lm(cpue~temp+fc+tc02)	277.7810
Mod3	lm(cpue~temp+fc)	276.3143
Mod4	lm(cpue~temp)	276.4321

Table 4.22: Summary of The Model Relating CPUE and Physicochemical Parameters of the Densu estuary

Table 4.23 Regression between Predictor Variables and Relative Abundance in Densu

Model	Coefficients Estimate	Std error	*t*	significant	95% confidence interval Lower	upper
Intercept	1166.77527	470.10729	2.482	0.0232 *	179.11649	2154.43
temperature	-35.51973	15.52782	-2.287	0.0345 *	-68.1424	-2.8969
Fecal coliform	-2.35879	1.98033	-1.191	0.2491	-6.5193	1.801
Total carbon dioxide	0.06490	0.04812	1.349	0.1942	-0.0361	0.16599

Model	R	R square	Adjusted R squared	Std Error of the estimates	P value
3	0.2605	0.1372	0.1342	113.7	

4.4.5.5 Predictive Shell Weight Model

The Akaike Information Criterion (AIC) selection of the best model (Mod 3) describing the relationship between shell weight with Physicochemical Parameters is showm in Table 4.24. The relationship between shell weight and Physicochemical Parameters is insignificant (p = 0.1168) (Table 4.25). There was no significant (p > 0.05) predictor variable (Table 4.25).

Table 4.24 The Akaike Information Criterion Selection of Best Model to predict shell weight of *C tulipa* in the Densu estaury

Model Identifier	Models	AIC
Mod1	lm(swt~temp+ta+fc02+ fc+tc02+ar)	199.6225
Mod2	lm(swt~temp+fc+tc02)	197.7159
Mod3	lm(swt~temp+fc)	196.0951
Mod4	lm(swt~temp)	198.0365

Temp=temperature; ta=total alkalinity, carbon dioxide fugacity; fc=faecal coliform; tco2=total carbon dioxide; ar=aragonite

Table 4.25 Model Summary

Model	R	R square	Adjusted R squared	Std Error of the estimates	*P* value
3		0.2732	0.1521	18.37	0.1168

Table 4.26 Regression between Predictor Variables and Shell Weight in Densu (2019-2020)

Model	Coefficients		*t*	significant	Lower	upper
	Estimate	Std error				
Intercept	140.0743356	75.928982	1.845	0.0816	-19.4465	299.595
Temperature	-4.546385	2.507963	-1.813	0.0866	-9.8154	0.72264
faecal coliform	-0.159612	0.319852	-0.499	0.6238	-0.8315	0.5123
Total carbon dioxide	0.014606	0.007772	1.879	0.0765	-0.00172278	0.0309

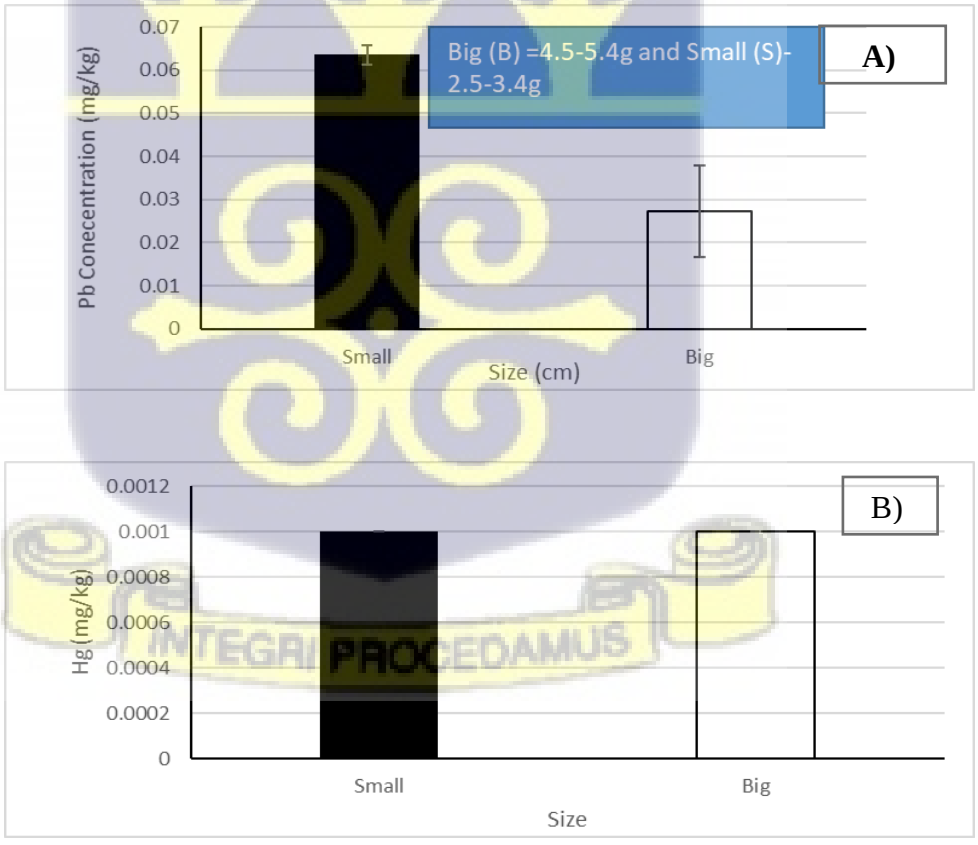
*Denotes significant at $p < 0.05$

4.4.6 Relationship between size of West African Mangrove Oyster and Concentration of Contaminants

This section highlights the ability of *C. tulipa* to bio accumulate contaminants in the Densu estuary estuarine environment for its use as a bio indicator of environmental changes

4.4.6.1 Trace Metals

Figure 4.3 shows the mean concentrations of trace metals in different sizes of *C. tulipa*. Small-sized oyster (2.5-3.5g) tissues significantly ($p < 0.05$) bio accumulated Pb?? and Cd than big- sized (4.5-5.4g) tissues (Table 4.27). However, Hg concentrations in small tissues was not significantly different ($p = 0.50$) from big oyster tissues.



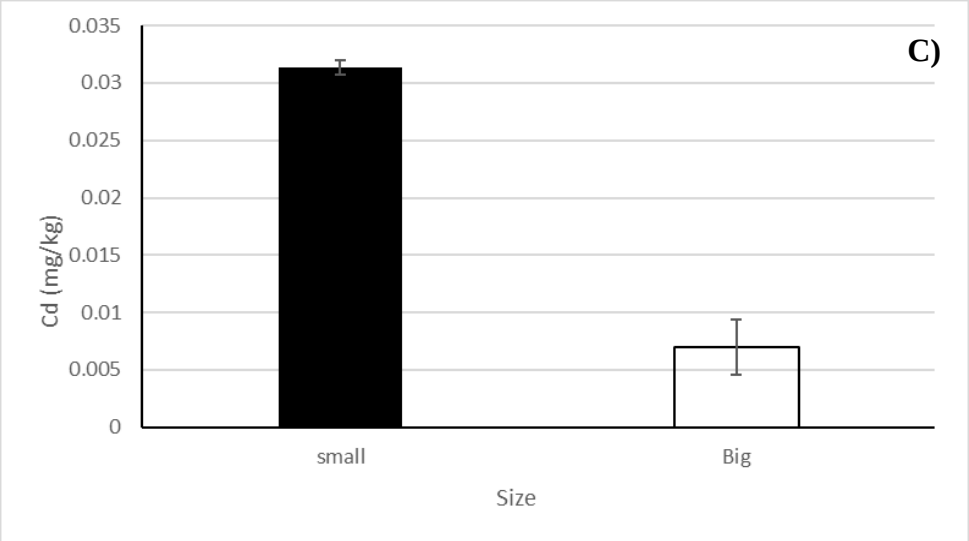


Figure 4.3 Mean concentration of A) pb B) Hg and C) Cd in C. tulipa tissues in Densu estuary (2019-2020) (Error bars = standard error of means)

Table 4.27: Mean Concentration of Trace Metals in Tissues of *C. tulipa* in Densu estuary

Trace metal	Average Concentration		Mean ± S. E			
	Small	**Big**	**Small**	**Big**	***T***	***p***
pb	0.06 -0.07	0.008-0.01	0.06 ± 02.2-e3	0.02 ± 0.01	-1.22	0.02
Hg	<0.001	<0.001	<0.01	< 0.01	0.23	0.81
Cd	0.004-0.006	0.003-0.082	0.005 ± 0.0006	0.032 ± 0.002	-2.18	0.01

Small= sizes ranging from 2.5kg-3.4g and Big = 4.5-5.4g (FAO, 1998); S.E indicates standard error of means

4.4.6.1 Bioaccumulation of Trace Metals and Health Risk Assessment

Lead and mercury bio accumulated in *C. tulipa* tissues more (BAF > 1) than in the water medium (Table 4.28). Cadmium concentration was more in water than was bio accumulated in the tissues (BAF <1) (Table 4.28). The concentrations of the three metals showed no potential health hazards (THQ <1; HI<1). The cancer risk limit for lead was 0.082 and the cancer risk for a lifetime is 5.11×10^{-5}.

Similarly, the total count of aerobic mesophiles (TVC), *faecal coliform* and *Escherichia coli* bio accumulated more (BAF>1) in tissues than in the estuarine water (Figure 4.4). The BAFs of total count of aerobic mesophiles, *faecal coliform* and *Escherichia coli* were 12.81, 34.20 and 26.19 (Table 4.4).

Table 4.28: Bio indicator and Health Risk Assessment Indices of *C. tulipa* in Densu estuary in Ghana (2019-2020)

Trace Metal	BAF (kg/L)	Target hazard Quoefficient	HI	CR	CRlim
Lead (pb)	1.50*		0.024	5.11 × 10-5	0.082
Mercury (Hg)	20.77*	0.06			
Cadmium (Cd)	0.36	0.003			
		3.99045E-05			

Asterix indicates BAF values > 1 indicate that the accumulation in the organism is > the medium

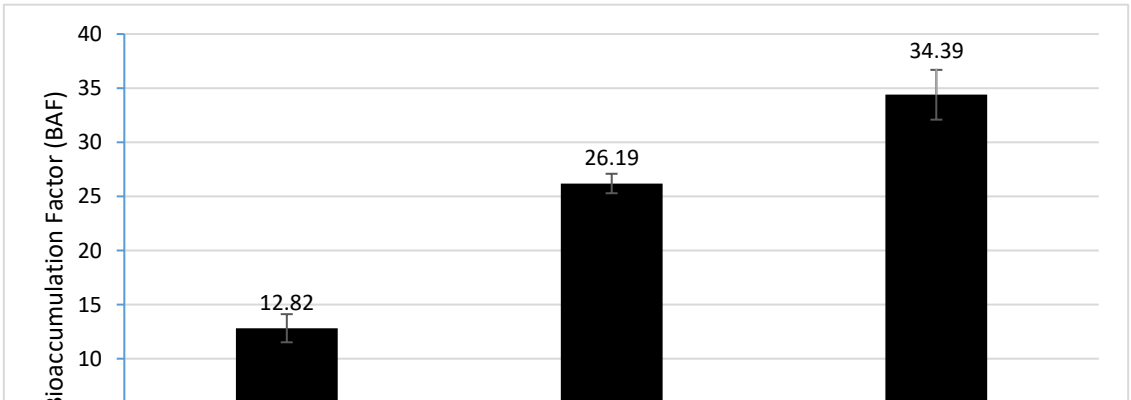


Figure 4.4: Bio accumulation Factors of Microbial Contaminants in C. tulipa, Densu estuary (2019-2020)

Figure 4.4 illustrates the bio-accumulation factor of faecal coliform, *Escherichia coli* bacteria and Total viable counts studied. *C. tulipa* tissues bio accumulates these contaminants in its tissues more than the water medium (BAF >1).

4.4. Discussions

4.4.1 Monthly Variations in Physicochemical Parameters

Table 4.2 shows monthly changes in physico-chemical parameters of the Densu estuary. Monthly water temperature ranged between 24.04-34.74 ^{O}C with a mean value of 28.83 ± 6.43 ^{O}C.

The monthly variations in temperature (24.04-34.74 ^{O}C) in Densu is similar to what was recorded in Pra (27-32 ^{O}C) and Benya (27-32) by Obodai et al. (1996) and Butuah (32.9 ^{O}C) estuary by Okyere et al. (2011) in Ghana. The slightly higher temperature in this study may be possibly due to the time of sampling, shallow water depth, low water volume and freshwater input from land drainage. Considering the range in depth of about 0.54-1.00 m, the Densu estuary estuary can be classified as a shallow system. Due to its shallowness, there is much absorption of sunlight deep to bottom waters thereby could explain the higher temperatures observed in this study. Earlier studies on the

Densu estuaryic system by Biney (1990) showed a range in temperature from between 27-33 ^{O}C and 26-33 ^{O}C by Enstuah-Mensah (1998) and a depth of 0.4-4.8 m and 0.8-3.8 m respectively. The decline in depth in recent times according to Atindana et al. (2016) could be a resultant effect of siltation.

In this study, the neutral to slightly basic (7.43-9.47) Densu estuarine water had total dissolved substances and dissolved oxygen levels ranging between 51.40-8801 mg/L and 1.85-24.27 mg/L respectively. In 1990, Biney observed dissolved oxygen levels of between 3.5-8.4mg/L while in 1998, Entua Mensah reported values between 3.0-8.4 mg/L. Denuitsui et al. (2011) recorded a pH of 7.5 and a TDS of 80-1750 mg/L.

The relatively more oxygenated water and higher pH levels in this study, suggests the occurrence of natural processes such as wind mixing and less decomposition activities in regulating these factors. The pH regime falls within the designed range of 6.5-9.4 for brackish systems by WHO (2007) and also the acceptable limits for growth and survival of oysters. However human activities that may likely alter the pH of the water need to be controlled. According to NERR (1997), in tropical estuaries, pH remains fairly constant because dissolved carbonate ions present in seawater tend to minimize or buffer pH changes by reacting with the ions that alter pH. The range and mean carbonate ions in the Densu estuary fell between -12.75-183.55 (70.62 ±16.20).

The mean TDS of Densu estuary estuary was 80-1750 mg/L and therefore comparable to that reported by WHO (Ref. date?) for estuaries (3394 and 2849-3450 mg/L) can be classified as being less turbid. The mean value of 3550 mg/L is suggestive of cloudy water. However, in relation to past records on the system, the findings of this study on TDS of Densu water is an indication of turbid conditions. The amounts of dissolved substances play a crucial role in filter feeding bivalves as this has the ability to clog

their gills and impede on feeding. The ability of the water to absorb sunlight for photosynthetic processes can be altered by suspended particles.

This phenomenon of higher levels of dissolved substances according to Fincham (1984) is common in estuaries than in adjacent open sea, because suspended materials in estuaries are derived from the river, the sea and from the reworking and resuspension of particles by currents and tides. Suspended particles in estuarine turbid waters can be removed by flocculation and coagulation induced by the increase in salt concentration seaward in the estuary (Chou & Wollast, 2006). This phenomenon is observed usually at a salinity of 5 ppt associated with a turbidity maximum.

The work of Biney (1990) revealed salinity levels of 2-28 ppt while in this study, Salinity varied between 0.36-35.11 ppt. The findings of this work corroborate with reports by Obodai et al. (1996) on the Benya (30-40‰) and Obodai et al. (1996) and Okyere (2019) on the Pra estuary (0 – 29‰ and 30.0‰ and 35.0‰) respectively. The increasing salinity levels in this current study from the assertion of Chumkiew et al. (2018), may be attributable to the location of the estuary, daily and storm-driven tides, and the volume of fresh water flowing into the estuary.Salinity is highest near the mouth and therefore the closer the estuary is to the mouth, the higher the salt content. Incidences of storm driven tides brings with it, high volumes of saline water from the sea into the estuary thereby incresing the salt content of the water. Also, reduction of freshwater input implies less dilution of saline waters resulting in high salinity levels.

C. tulipa thrives well under high salinity levels. The range of salinity of the Densu estuary is suitable for growth and survival of the mangrove oyster. Low salinities (below 10 ppt) have been documented to be the major cause of mortalities, reduced growth,

recruitment and reproduction among oyster populations in Louisiana and the Gulf of Mexico, (Cake, 1983; Chatty et al., 1983; Pollack et al., 2011).

Silicate ions concentration in the water were from 3-19.90mg/L and chla were 1.2611.49mg/L. In earlier studies, Biney (1990) recorded mean and average silicate levels of 5.12mg/L and Entua Mensah (1998) found 1.7-17.6mg/L. This corroborates with reports of the pearl (6.5981mg/L) and Liaohe estuary (0.78-17.26mg/L) in China and São Marcos Bay (0.043-0.093mg/L) in Brazil (Long et al.2020) and Nagavali (Santos et al., 2020). The range of values for silicates level in Densu conforms with the range set by WHO (2005) for brackish systems. The oyster feeds feed on diatoms a group of phytoplankton which require silicates to build its frustules.

The abundance of silicates in the system is an indication of suitable environmental conditions for the growth of diatoms. Therefore, the proliferation of Densu estuary with diatoms will will result in food availability and enhanced growth of the WAMO.

Total viable counts of aerobic mesophiles (TVC),coliforms (faecal coliforms and *Escherichia coli*) were 19.00-99.00 CFU/ml, 0.00-55.0OCFU/ml and 0.00-50.00 CFU/ml respectively. Karikari & Ansa-Asare (2006) found the mean counts of total coliform bacteria to be between 1136 and 1880 CFU/100 ml while the faecal coliforms ranged between 336CFU/ml and 739 CFU/ ml in the Densu river suggesting high microbial load of the river water. Despite the relatively lower microbial counts in the Densu estuary, the presence of these organisms is a threat to oyster growth and human life. The use of the system as a place of convenience by inhabitants need a redress. The release of human excreta directly into the system is a possible source of contamination. Similarly, the concentration of trace metals of arsenic, lead, cadmium and mercury ranged from 0.001-0.088mg/L, < 0.0001-0.068 mg/L, 0.043-0.088 and <0.0001mg/l. Except for Hg which fell within acceptable limits (0.001), arsenic, cadmium and lead

were above recommended limits of 0.010mg/kg, 0.005mg/kg and < 0.0015mg/Kg respectively (EPA,2013). Pb is known to affect vascular, renal, hematopoietic, reproductive systems and cause metabolic poison in aquatic organisms (Mielke et al., 2007). High levels of Cd and As is known to decrease DNA repair capacity and cytological effects on oysters.

4.3.2 Seasonal Changes in Physicochemical Parameters

Mean water depth, cadmium, total alkalinity, pH, carbon dioxide, lead, TCO_2, $fC0_2$, chlorophyll a and $xc0_2$ were significantly higher ($p < 0.05$) in the wet season than the dry season. During the wet season, water inputs from rains primarily could be the cause of higher water depth (5.29 ± 0.25 m).

Changes in pH 97.94 ± 0.04), during rains may be governed by the dilution of weathering products by rain, and also are compensated by the increased weathering flux and other sources during wet seasons. Similar to the works of Joesoef et al. (2017) in Delaware estuary and Perero et al. (2016) of the coastal river in Sri Lanka, pH was observed to be as high as 8.8 and 8.9 respectively and during the wet season than the dry period. In relation to total alkalinity, the Densu estuary recorded mean values as high as 1115.32 ± 104.69 in the wet season and as low as 911.79 ± 27.80 in the dry season

Similarly, maximum total alkalinity was observed in the wet season in the studies of Gaspar et al. (2018) in estuary plumes (Brazil) and Delware estuary (US) were 6221859 and 189-2000 $\mu mol\ kg^{-}$ respectively. Contrarily, low TA values were observed during

the wet season (<65 μmol kg^{-}) and high values during droughts in Sri Lanka by Perero et al. (2016).

Disparity in mean concentrations of total alkalinity suggest losses due to nitrification and intake through aerobic respiration, sea level rise and carbonate dissolution. Also, the observed alkalinity decrease may be caused by decline in precipitation due to drought resulting in reduced riverine alkalinity export, freshwater diversion for human consumption, and calcification in these bays.

The mean total alkalinity levels of the Densu estuary estuary was between 99.91-11511 μmol/kgSW (998.20-115000.49mg/L). According to Jury et al. (2013) the total alkalinity of estuaries ranges between 30-116 mg/L.

The higher concentrations of TA in Densu is an indication of the system's strong ability to neutralize acids particularly carbonic acids which is a main driver of estuarine acidification.

In furtherance to that, recent concerns are that in the 21st century, seawater buffering capacity is expected to decline as a result of increasing carbon dioxide and the subsequent decrease in pH (Hofmann et al., 2006; Egleston et al., 2010; Hagens et al., 2014). As a result, one would predict a greater seasonal pH variability (Frankignoulle, 1994; Egleston et al., 2010 as cited in Jury et al., 2010).

Also, at Densu, mean concentrations of carbon dioxide, lead, TCO_2, $fC0_2$ and chlorophyll a was significantly higher in the wet season than the dry season. Seasonally, maximum mean $pC0_2$ was found during flooding period in Aby and Tendo lagoon in Ivory Coast (Kone et al., 2009). Though these observations were similar to conditions at Densu, mean, negative values in this study are an indication of reduced $pC0_2$ and a

resultant effect of increase in pH. In addition,pPartial pressure of carbon dioxide ($pC0_2$) in Densu ranged between -14.50-10612.63 µatm similar to a value of 487-9160 µatm by Oliveira et al (2015). According to Gazeau et al. (2013) increase in $pC0_2$ ensures less dissolution of calcite saturated shells of calcifying organisms such as oysters. Elevated $pC0_2$ may promote phytoplankton growth, and potentially alleviate carbon limitation during dense blooms.

Total alkalinity (1115.32 ± 104.69), carbon dioxide (6.70 ± 1.37), TCO_2 (1080.00 ± 118.45), $fC0_2$ (2956.37 ± 72.97), and $xc0_2$ was 220. ± 33.73 (Table 4.3).

The dry season values were; depth (4.32 ± 0.03), cadmium (0.04 ± 0.01), total alkalinity (911.79 ± 27.80), pH (7.82 ± 0.12), carbon dioxide (4.55 ± 1.89), total viable counts (83.25 ± 5.96), total carbon dioxide (753.27 ± 44.00), carbon dioxide fugacity (178.47 ± 11.23), chlorophyll a (3.12 ± 0.58) and $xc0_2$ (187.70 ± 76.40).

Furthermore, for cadmium, the Densu system value for the wet period was 0.05 ± 0.01, similar to Duncan et al (2018) in their study of the river Pra tributaries in Ghana, where concentrations were higher during the wet season than the dry season. In contradiction, Monbet (2004) in the Morlaix river estuary in France, found higher values of cadmium (0.04-0.48mg/kg) in the dry season.

In the investigation of Neto et al. (2015) of the Delware estuary in Brazil, higher concentrations of chlorophyll a were found in the rainy season (0.721mg/m3) and lower in the dry season (0.376 mg/m3). The considerably higher mean values of chlorophyll a (3.66 ± 0.40 units) in the Densu system is an indication of relatively high primary productivity. Surface water temperature, total viable counts, total dissolved substances, lead, aragonite and buffer alkalinity were significantly higher ($p < 0.05$) in the dry

season than the wet season. The mean values of water temperature, Total viable counts, total dissolved substances, lead and buffer alkalinity were 30.78 ± 0.83, 83.25 ± 5.95, 3083 ± 12.25, 19.27 ± 2.00, 0.05 ± 0.01, 79.98 ± 30.74, 1.41 ± 0.55 and 68.91 ± 10.85 respectively in the dry season.

Surface water temperature, TVC, TDS and buffer alkalinity were higher (27.49 ± 0.25, 65.59 ± 10.90, 17386 ± 15.90 and 36.46 ± 3.73 respectively) during the dry season than flooding periods. Wet season values were, water temperature (27.49 ± 0.25), Total viable counts (65.59 ± 10.90), total dissolved substances (17386 ± 15.90), lead (0.03 ± 0.01) and buffer alkalinity (36.46 ± 3.73). Dry seasons are characterized by prolonged exposures to sunlight with its resultant effects being increased surface water temperature, high solubility of solids and conducive environments for the growth of disease-causing microbes. According to several authors (Barnes & Mann, 1995; Howland et al. 2000; Zuma, 2010; Fatema et al., 2014) variability in temperature is a main driving force influencing water chemistry of estuaries.

Lead content in the Densu estuary estuary was higher during the wet season which contradicts the assertion by Rumanta (2014) in Jakarta Bay in Indonesia where Pb content was much higher in the dry season. The high concentrations in this study, may be attributable to high solubility during rains. According to Rumanta (2014) lead is less soluble if pH < 5. The pH of the delta was greater than 5 (7.94± 0.04) and therefore favorable for the solubility of contaminants like lead. This explains high concentrations even during the dry periods of the year where losses due to evaporation could be high.

Total dissolved substances, lead, aragonite and buffer alkalinity were significantly higher ($p < 0.05$) in the dry season than the wet season. The mean values of water

temperature, total viable counts, total dissolved substances, lead and buffer alkalinity were 30.78 ± 0.83, 83.25 ± 5.95, 3083 ± 12.25, 19.27 ± 2.00, 0.05 ± 0.01, 79.98 ± 30.74, 1.41 ± 0.55 and 68.91 ± 10.85 respectively in the dry season.

The high buffer alkalinity values during the dry season (68.91 ± 10.85 µmol/kg SW) may be explained by high dissolution of bedrock of the estuary. Estuaries according to Howland et al. (2020), have naturally low pH buffering capacity.

4.3.3 Tidal Influences on Physicochemical Parameters

Water depth, *E coli* and revelle factor were significantly higher ($p < 0.05$) at high tide than low tide. Mean water depth was 0.71 ± 0.05 at high tide and 0.14 ± 0.06 at low tide. The levels of *e coli* at high and low tide were 22.23 ± 3.43 and 11.83 ± 1.81 respectively. Revelle factor was 11.79 ± 1.13 at hightide and 9.07 ± 1.28 at low tide. Conversely, mean silicates level was significantly higher ($p<0.05$) at low tide (15.37 ± 3.08) than at high tide (8.21 ± 2.00).

Water depth varied from 0.71 ± 0.05 at high tide and 0.14 ± 0.06 at low tide. Increase in water depth may be due to saline water influx from the ocean. In the Black estuary in UK and Australian's microtidal estuary, high concentration of *E coli* in waters during strong currents (high tide) overlying oyster beds (Javoanonic et al., 2017; Florini et al., 2020), indicative of a freshwater input of faecal pollution in oyster bed waters, increased resuspension of estuarine sediments during low tide and salt water intrusion due to die off related processes . High counts during high tides in Densu may be due to inputs from ocean waters. Tidal forcing transports debris and materials which may be potential sources of microbial contamination.

The Revelle factor (buffer factor) from the Welch *t* test was higher during hightide (11.79 ± 1.13) than low tide (9.07 ± 1.28) at the Densu system. Increased buffering capacity of the system at high tidal forcing is attributable to higher dissolution of limestone containing bedrock and influx of municipal wastewater from the Weija dam likely to contain large amounts of calcium and bicarbonates. According to Grochowska (2020), lake contamination is capable of shaping the specific buffer conditions of surface waters.

Conversely, mean silicates level was significantly higher ($p<0.05$) at low tide (15.37 ± 3.08 mg/L) than at high tide (8.21 ± 2.00 mg/L).

Brackish estuaries according to WHO (2007) have silicates level of about 25 mg/L. Therefore, the concentrations in Densu estuary fall within the accepted limits. Silicates play an essential role in regulating the buffer capacity of water.

In the Densu estuary, freshwater input from the two inlets (Weija dam and the artificially created inlet) could have contributed to releasing silicate ions into the delta at low tide. According to Chou & Wollast (2006) dissolved silica (DSi) is more concentrated in rivers than in the ocean. Therefore, the variations in silicates level at different tides is possibly due to it being abound in freshwater (during low tide) and low in the sea (during high tide). Low silicates concentration at high tide might also be as a result of removal by phytoplankton. And aquatic siliceous organisms such as diatoms, radiolarians and sponges.

Silicate losses due to abiotic processes namely reactions of silicates with dissolved substances such as clay, formation of colloidal silica due to increase ionic strength during mixing of seawater and freshwater, low biological activity due to environmental stressors and adsorption of silica on ferrihydrites occur in estuarine systems are potential contributors to the observations in this study. In estuaries, these abiotic factors are significant in the water column under optimal conditions such as low salinity (0-5ppt), high concentrations of suspended matter and silicates and concurrent rapid increase in salinity for uptake to occur. Biney (1990) in a study of the Densu river, a tributary to Densu estuary, recorded mean and average silicate levels of 5.12 mg/L and 1.7-17.6 mg/L respectively. The Silicate concentrations were higher in the rainy season than the dry season. In this study, mean silicates level at both tides was 11.79 ± 3.65.

The considerably higher values in this present study could be due to occurrences of both biotic and abiotic processes over the years and is an indication of a high productivity of the Densu estuary.

Mean water Temperature, Dissolved oxygen, Chlorophyll a, Conductivity, Salinity, Total Dissolved Substances, pH, Total Viable Counts, faecal Coliform, Arsenic, Lead, Cadmium, Mercury, Aragonite, Calcite, Total Alkalinity, Total Carbon Dioxide, Fugacity carbon dioxide, Bicarbonates, Carbonates, Carbon dioxide and Buffer alkalinity, did not show any significant differences ($p > 0.05$) during tidal changes.

The Densu estuary is a shallow system (0.54-1.00m at high tide and 0.61-0.65 at low tide) as such the indifference in most Physicochemical Parameters at low and hightide may be due to depth. Water depth, according to Grochowska (2020) is a critical factor controlling variability in water quality of coastal wetlands.

4.4.4 Relationship between Physico-Chemical Factors, Relative Abundance and Morphological Characteristics of the West African Mangrove Oyster

From the CCA, faecal coliform, carbon dioxide fugacity and temperature collectively influenced shell width and shell length. Total alkalinity influenced shell height, condition factor and shell weight whereas, total carbon dioxide and aragonite affected CPUE.

Mean concentrations of faecal coliform, carbon dioxide fugacity and temperature resulted in declining shell weight and shell length.

This contradicts with Nour (2020) in a study of oysters in Egypt where a positive correlation was observed between level of contaminants and size.

Dickie et al. (1984) demonstrated that a strain of mussels growing in their native harsh environment had a significant growth advantage over those transplanted. In Louisiana results demonstrate that under optimal conditions of high temperature and reduced salinity, *Crassotrea gigas* experienced reduced mortality and fast growth rates.

Similarly, shell growth of pearl oyster increased with temperature (Latchere, et al., 2018). Declines in partial pressure of fugacity carbon dioxide results in an increase in pH and more alkaline conditions favorable for the growth and development of *C. tulipa* shells. According to Rudd et al (2013) in a study of *C. virginica* in Florida, short-term immediate exposure to increased acidity does not induce a substantial decline in shell size. Consequently, prolonged increases in pH due to declines in fugacity carbon dioxide may pose threats to the sustainability oyster fishery in Densu. Meanwhile, among eastern oysters, elevated pCO_2, leads to oxidative stress and basal metabolic costs in the bivalve.

Similarly, reduced total alkalinity of the surface water of Densu estuary is correlated with decreased shell height, condition factor and shell width. From the observations of Gazeau et al (2011), carbonates content largely affect the development stages (D veliger stage) and growth (shell size) than pH and aragonite. In Densu, the model revealed that aragonite content and total carbon dioxide are the drivers of relative abundance (CPUE) of the West African oyster. This agrees with Gazeau et al. (2011) on the relation between these carbonate chemistry factors and abundance.

Dickinson et al. (2012) explains that long term exposures to elevated CO_2 levels a driver of total alkalinity, often co-occurs with other stressors, such as reduced salinity, which enhances the acidification trend, affects ion and acid–base regulation of estuarine calcifiers and modifies their response to estuarine acidification.

C. tulipa require alkaline conditions to build its shell. A reduction in total alkalinity affects this process and enhances the lowering of pH levels. Acidic conditions have proven to be detrimental to shell growth. Therefore, this probably explains the results of the CCA model on low alkalinity levels influencing shell height and width.

From Quayle (1989), tissue production is related to size of oyster. Oysters that have built up bigger shells presumably produce bigger tissues. Albeit other factors, total alkalinity is a main driver of calcification in oysters. Consequently, interminable total alkalinity may contribute to reduction in condition index or tissue fatness due to reduced calcification.

4.4.5 Relationship between Size of West African Mangrove Oyster and Concentration of Contaminants

This section highlights the ability of *C. tulipa* to bio accumulate contaminants in the Densu estuary estuarine environment for its use as a bio indicator of environmental variability.

4.4.5.1 Trace Metals and Microbial Load Contamination

From the chemical analyses of the tissues of *C. tulipa*, small- sized oyster (2.5-3.5g) tissues significantly ($p < 0.05$) bio accumulated more Pb and Cd than big- sized (4.5-5.4g) tissues. This is in contradiction with observations by Yesudhason et al. (2013) where there was no direct relationship between size of oyster and metal contamination.

Furthermore, this study conforms to the findings of Woke et al. (2016) on *C. gasar* in Nigeria. Size specific differences was observed in lead contaminated tissues.

Small- sized (2.5-3.5g) oysters in Densu estuary bio accumulated metals more than the larger sized (4.5-5.4g) ones. This may probably be due to a more active filtering capacity (feeding) in small oysters than the bigger sized individuals. According to Ozbay & Brown (2006) the average clearance of contaminants in oysters decreases with increasing size and that, smaller sized oysters are more efficient in their filtering.

Mercury (Hg) concentrations in small tissues was not significantly different ($p = 0.50$) from big oyster tissues. Similarly, copper concentrations according to Woke et al. (2016) were not significantly different among different sizes (small, medium and large) of oysters likewise that of pb in Densu. Close variation in size limits for each size class might have contributed to the insignificance in levels of concentration.

The disparity in these findings from the study in Densu might be due to physiological differences among the different populations of oysters. According to Quayle (1989), differences in species of oysters play an important role in its metabolic and physiological traits. Information obtained on a species in one geographical area may therefore not be applicable elsewhere.

4.4.5.1 Trace Metals and Microbe Bio-accumulation and Health Risk Assessment

Lead and mercury bio accumulate in *C. tulipa* tissues more (BAF > 1) than in the water medium (Table 4.12). Cadmium concentration was more in water than was bio accumulated in the tissues (BAF <1) (Table 1). Similarly, the total count of aerobic mesophiles (TVC), faecal coliforms and *Escherichia coli* bio accumulate more (BAF>1) in tissues than in the estuarine water (Figure 4.3). The BAFs of total count of aerobic mesophiles, faecal coliforms and *Escherichia coli* were 12.81, 34.20 and 26.19 (Table 4.27).

In the works of Apeti et al. (2005) in the Apalachicola bay in Florida, trace metals concentration in water correlated significantly with concentration in the *C. virginica* tissue. According to Onwuteaka et al. (2015) tissue concentration of metals are usually higher than the surrounding environment. Physiologically, oysters are able to bio accumulate substances in their body tissues in comparison with the water medium in which it thrives.

This explains why *C. tulipa* tissues in Densu bio accumulate metals than cocnentrations found in the water. Similar findings have been identified among other species of

Crassostrea and *Egeria* in Nigeria (*C. gasar*), Congo (*Egeria congica*) and China (*C. rivularis*) (Onwuteaka et al., 2015, Luo et al., 2018 & Suami et al. 2019). Among other factors pH, temperature, salinity, nutrients, and environmental conditions of the estuarine ecosystems influence the bioavailability and bioaccumulation rate of metals.

The concentrations of the three metals showed no potential health hazards (THQ <1; HI<1). The cancer risk limit for lead was 0.082 and the cancer risk for a lifetime is 5.11 × 10-5. This implies there is no cancer risk related effects for a lifetime at the current state of contamination levels.

4.4.1 Multiple Linear Regression Models for Predicting Shell Size, Condition Index and Relative Abundance

Results of the CCA identified main drivers of shell size and *C. tulipa* abundance. However, in the multiple linear regression models developed some of these drivers were insignificantly correlated with oyster abundance and growth (Table 4.8).

Variability in shell dimensions due to differences in environment and habitat have been observed by several authors (Miller et al. 2017; Chumkiew et al. 2018; Sehlinger et al.,2019). Reduction in carbon dioxide fugacity results in increasing pH which impedes on calcification in oysters and size of shell as reported in literature (Rudd et al. 2013; Latchere, 2018). While many authors in their studies identified the less influence of aragonite content on growth of some species (*C. ariakensis*) of oysters (Dickinson et al., 2011) other species (*C. gigas* and *C. virginica*) were affected by changes in aragonite content (Miller et al., 2009). Variations in condition index of Densu population of *C. tulipa* is influenced by changes in aragonite concentrations. According to the classification scheme of Miller et al. (2009), aragonite content > 1 is classified as

supersaturated and < 1 is undersaturated. Therefore, the Densu system is classified as supersaturated with aragonite.

Estuaries are highly variable and has profound effects on oyster growth and density. The model has identified declining temperature as a major driver of *C. tulipa* abundance.

Among tropical oysters, temperature effects are best assessed in combination with other hydrographic factors such as salinity, chlorophyl a, depth, total alkalinity and among other drivers. *C. tulipa* in Ghana have been reported to thrive within temperatures of 25-30°C in estuaries in Ghana (Sutton et al., 2012). Other populations thrived within temperatures of 27-31.5 in Benya and 27-32 in Pra (Obodai et al., 1996). In Densu temperature varied between 24.04-34.74. In terms of CPUE (relative abundance) low water temperatures probably will affect effort of oyster collectors and directly impact catch. The effects of reduced temperature on larval growth, shell development and settlement success have been well documented

(Yankson, 1990; Yankson, 1996; Sutton et al., 2012).

4.5 Conclusions and Recommendations

Densu estuary estuary is a dynamic shallow system therefore there is less variability in most Physicochemical Parameters. Tidal action has influences on the pattern of environmental parameters of the system. Also, seasonal changes affect physicochemical features of the delta estuary. The principal Physicochemical Parameters influencing shell size and abundance are total alkalinity, saturation state of aragonite, temperature, carbon dioxide fugacity, total carbon dioxide and faecal coliform bacteria. Densu estuary estuary is high in total alkalinity and presents a strong ability to neutralize acids thereby contributing to controlling estuarine acidification.Trace metals such as

cadmium, arsenic and lead are threats to the West African oyster fishery and health of the Densu estuary. The mesophiles and bacteria load in the oyster tissue may pose health risk to consumers and aesthetic value of the system.

There is an urgent need for the municipal assembly and other stakeholders to control anthropogenic sources of contaminants particularly the landfill situated at the bank of the wetland and sewage outlet (Weija dam drain) to enhance the fishery and maintain the status of the wetland as a Ramsar site. The study provides evidence that the West African oyster is a good organism for use as bioindicator of environmental contaminants in the Densu estuary. Lead and mercury bio accumulate in *C. tulipa* tissues more (BAF > 1) than in the water medium . Cadmium concentration was more in water than was bio accumulated in the tissues (BAF <1) . Similarly, the total viable count of aerobic mesophiles (TVC), faecal coliforms and *Escherichia coli* bio accumulated more (BAF>1) in tissues than in the estuarine water . Therefore, Lead, mercuty, total viable counts, faecal coliform and *Escherichia coli* levels *in* Densu estuary can be determined using *C. tulipa*.

The predictor variables for shell height are faecal coliform, total carbon dioxide, carbon dioxide fugacity. Aragonite content and temperature levels are the main drivers of condition factor and relative abundance respectively. Knowledge on shell height of the mangrove oyster could be a useful predictive indicator of faecal coliform, total carbon dioxide and carbon dioxide fugacity concentration of the water vis a vis. Also, condition factor of the oyster may indicate aragonite content of the estuarine water and relative abundance a clue to the degree of hotness or coldness of surface water. In conclusion, oyster biodata such as shell height, width and condition factor can be used as bioindicator indices.

CHAPTERFIVE

5.0. MODEL PROJECTIONS OF LONG-TERM EFFECTS OF CLIMATE VARIABILITY ON SHELLFISH PRODUCTION AND ITS IMPLICATIONS ON SUSTAINABLE MANAGEMENT OF OYSTER FISHERIES

5.1 Introduction

Ghana is known to have the fifth largest exclusive economic zone (EEZ) of about 225,000 km ^{2} in West Africa (Asare et al., 2015). The country with an approximate coastline of about 550 km and a continental shelf area of 24,300 km, has one of the most vibrant fisheries in Africa (Asare et al., 2015). The coastline also supports diverse groups of aquatic organisms which are inhabited in numerous coastal wetlands. The Gulf of Guinea is fed by these coastal wetlands. The wetlands provide critical habitats for diverse groups of estuarine and marine fauna, such as shellfish, finfish and migratory birds. Besides serving as sinks for the collection of flood waters, they protect shorelines from coastal erosion and thereby stabilise these environments and reduce the adverse effects of climate change from associated mangrove ecosystems (Casas et al, 2015).

The artisanal fisheries sub-sector of Ghana primarily dominates total production in the marine sector. The diet of Ghanaians is made up of about 60 % of animal protein averaging about 27.3kg mean yearly per capital consumption of fish (USAID-BC, 2016). Furthermore, the marine artisanal fisheries is of huge importance through the provision of livelihood source and food.

In general, globally the quantity of fish obtained in the artisanal capture fisheries is increasing (FAO, 2020). Between 2006 and 2018, catches increased from 79.3 million tonnes (MT) live weight in 2006 to 84.4 MT (FAO, 2020). Conversely, catch from

coastal artisanal capture fisheries in 2014 was about 79.9 MT but later declined to 79.3 ??? (FAO, 2020). However though production has showed decreases, many people in Ghana still depend heavily on shell and fin fish for not less than 59 % of their protein intake. (USAID-BC, 2016). The reasons for these decreases can be attributed to human influences and natural factors.

In this 21st century, climate change as a natural factor has become an area of extreme concern. Globally between 1993 and 2020, annual sea level rise has been approximately 3.2 mm while the rise in temperature is reported to be between 0.85–1.06°C . Ghana's coastal shell fisheries remains highly vulnerable to the phenomenon of continual increase in temperature, rainfall, intensity of floods and decrease in rainfall. The resultant effects will be on organisms physiological, morphological, reproductive, migratory and behavioural patterns.

Yearly, Ghana experiences a phenomenon known as upwelling in her coastal waters. This occurs twice a year and is usually characterised by the transport of cold-water rich in fish and nutrients to its shore and a concurrent transport of warm less rich water beneath to the bottom waters. This process results in fish abundance and after the season, there is a subsequent reduction in fish quantity stemming from natural occurrences such as breeding. The reduced quantities of fish during this season is further heightened by anthropogenic interferences. Among some of these interferences are overfishing, unsustainable fishing methods and low enforcement of regulations (World Bank, 2017).

Whereas anthropogenic stressors may be regulated, natural factors are complex to deal with. In predicting the influences of natural drivers on fish production requires gearing

concerted efforts towards addressing climate related issues in fisheries sector. Key among these interventions are the development of models for forecasting the potential impact of environmental variability on fisheries activities and the identification of pragmatic measures in addressing these issues to ensure resilience and enhance sustainable fisheries (Rocha et al., 2009).

In the conservation of wetland ecosystems, the use of models as predictive tools is an important area required for sustainable management of both flora and fauna resources. Distinctively among these tools are multiple linear regression models. Though in the tropics, very few of this type of models have been developed in the area of fisheries and their development and adoption requires few numbers of variables and large data sets, they are excellent for projecting future changes in natural aquatic systems (Pace, 2001; Rocha et al., 2009). Future predictions using regression models is challenged with the fact that consistent collection of data on catch and climate on most tropical coastal systems and fisheries is usually inadequate if not lacking (Pace, 2001; Rocha et al., 2009).

Recent studies shows that various groups such as the Intergovernmental Council for the Exploration of the Sea (ICES) and the North Pacific Marine Science Organisation (PICES) are putting in efforts through interdisciplinary research in contributing to knowledge and providing well informed data on adverse impact of climate on fishery resources. Some of these efforts include the development of prediction scheme mechanisms and documentation of data on marine, freshwater and coastal wetland resources (Brander, 2008; Hollowed et al., 2008; ICES; 2008). In the tropics and sub tropics, similar efforts are on preliminary basis with major setbacks stemming from inadequate up to date data on fisheries resources (ICES; 2008). Meanwhile the

importance of commercial fisheries resources such as shellfish is vital in reducing malnutrition and eliminating food insecurity in sub-Saharan Africa. Apart from food, clams and oysters provide employment to people engaged in fishing and serve as a source of income to coastal communities in Ghana (Ofori-Danson et al., 2019). The West African oyster (*Crassostrea tulipa*) as a filter feeder, is capable of bioaccumulating pollutants from its habitat and useful in biomonitoring programmes. For example, their usage in assessing the concentrations of trace metals in water has been well documented (Quayle, 1989). Therefore, a stable oyster production indicates good water quality. The use of the shells of oysters for the preparation of components of paint, feed for animals and preparation of drugs for mankind is recognized (Obodai, 1999; Ansa & Bashir, 2007).Furthermore, the importance of fish and fishery resources of Ghana to the people cannot be underestimated as it provides food in the form of fish and employment to fishing dependent communities. There exists data on the fish of commercial importance; however, these official data fail to include the catches of other sectors, especially shellfisheries (Nunoo et al. 2014). This chapter was aimed at assessing the trend in shellfish production in the artisanal fisheries sub sector over the years and the potential influence of sea surface temperature, rainfall and relative humidity on shell fish abundance and its implications on oyster fisheries in Ghana.

5.2 Materials and Methodology

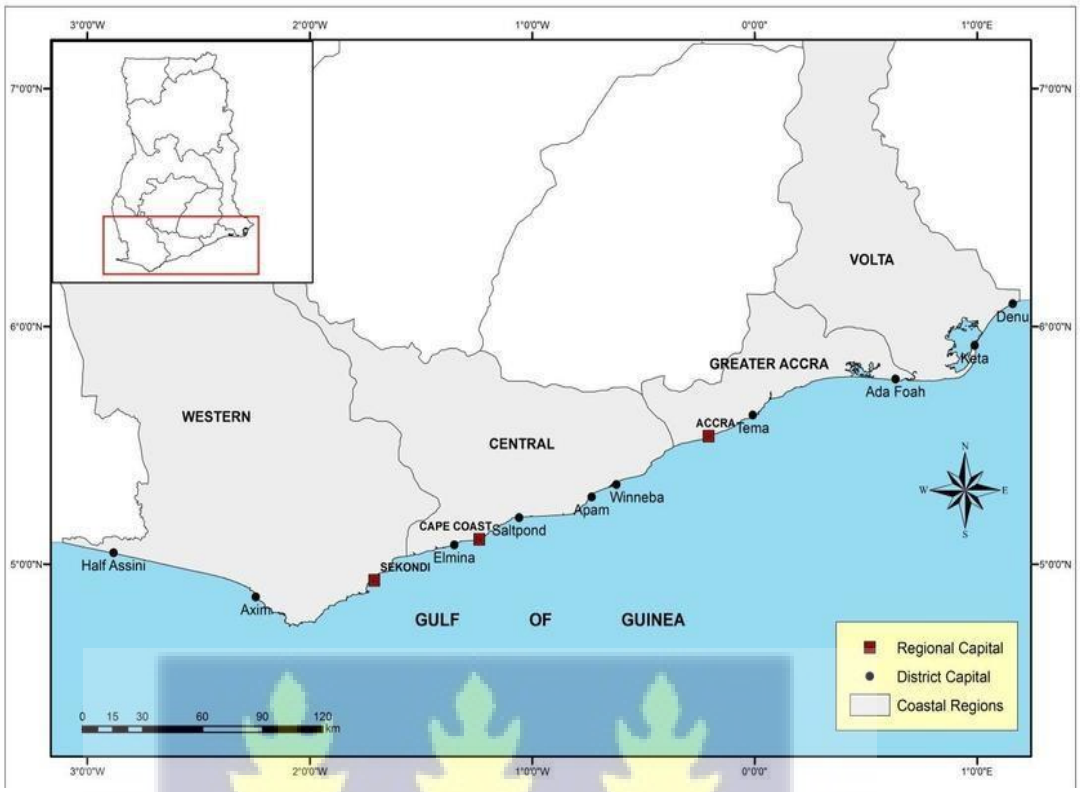


Figure 5.1 Map of the Coastline of Ghana Showing Ghana's Coastal Regions

5.3 Description of Study Areas

The research was conducted across the coastal plains of Ghana from the Volta, Greater Accra, Central and the Western Regions of Ghana. All landing sites from these Regions namely Keta in Volta, Tema in Accra, Elmina in Central and Takoradi from Western Regions together with their adjoining lagoons and estuaries were studied. Catch from lagoons and estuaries along these regions were also included in the research.

This was achieved by collating catch data from the four fishing areas (Keta, Tema, Elmina and Takoradi) and the estuaries and lagoons obtained from the Fisheries Scientific Survey Division (FSSD) at Tema, MOFAD Ghana.

The Keta coastline is located 160 km from Accra and lies within Longitude 0.30° E and 1.05° E and Latitude 5.45° N and 6.005° N. . Keta is a low-lying coastal plain. The area is prone to coastal erosion (GSS, 2014).

Tema metropolis is located within the Greater Accra Region with a distance of about 30 kilometres East of the region. The metropolis is found at North East of the Dangbe West District. South West of Tema and North West of it lies the Ledzokuku Krowor Municipality and Adentan and Ga East Municipalities respectively. Tema is bordered to the North - East by Akuapim South District and to the South by Gulf of Guinea. The land of Tema is flat and has an area coverage of about 87.8 km^2. The terrain of Tema barely rises up to 35 m above sea level (CRC/FON, 2010; GSS, 2014). South east of Tema, lies the Keta coastline in Volta Region.

Elmina is located 135.8km South West of Accra, Ghana. Elmina also known as Edinais town and capital of the Komenda/Edina/Eguafo/Abirem district on the south coast of Ghana in the Central Region.The town is primarily a fishing port.

About 210 km west of Accra lies the Takoradi coastline. North of the Takoradi metropolis is the Mpohor Wassa East district. The Takoradi metropolis lies 6 m below sea level (STMA, forthcoming). The Takoradi coastline is characteriesed by coastal engineered structures, sandy beaches, rocky headlands and intertidal rocky bottoms (CRC/FON, 2010). A major challenge confronting the coastline is the frequent incidences of coastal erosion with recent past records of the area eroding not less than 10 to 100 m (GSS, 2014).

5.4 Sampling Design

5.4.1 Collection of Historic Data on Shellfish Production

Artisanal shellfish catch data collected between 1970–2015 from the Ministry of Fisheries and Aquaculture Development (MOFAD) (2016), Tema and FAO (2016) were used to run the linear regression model. Except for the cephalopods, data on the shellfish groups were made up of bivalves, gastropods and shrimps. Annual production data that were incomplete were filled by first calculating an average value from pre-existing data (2013–2015). This value was an estimation of the percentage contribution of shellfish to the overall marine capture fisheries catch, as reported in the FAO Fisheries Statistics (FAO, 2016). Annual shellfish production data from 1970 to 2000 was estimated using the formula below:

$$\text{Shellfish Production} = \frac{\text{Average value}}{\text{Overall marine artisanal catch in each year}} \times 100$$

The gaps in data were corrected by calculating the difference in catch data in each year and subsequently dividing by the number of gaps obtained in cumulative years for the period.

Based on the trend (increasing or decreasing) in production, the value obtained was further subsequently added or subtracted by previous or preceding years. Due to observed lapses in the data, in order to obtain comprehensive information on shellfish production detailed literature search was conducted. This was carried out in the form of compilation of fragments of data from MOFAD, Tema area (Fisheries Scientific Survey Division, FSSD) FA0 reports (FAO, 2020).

5.4.2 Meteorological Data

To obtain data on relative humidity, rainfall and sea surface temperature, the study focused on meteorological information from the Ghana Meteorological Agency (GMet) in Tema. The location of the Densu estuary in the Greater Accra Region informed the choice of Tema meteorological data for use in running the model with the assumption that it is representative of conditions at Densu estuary. Both catch and climate data were from the year 1970 to 2015. To assess a linear relationship between shellfish production and climate within the specified period, a regression analyses was performed on meteorological and catch data from GMet (Tema) and FSSD of MOFAD, Tema office respectively (Atindana et al. 2019).

5.5 Statistical Analyses

Data was entered into Microsoft Excel 2010, cleaned and coded in SPSS for Windows version 12.0 (SPSS, Chicago, USA). Before the model was run, a normality test was performed and Pearson correlation analyses was run to identify the climate factors which associated strongly or otherwise with data on abundance (Atindana et al., 2019). After the correlation analyses, a stepwise multiple linear regression was performed on abundance data and climate indices which did no show strong correlation with catch. To remove all biases, the assumptions of the model were that all important climate data were considered, catch data was constant with negligible contributions from other socio-economic factors.

In the case of highly complex models, regression methods can be used as substitutes. These regression methods substitute the simplified response surface contained in complex models which represent approximations of the model outputs in the form of regression equations.

In the model outputs, regression coefficients are vital in ranking the input parameters (Field, 2006). Regression techniques are used to determine the sensitivity ranking from the relative magnitude of the regression coefficient which is an indication of the amount of influence the parameter has on the whole model (Hamby, 1994). There is the need to identify ways of overcoming challenges posed by using complex models. One such solution is the use of regression methods (Hamby et al., 1993). In this method are inbuilt regression equations known as response surfaces that gives an approximation of the output of the model. The coefficients of such regression equations are used to test the sensitivity of the model through a sensitivity ranking the relative magnitude of the regression coefficient is a measure of the sensitivity ranking and further determines the influencing power of the parameter on the significant model (Hamby et al., 1993).

5.6 Results

5.6.1 Historic Shellfish Production and Climate Indices

Linear trends in production data on shellfish and predetermined climate indices are illustrated in Figures 5.2 and 5.3 respectively.

Between 1970 and 1980, , production increased from 25.23 metric tonnes (Mt) to 189.1 Mt in 1980 and 211.3 Mt respectively. The corresponding percentage increase was 86.66% (1970 to 1980) (Figure 5.2). Subsequent years recorded decreases in abundance for not less than 2.4 decades by 59.65 Mt from 155.1 Mt in 2000 to 95.45 Mt in 2015 (Atindana et al., 2019).

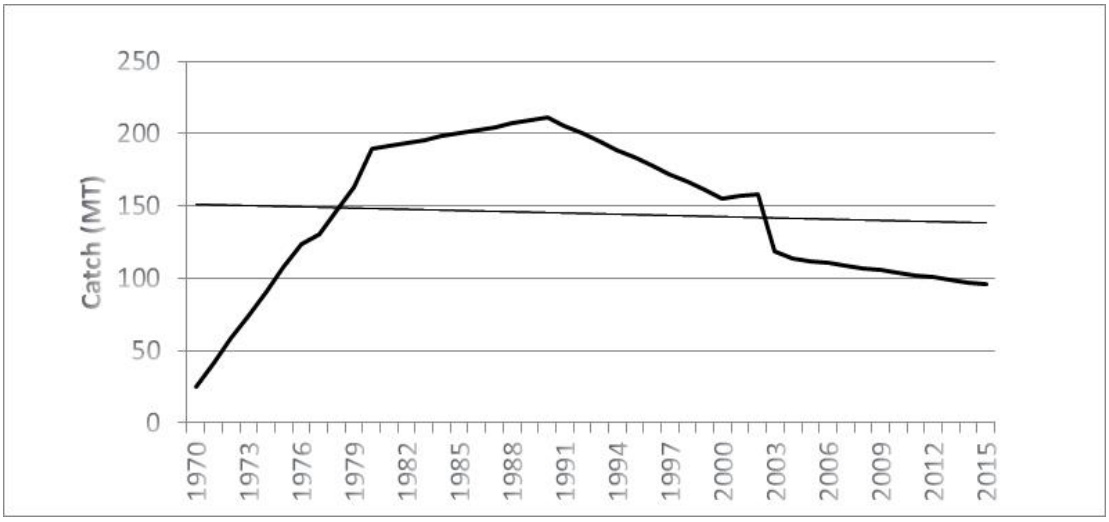


Figure 5.2: Historic Shellfish Catch from 1970 to 2015 in Artisanal Fisheries, Ghana.

The trend in amount of rainfall has reduced over the years, with values ranging between 27.45 mm and 120 mm (Figure 5.3).

Additionally, for over 55 years, trend in relative humidity showed low values varying between 79.80% and 86.7%. In Figure 5. 3, there was a steady decline in average temperature with some years being reported to be experiencing intermittent fluctuations. The degree of hotness or coldness of the marine waters were found to have risen from 28.90°C to 30.75°C thus an increase of about 1.85°C.

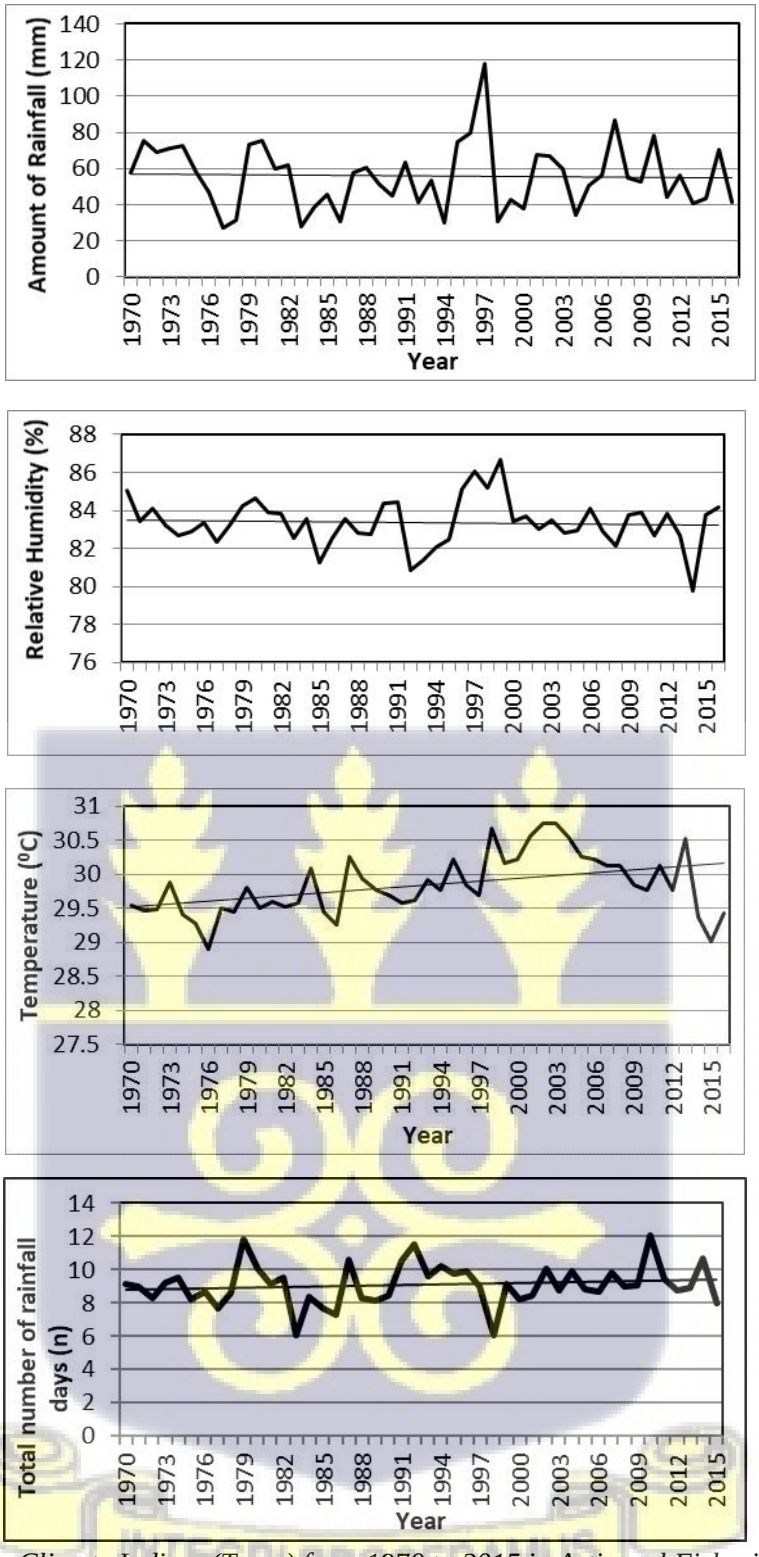


Figure 5.3: Climate Indices (Tema) from 1970 to 2015 in Artisanal Fisheries, Ghana (Source: FSSD, MOFAD)

Relative humidity in the area also showed normal to humid conditions (79.80–86.7%) (Figure 5.3). High mean temperature of about 1.6°C was observed in recent years.

5.6.2 Predictive Shellfish Catch Model

The multiple linear method used was the stepwise selection approach. This was used to determine the influence of climatic factors on abundance. The results showed that only one factor Sea surface temperature (SST) was significant (Table 5.3 and Figure 5.1). SST was the determinant factor influencing shellfish catch (P = 0.011) (Table 5.3). There was a positive correlation (b = 265.312) between catch and mean SST (Table 5.3). Therefore, for every 1unit rise in SST, there will be a corresponding 265.312 units rise in shellfish catch. Therefore, for every 1°C rise in temperature, production increases by 265 MT.

With a multiple correlation coefficient (R) of 0.956 (Table 5.2) and a coefficient of determination, R^2, of 0.913, the determinant factor, SST explains about 91% of the variations in shellfish catch. Knowledge on temperature could be a predictive indicator of shellfish abundance in Ghana. The stepwise multiple linear regression model that explains the relationship between SST and catch is as follows:

$$\text{Shellfish catch per unit effort (MetricTonnes)} = -7788.067 + (265.312\ \text{SST})$$

With an adjusted R^2 value of 0.884, its closeness to the coefficient of determination value of 0.913 suggests the ability of the model to be generalised . Therefore, in this study where sample catch information was used for developing the model, the findings were representative of the entire population because if the model was obtained from population catch data it would have a very low variation of about 2.9% from the population mean (Atindana et al. 2019). The results of the Pearson correlation analyses showing the relationship between catch, rainfall, SST and humidity are presented in Table 3.

Shellfish catch and amount of rainfall did not show any significant correlation between (P = 0.460). Similarly, catch and humidity were not correlated (P = 0.393).

Table 5.3 Pearson Correlation Matrices Showing Relationship between Climate Indices and Shellfish Catch, March 2019–August, 2020

Statistical method	Variable	Catch	Rainfall	Temperature	Humidity
Pearson correlation	Catch	1.000	0.460	0.956	0.393
	Rainfall	0.460	1.000	0.486	0.586
	Temperature	0.956	0.486	1.000	0.168
	Humidity	0.393	0.586	0.168	1.000
Sig. (1-tailed)	Catch	-	.218	0.006	0.256
	Rain	0.218	-	0.203	0.150
	Temperature	0.006	0.203	-	0.393
	Humidity	0.256	0.150	0.393	-
N	Catch	55	55	55	55
	Rain	55	55	55	55
	Temp	55	55	55	55
	Humidity	55	55	55	55

Table 5.1 Model Summary of Shellfish Catch and Mean Sea Surface Temperature from MOFAD and Gmet (Tema), March 2016 to March 2017

Model	R	R^2	Adjusted R^2	Std. error of estimate
1	0.956*	0.913	0.884	29.461

*Predictors: (Constant), sea surface temperature

Table 5.2 Analyses of Variance and Coefficients of Regressionbetween Catch and Temperature Obtained from MOFAD and GMET (Tema)	Sum of squares	df	Mean square	Unstandardized coefficients		Standardized coefficients		
				F	Sig.	B		S.E
						β	T	Sig.
Regression	27,446.153	1	27,446.153	31.622	0.011[b]			
Residual	2603.847	3	867.949					
Total	30,050.000	4				-		
(constant)						7788.067	-5.534	0.012

temp	(df, degrees of freedom)	547.181	1407.247	0.956	5.623	0.011

5.7 Discussions

Historic Shellfish Production and Climate Indices

The decline in abundance of shellfish in Ghana could be due to climate and human factors. Some human perturbations such as socio-economic factors, overfishing, low technological development and unsustainable fishing methods and gears may be reasons for this observed trend in abundance. There were sharp increases in catch from 1988 to 1991, 1976-1982 and 2000 to 2003. These periods also coincided with increases in temperature, reduced rainfall and suggests possible influence of climate variability on production (Figure 5.3).

Inadequate data on catch, among other factors, may probably be a cause of decreased abundance. Furthermore, contributions from oil and gas industry and other fishery and agricultural resources to Ghana's GDP may have eluded that obtained from shellfisheries and so recorded as declines (Atindana et al., 2019).

Rainfall patterns in Tema concur with the trend in rainfall for West Africa (IDRC, 2015). There was a concomitant reduction in amount of rainfall with a corresponding increase in frequency of rainfall (Number of rainy days). Ghana experiences both events of El Niño

(every 7–9 years) and La Niña along her coast where the amount of rainfall rises or falls (Figure 5. 3). La Niña occurs during periods of high rainfall when upwelling begins. This time period is characterised by the high abundance of fish (Atindana et al., 2019).

The trend in temperatures concur with the projections that there will be high temperatures in Ghana (IPCC, 2007). Several studies confirm that Ghana will experience a rise in sea level and high temperature regimes (IDRC, 2015; IPCC, 2007).

Environmental changes including the frequency and amount of rains as well as humidity may affect the abundance of fishery resources. Between these two factors, climate may likely be a major factor influencing interannual variability in rainfall (Atindana et al., 2019).

Predictive Shellfish Catch Model

There was a relationship between SST and abundance (Table 5.2). The positive correlation (r = 0.956) between shellfish catch and SST in this study depicts possible adaptation of the shellfish groups under study to tropical conditions in Ghana. Temperature has been documented to be an influencing factor in growth of oysters (Quayle, 1989). The genera crassostrea is noted to thrive within temperature ranges of 23°C - 35°C. Therefore, temperatures above this range will have detrimental effects on the bivalve. This has been reiterated by Parker et al. (2013) that moderate increases in temperature may influence abundance of oysters and scallops, but above acceptable limits will impede growth and reproduction in oysters. A report confirming this assertion is by Shumway (1996) who stated that the rate of filtration during feeding in tropical oysters can be abruptly halted when exposed to continuous high temperature of about 35°C. Distribution and abundance of these bivalves are adversely affected during rise in temperature. From the work of Quayle (1989), the building up of calcifying coverings of the shellfish as well as the development of its foot are impaired

by rising temperature. In furtherance to that, young oysters particularly the D veliger stage during growth are affected and its ability to resist diseases are affected though other populations may be favoured. The influences of temperature on growth of body coverings of shell bearing fauna are pronounced. For instance, warm temperatures interfere with the absorption of carbon dioxide. This serves as a driver of estuarine and ocean acidification.

The extremely diverse aquatic fauna like shellfish being sessile lack the ability to shift habitats to adapt to drastic changes in the environment and so heightens their vulnerability in comparison with finfishes (Atindana et al., 2019). Similarly, disease infestation through parasitic infections is prevalent under extreme high temperature (Wright et al., 2011).

Crassostrea tulipa as a tropical euryhaline species survives well under optimal temperatures of 23°C and 31°C (Sutton et al., 2012; Atindana et al., 2019). Climate related research shows that *Crassostrea* sp. and *Littoraria* sp. are extremely affected by fluctuations in temperature. (Chapperon & Seuront, 2011). From the physiological assertions, continuous high temperatures exposures of above 34°C in oysters may result into low feeding rate and water transport from gills and high incidences of disease. This will be enhanced by high levels of carbon dioxide and salinity (Levinton et al., 2011; Wright et al., 2011; Sutton et al., 2012; Atindana et al., 2019). Oyster populations across the globe are indicated to be affected with and within species albeit at different geographical locations. For example, in Japan, Sweden and Australia, fertilization of Pacific oysters, *Crassostrea gigas* are reported to be similarly affected by changes in temperature and rainfall irrespective of geographically differences (Chapperon & Seuront 2011).

Meanwhile Vance et al. (1985), Meynecke et al. (2006) and Staunton-Smith et al. (2014) have observed other climate factors to be predictor variables of growth in fish. For instance, in

Queensland Australia, fish from a brackish wetland was shown to increase in abundance during seasons of high rainfall (Meynecke et al., 2006). For a viable shellfish industry in Ghana, pragmatic management interventions in the form of restricted harvest through community byelaws, adoption of sustainable fishing methods, controlled land use activities such as sand minning, farming close to coastal wetlands will protect fishery resources for sustainable use (Atindana et al., 2019).

The abundance of shellfish is also affected by fishers fishing effort, seasonal changes, reproduction, other physiological, low salinity regimes and estuarine acidification are factors which unregulated and properly monitored may lead to massive mortality among oysters and scallops (Laakkonen, 2014; Atindana et al., 2019).

Relative humidity is known to be a stressor to some natural negative drivers such as rate of disease infestation. Though shellfish is not directly impacted by changes in humidity as reported in literature, other variables which are affected by humidity such as growth rate, predation and disease have influences on distribution (Levinton et al., 2011; Wright et al., 2011; Atindana et al., 2019). Within the context of these influencing factors, tropical fisheries may be highly disturbed (NOAA, 2013).

5.8 Conclusions and Recommendations

Climate differences have effects on shellfish abundance in Ghana. Sea surface temperature explained about 91 % of the changes in abundance. .Climate variability due to temperature in the sea has adverse effects on adjoining coastal wetland waters like the estuaries and lagoons in Ghana.

Though the findings of this research showed no relationship between humidity and production, much detailed study on these indices should be undertaken to further verify the trend in this

study. This is necessary because humidity may impact at different scales in the presence of other system conditions. Also, in view of the fact that this is the first model developed for shellfish in the country based on a number of assumptions, further research should be done to improve upon it. The model developed for shellfish catch is;

$$\text{Shellfish catch per unit effort (MetricTonnes)} = -7788.067 + (265.312\ SST)$$

Taking into consideration data deficiency on oyster production in Ghana's estuaries and lagoons, it is recommended that MOFAD should collect catch data on these coastal wetlands.. Also, the Ministry of Fisheries and Aquaculture Development, Wildlife and Forest Division and Water Resources Commission should apply these relatively simple predictive models developed for the management of shell fishery resources in Ghana.

CHAPTER SIX

SUMMARY CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The Densu population of the oyster, *C. tulipa* shows that the species has a fast growth rate (K=0.81; L∞ = 10.53 – 13.24 cm) similar to the findings of Osei (2019) on the species in Densu (L∞ = 14.78 cm) and the Zowla-Aneho lagoon population (L∞ = 10.86) in Togo (Solitoke et al., 2020). This is a clue of the system having a healthy oyster population capable of replenishing its stock. The fast growth rate of the West African Mangrove Oyster in Densu estuary, could serve as a good economic prospect for the culture of oyster in Densu estuary. Catches are higher in experimental fishing (6.00-200kg/hr/fisher/day) which utilized motorized canoe and protective clothing than commercial fishing (3-100kg/hr/fisher/day). With seasonal fishing, the dry season catches were higher than the rainy season due to easy access to the shellfish and reduced fishing pressure. There is a high species diversity (D = 6.60 ± 0.10 - 7.01 ± 0.03; *H* '= 0.30 ± 0.12 - 0.32 ± 0.05) among the food items ingested by the filter feeder. Golden algae from the phylum Ochrophyta, is the predominant IRI= 56%) food item followed by red algae (Phylum Rhodophyta) (IRI = 16%) and the diatoms from the phylum Bacillariophyta (IRI = 13%) The mangrove oyster is a plantivore omnivore. This implies that in the development of the oyster industry in Ghana, oyster farmers could rely on the wild for feed and supplement if the need be, with artificial feeds. Therefore, feeding cost

could be minimized by oyster farmers for the Densu population if proper management systems are put in place.

Densu delta estuary is a dynamic shallow system with less variability in most Physicochemical Parameters. Environmental variables vary with tides and seasons. The principal Physicochemical Parameters influencing shell size and abundance are total alkalinity, saturation state of aragonite, temperature, carbon dioxide fugacity, total carbon dioxide and faecal coliform bacteria.

Densu estuary estuary is high in aragonite and total alkalinity with a strong ability to neutralize acids. This enables the system buffer acidic conditions, contribute to controlling estuarine acidification and promote the formation of calcareous shells which ensures the sustainability of the resource.

The concentration of trace metals such as cadmium (0.043-0.088mg/L), arsenic (0.001-0.088mg/L) and lead (<0.0001-0.068mg/L) are above the WHO (2007) standards of 0.005mg/L, 0.010mg/L and 0.0015mg/L respectively. These are threats to the West African Mangrove Oyster fishery, health of the Densu estuary and consumers. The mesophiles (64.36 ± 10.58CFU/ml) and bacteria load (22.89 ± 3.76 CFU/ml; *e coli* = 17.08 ± 2.81CFU/ml) in the oyster tissue may pose health risk to consumers and aesthetic value of the system.

The Densu population of oyster is common and currently being harvested for commercial use. *C. tulipa* in Densu was able to provide a measurable response by its ability to accumulate pollutants from the environment drawing evidence from the values obtained in this study. Lead and mercury bio accumulated in *C. tulipa* tissues more (BAF > 1) than in the water medium

(Table 4.12). Cadmium concentration was more in water than was bio- accumulated in the tissues (BAF <1) (Table 1). Similarly, the total viable count of aerobic mesophiles (TVC), faecal coliforms and *Escherichia coli* bio- accumulate more (BAF>1) in tissues than in the estuarine water (Figure 4.3).

Similarly, the BAFs of total count of aerobic mesophiles, faecal coliforms and *Escherichia coli* were 12.81, 34.20 and 26.19 (Table 4.12). This suggests that the oyster has a good indicator ability and implies, it could be useful for wastewater management and ecological rehabilitation by being incorporated in mitigation efforts to address water quality standards in the Densu estuary.

The predictor variables for shell height are faecal coliform, total carbon dioxide, carbon dioxide fugacity. Aragonite and temperature are the main predictor variables of condition factor and relative abundance respectively. Therefore, knowledge of shell height of the mangrove oyster could be used as an indicator of faecal coliform, total carbon dioxide and carbon dioxide fugacity concentration of the water. Likewise, condition factor of the oyster could be indicative of the aragonite content of the estuarine water and relative abundance a clue to the degree of hotness or coldness of surface water. Hence, shell height, shell width and condition factor are the aspects of oyster biodata which could best serve as bio indicators of the aquatic environment. Therefore, the study provides evidence that the West African oyster is a good organism for use as bioindicator of environmental variability in the shallow coastal wetland of Ghana. Heavy metal concentrations investigated in *C. tulipa* presents potential consumer human health risks.

6.2 Recommendations

There is the occurrence of contamination of the Densu oyster population by some trace metals and microbes hence an urgent need for the municipal assembly and other stakeholders to

control anthropogenic sources of contaminants particularly the landfill situated at the bank of the wetland and sewage outlet (Weija dam drain).

To reduce trace metal content it is essential to control conditions which may likely trigger algal blooms such as sources of nutrient discharge. This will enhance the fishery and maintain the status of the wetland as a Ramsar site. The occurrence of some species of cyanobacteria in the gut contents of the oyster requires further investigation to prevent cyanobacteria toxins from being passed on to the food chain. Also oysters should be cooked well before consumption to reduce the risk of contamination.

Also, regular monitoring of contamination levels and enactment of control measures by management is needed. Development Action Association (DAA) should provide depuration facilities for oyster collectors involved in the commercial fishery.

It is recommended that the Densu population of *C. tulipa* should be cultured by researchers for age determination. In addition, a laboratory or field culture of the West African Mangrove Oyster should be done to determine the factors which determines changes in shell weight, length and abundance of the oyster. This will provide more information for the development of the oyster fishery since the findings of this study could not identify any significant predictor variables influencing these morphometric parameters.

Due to paucity of catch data on estuarine capture oyster fisheries, development of a model for its prediction was challenged. There is an urgent call for collection of data on estuarine/lagoonal shellfisheries in Ghana by Fisheries Commission and other stakeholders on catch trends, gears, effort and income of artisanal oyster collectors.

REFERENCES

Addo, A. A. (2017). *Assessing Heavy Metal Load of Fish and Shorebirds in The Densu estuaryRamsar Site, Ghana.* Thesis submitted to the Department of Marine and Fisheries Sciences University of Ghana, Legon Ghana.Http://doi//ugspace.ug.edu.gh/handle/123456789/24672

Adjei-Boateng, D. & Wilson, J. G. (2011). Body condition and gametogenic cycle of Galatea paradoxa (Mollusca: Bivalvia) in the Volta River estuary, Ghana. *Estuarine, Coastal and Shelf Science,1*-5. Https://doi:10.1016/j.ecss.2011.06.018.

Adjei-Boateng, D., Agbo, N. W., Agbeko, N. A., Obirikorang, K. & Amisah, S. (2012). The Current State of the Clam, Galatea paradoxa, Fishery at the Lower Volta River, Ghana. In IIFET 2012 Tanzania Proceedings (pp. 1-12).

Ajana, A.M. (1980). Fishery of the mangrove oyster, *Crassostrea gasar*, Adanson in the Lagos area, Nigeria. *Aquaculture, 21,* 129-137.

Allison, E. H., Perry, A. L., Badjeck M.C., Adger, N., Brown, K, Conway, D., Halls, A. S., Pilling,G. M., Reynolds, J. D., Andrew, N. L. & Dulvy, N. K. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fisheries, 10(*2), 173–196.

Amin, S. M. N., Zafar, M. & Halim, A. (2006). Population dynamics of the oyster *Crassostrea virginica* from the offshore Island of St. Martin in the coast of Bangladesh. *Journal of Sustainability Science and Management, 1(*2), 65-78.

Amin, S. M. N., Zafar, M. & Halim, A. (2008). Age, growth, mortality and population structure of the oyster, *Crassostrea madrasensis* in the Moheskhali Channel (Southeastern coast of Bangladesh). *Journal of Applied Ichthyology*, 24(4), 180-25.

Ampofo-Yeboah A, Owusu-Frimpong M. & Yankson, K. (2009). Gonad development in the freshwater oyster, *Etheria elliptica* (Bivalvia: Etheriidae) in northern Ghana. African *Journal of Aquatic Science*, *34*, 195-200.

Ampofo-Yeboah, A. & Owusu-Frimpong, M. (2014). The Fishery of the Freshwater Oyster *Etheria elliptica* (Etheriidae) in Northern Ghana: Its Distribution and Economic Importance. *Journal of Agriculture and Sustainability*, *5*(2), 211-220.

Amoah P., Keraita B., Drechsel P., Abaidoo R., Konradsen F.& Akple M. (2011). Low cost options for health risk reduction where crops are irrigated with polluted water in West Africa. IWMIresearchReportNo 141,Colombo,SriLanka.50pp

Angell, C. L. (1973). Maduracion gonadicay fijacion de Crassostrea rhizophorae en una laguna hipersalina del nororiente de Venezuela. *Mem. Soc. Cienc. Nat. La Salle 33*(93), 216-240.

Angell, C. L. (1986). The biology and culture of tropical oysters. *studies and reviews. Volume 13, Manila, Philippines*: ICLARM. Retrieved from http://doi.org/10.1073/pnas.0703993104.

Anim-Gyampo, M., Kumi, K. & Zango, M. S. (2013). Heavy Metals Concentrations in some selected Fish Species in Tono Irrigation Reservoir in Navrongo, Ghana. *Journal of Environment and Earth Science, 3* (1).109-119.

Ansah, E., Nukpezah, D. & Hogarh, J. N. (2018). Levels and Distribution of Heavy Metals in Weija Reservoir, Accra, Ghana (2018). *West African Journal of Applied Ecology, 26(1*), 74 – 88.

Ansa, E. J. & Bashir, R. M. (2007). Fishery and culture potentials of the mangrove oyster (*Crasosstrea gasar)* in Nigeria. *Research Journal of Biological Sciences, 2*, 392-394.

Apau, J., Appiah, S. K. & Marmon-Halm, M. (2012). Assessment of Water Quality Parameters of Kpeshie Lagoon of Ghana. *Journal of Science and Technology*, 32 (1)22-31.

Arendse, C.J. Govender, A. &Branch, G. M. (2007). Are closed fishing seasons an effective means of increasing reproductive output? A per-recruit simulation using the limpet Cymbula granatina as a case history. *Fisheries Research*, 85, 93-100.

Asante, F. A. & Amuakwa-Mensah F. (2015). "Climate Change and Variability in Ghana: Stocktaking" *Climate* 3, 1, 78-99. Https://doi.org/10.3390/cli3010078.

Asare C, Nortey D. D. N., Lazar N, Kankam S. & Agbogah K. (2015). Results of the Field Survey on the Small Pelagic Fisheries. The USAID/Ghana Sustainable Fisheries Management Project (SFMP), Narragansett, RI: Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island and Hen Mpoano, Windy Ridge – Takoradi. Http://www.crc.uri.edu › projects_page.52pp.

Asare, M. L., Cobbina, S. J., Akpabey, F. J., Duwiejuah, A. B. & Abuntori, Z. N.

(2018). Heavy Metal Concentration in Water, Sediment and Fish Species in the Bontanga Reservoir, Ghana. Toxicological and environmental studies. *Toxicology and Environmental Health Sciences,10 (*1), 49–58.

Atindana, S. A., Blay. J. & Yankson, K. (2016). Evaluation of Aspects of theLimnology of a Coastal Reservoir in Ghana. *Journal of Applied Sciences, 1*(4), 6-13.

Atindana, S. A., Olajire, F., Ajani, E., Alhassan, E. H. & Ampofo-Yeboah, A. (2019). Coping with climate variability and non-climate stressors in the West African Oyster (*Crassostrea tulipa*) fishery in coastal Ghana. *Maritime Studies,* 2, 1-12.

Audzijonyte, A., Fulton, E. & Kuparinen, A. (2014). The impacts of fish body size changes on stock recovery: A case study using an Australian marine ecosystem model. ICES *Journal of Marine Science, 72,* 782-792. 10.1093/icesjms/fsu185.

Bagenal, T. B. & Tesch, T. B. (1978). *Age and growth. In T. Bagenal (Ed.), Methods for assessment of fish production in fresh waters, (*3rd ed.) (pp 101-136). IBP Handbook No. 3, Oxford: Blackwell Science Publications.

Bagne, K. E., Friggens, M. M. and Finch, D.M. (2011). A System for Assessing Vulnerability of Species (SAVS) to Climate Change. USDA Technical Report.https://www.fs.usda.gov/treesearch/pubs/37850.DOI:https://doi.org/10. 2737/RMRS.

Bailey, J. (2009). Shell orientation terminology among the Bivalvia (Mollusca): Problems and proposed solutions. *Journal of Paleontology*, 83(3), 493-495. Retrieved from www.jstor.org/stable/29739114.

Baker, P. & Mann, R. (2003). Late-stage bivalve larvae in a well-mixed estuary are not inert particles. *Estuaries* 26, 837–845 (2003). https://doi.org/10.1007/BF02803342.

Barbour, M., Bierwagen, B., Hamilton, A. & Aumen, N. (2010). Introduction to benthic in nvertebrates . *Journal of the North American Benthological Society, 29*(4), 1349-1353.

Barton, A., Hales, B, Waldbusser, G. G., Langdon, C. & Feely, R. A. (2012). The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnological Oceanography, 57(*3), 698– 710.

Bellinger, E. G. & Sigee, D. C. (2015). *Freshwater algae: identification, enumeration and use as bio-indicators (2nd edn.).* Wiley-Blackwell. 290 p.

Biney, C. A. (1990). A review of some characteristics of freshwater and coastal ecosystems in Ghana *Hydrobiologia 208* 45–53.

Brander, K. M. (2007). Climate change and food security special feature: global fish production and climate change. Proceedings of the National Academy of Sciences. 104, 19, 709–714. Https://doi:10.1073/PNAS.0702059104.

Brander, K. (2008). A history of climate-related research in ICES. ICES. *Insight, 45*, 32– 35.

Botwe, B. (2018). *Sediments in the Tema Harbour (Ghana):* Chemical Pollution and Sedimentation Rates. PhD Thesis. Wageningen University.293pp.

Brick, R.W. (1970). Some aspects of raft culture of oysters in Hawaii. University of Hawaii, Institute of Marine Biology Technical Report. No.24.

Brown, J. E, Fitzhugh, Jr. H. A & Cartwright, T. C. (1976). A comparison of nonlinear models for describing weight–age relationships in cattle. *Journal of Animal Science, 42*,810–818.

Carney, J. A. (2017). Shellfish Collection in Senegambian Mangroves: A Female Knowledge System in a Priority Conservation Region. *Journal of Ethnobiology, 37(3*), 440-457.

Cake, E. W. (1983). Habitat suitability index models: Gulf of Mexico American oyster. FWS/OBS-82/10.57. Washington, DC: Department of Interior Fish and Wildlife Service. 37 pp.

Casas, S. M., La Peyre J. & La Peyre, M. K. (2015). Restoration of oyster reefs in an estuarine lake: population dynamics and shell accretion. *Marine Ecological Progress. Series*. 524, 171–184.

Castro, P. & Huber, M. (2005). *Marine Biology (5th ed.).* New York: McGraw-Hill Companies, Inc.452pp.

Chatry, M., Dugas, R. J. & Easley, K. A. (1983). Optimum salinity regime for oyster production on Louisiana's state seed grounds. *Contributions in Marine Science, 26,* 81– 94.

Chandran A. & Mohammed-Hatha, A.A.M. (2005). Relative survival of *Escherichia coli* and *Salmonella typhimurium* in a tropical estuary. *Water Research, 39*(7), 1397–1403.

Chang, Y. (1967). Accuracy of Fossil Percentage Estimation. *Journal of Paleontology*, 41, 2, 500-502.

Chou, L. & Wollast R. (2006). Estuarine silicon dynamics. D. Ittekkot, C. Unger, C. Humborg, N. Tac An (Eds.), The Silicon Cycle: Human Perturbations and Impacts on Aquatic Systems. *Scope, 66,* 93-120.

Crampton, J.S., Cody, R.D., Richard Levy, R., Harwood, D., McKay, R. & Naish, T.R. (2016). Southern Ocean phytoplankton turnover in response to stepwise Antarctic cooling over

the past 15 million years: *Proceedings of Natural Academy of Science 113 (25*), 6868–6873.

Chuku, E.O. (2019). *Promoting coastal aquaculture in Ghana: Strategies for optimizing seed collection and culture performance of oysters (Crassostrea tulipa, Lamarck, 1819), in coastal water bodies.* Mphil Thesis, Unpublished. University of Cape Coast.174pp.

Clark M.R. (1985). Food and feeding of seven fish species from the Campbell Plateau, New ZealandNew Zealand. *Journal of Marine and Freshwater Research, 19,* 339-363.

Coastal Resources Centre/Friends of the Nation (2010). Report on Characterization of Coastal Communities and Shoreline Environments in the Western Region of Ghana. Integrated Coastal and Fisheries Governance Initiative for the West. Coastal Resources Centre, University of Rhode Island, pp. 425. https://unfccc.int/resource/docs/natc/ghanc3.pdf.

Cox, N. D. (1977). Comparison of two uncertainty analysis methods. Nuclear Science *Engineering. 64*, 258–265.

Dame, R. D., Bushek, D., Allen, D., Koepfler, E., Lewitus, A. & Edwards, D. (2002). Ecosystem response to bivalve density reduction: Management implications. *Aquatic Ecology*, 36 (1), 51-65.

Dame, R. F. (2012). *Ecology of marine bivalves*: An ecosystem approach (2nd ed.). CRC Marine Science. CRC Press. 284pp.

Darboe L. B. (2015). Gambia: Oysters Business and Its Economic Importance to Gambia.https://allafrica.com/stories/201507171337.html.Retrieved077/05/209.

De Groot, R., Ketner, P., & Ovaa, A. (1995). Selection and Use of Bio-Indicators to Assess the Possible Effects of Climate Change in Europe. *Journal of Biogeography*, 22(4/5), 935- 943. Https://doi:10.2307/2845994.

Debrah, J. S, Obodai E. A. Aheto D. W, Ameworwor D. H. A. K. & Sarpong-Baidoo, M. (2011). Analysis of the genetic diversity in coriander. *Journal of Microbiology and Biotechnology Research, 1*(4), 98-205.

Debrah, C. (1999). *Speciation of heavy metals in waters and sediment from the Densu Basin. Department of Chemistry*. University of Ghana, Legon-Accra, Ghana.155p.

Denutsui, D., Akiti, T., Osae, S., Dampare, S., Tutu, A., Blankson-Arthur, S., Ayivor, J. & Adomako, D. (2011). Assessment of Pollution into the Densu Delta Wetland Using Instrumental Neutron Activation Analysis. Research Journal of Environmental and *Earth Sciences. 3,* 772-781.

Desmarais, T. R., Solo-Gabriele, H. M., Palmer, C. J. (2002). Influence of soil on faecal indicator organisms in a tidally influenced subtropical environment. Applied *Environmental Microbiology, 68*(3), 1165–1172.

Diaz, R.J. & Rosenberg, R. (1995). Marine benthic hypoxia: A review of its ecological effects and the behavioral responses of benthic macrofauna. Oceanography and Marine Biology: *An Annual Review 33*, 245–303.

Dodoo, D., Essumang, D. & Jonathan, J. (2012). Accumulation profile and seasonal variations of polychlorinated biphenyls (PCBs) in bivalves Crassostrea tulipa (oysters) and Anadara senilis (mussels) at three different aquatic habitats in two seasons in Ghana. Ecotoxicology and environmental safety.

10.1016/j.ecoenv.2012.10.013.

Donelson, J. M., Munday, P. L, McCormick, M. I. & Pankhurst, N. W. (2010). Effects of elevated water temperature and food availability on the reproductive performance of a coral reef fish. *Marine Ecological Progress Series, 401*, 233–243.

Durve, V.S. (1965). On the seasonal gonadal changes and spawning in the adult oyster 'Crassostrea gryphoides' (Schlotheim). *Journal of Marine Biology Association India 7*(2), 328-344.

Duong, T. (2019). Ks: Kernel Smoothing. Retrieved from https://cran.r project.org/package=ks.Doi:10.1201/9780429485572.

Ebinimi J., Ansa, A. & Bashir, R.M. (2007). Fishery and Culture Potentials of the Mangrove Oyster (Crassostrea gasar) in Nigeria. *Research Journal of Biological Sciences, 2*(4), 392-394.

Entsua-Mensah, R. E. M. (1998). Comparative Studies of the Dynamics and Management of Fish Populations in an Open and Closed Lagoon in Ghana. Department of Marine and Fisheries Sciences..University of Ghana. PhDThesis. 154 pp.

Essuman, D. K. & Nortsu, B. K. (2008). Analysis of silver in the water column of the Pra and the Eture estuaries in Ghana. *Chemistry and Ecology*, 24:4, 297-303,Https://doi:10.1080/02757540802253944.

Environmental Protection Agency (EPA) (2001). *National communication for the Republic of Ghana. United Nations Framework Convention on Climate Change*.Ghana Climate Change Report. p. 240.

Ewart, J. W. &. Ford, S. E (1993). History and impact of MSX and Dermo diseases on oyster stocks in the Northeast Region. Northeastern Regional Aquaculture Center Fact Sheet no. 200. University of Massachusetts Dartmouth, North Dartmouth, Massachusetts.NRAC Factsheet No. 200. 7pp.

Farfarsie, I. P. (1954). El ostion comercial en Cuba. Centro de Investigaciones Pesqueras Contribution No. 3. Cuba.5pp.

Fierro, P., Valdovinos, C., Vargas-Chacoff, L., Bertrán, C.& Arismendi, I. (2017). Macroinvertebrates and Fishes as bio indicators of Stream Water Pollution. Water Quality. Intech Open. https://doi10.5772/65084.

Fincham, A. A. (1984). *Basic Marine Biology*. London: British Museum (Natural Science)157.pp.

Fianko, J. R., Lower, S. T., Donkor, A. & Yeboah, P. O. (2010). Nutrient chemistry of the Densu River in Ghana. *The environmentalist., 30, 145*-152.Https://doi: 10.1007/s10669-010-9254-0.

Food & Agricultural Organisation (FAO) (2020). The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. https://doi.org/10.4060/ ca9229en

Food & Agriculture Organisation (FAO) (2018). The state of world fisheries and aquaculture 2018 - Meeting the sustainable development goals. Rome. Licence: CC BY-NC-SA

3.0 IGO. FAO. (2018b). Globefish highlights: A quarterly update on world sea food markets, 4th issue. Food and Agriculture Organisation, Rome. 227pp.

Food & Agriculture Organisation (FAO) (2016). Fishery and aquaculture country profiles. Country Profile Fact Sheets. In: FAO Fisheries and Aquaculture Department. Rome. http://www.fao.org/fishery/.

Food & Agricultural Organisation (1998). Rome Declaration on World Food Security and World Food Summit Plan of Action. (available at www.fao.org/docrep/003/w3613e/w3613e00.htm).

Food & Agricultural Organisation (FAO) (2015). The state of world fisheries and aquaculture. Rome: Author. 2016; 190. 224pp

Forbes, M. (1973). *Setting and growth of Crassostrea rhizophome*. College of the Virgin Islands, St. Croix Campus. Virgin Is. Mimeo. In:Roels, O. E.(ed.). Artificial upwelling progress reports for 1973.USVI Sea grant Prog.No.04--3-158-66.

Fulton, E. A., Link, J. S., Kaplan, I. C., Savina-Rolland, M., Johnson, P., Ainsworth, C. Horne, P., Gorton, R., Gamble, R. J., Smith, A. D. M. & Smith, D. C. (2011). Lessons in modelling and management of marine ecosystems: the Atlantis experience. *Fish and Fisheries*, *12*(2), 171-188.

Galimany, E. Lunt, J. & Christopher. I. (2020). Bivalve Feeding Responses to Microalgal Bloom Species in the Indian River Lagoon: the Potential for Top-Down Control. *Estuaries and Coasts. 43*, 1519–1532.

Galtsoff, P. S. (1964). The American Oyster, Crassostrea virginica Gamelin: Larval development and metamorphosis. In Fishery Bulletin of the Fish and Wildlife Service, Volume 64 (pp. 355-380). Washington DC: U.S. Government Printing Office.

Gaspar, F., Pinheiro, B., Noriega, C., Araujo, M., Lefèvre, N. & Flores, M. (2018). Alkalinity, inorganic carbon and CO2 flux variability during extreme rainfall years (2010-2011) in two polluted tropical estuaries NE Brazil. *Brazilian Journal of Oceanography. 66,* 115-130. Https: doi.10.1590/s1679-87592018149406601.

Gayanilo, F. C. Jr., Soriano, M. & Pauly, D. (1989). A draft guide to the Compleat ELEFAN. ICLARM Software 2.

Gayanilo, Jr. F. C., Sparre, P. & Pauly, D., (2005). FAO-ICLARM stock assessment tools II (FiSAT II) revised version user's guide. FAO Computerized Information Series (Fisheries) No 8. Revised version. FAO, Rome 16pp.

Gerhart, A. (2011). Bioindicator species and their Use in Biomonitoring. Environmental Monitoring, Volume 1. UNESCO, EOLSS. http://www.eolss.net/Eolss- sample AllChapter.aspx

Ghana Statistical Service (2014). National Accounts Statistics. Gross Domestic Product 2014. Final 2012 Gross Domestic Product & Revised 2013 Gross Domestic Product.7p. Retrieved from www.statsghana.gov.gh.

Ghana Statistical Service (GSS) (2016). 2015 Labour force report of final results. Accra.86 pp.

Gillooly, J., Charnov, E., West, G., Savage, V. M. & Brown, J. (2002). Effects of Size and Temperature on Development Time. *Nature, 417,* 70-73.

Gilmour, C.C., Henry, E.A., & Mitchell, R. (1992). Sulfate stimulation of mercury methylation in fresh-water sediment. *Environment, Science and Technology, 26*, 2281–2287.

Goodwin, H., Cohen, A. N. & Roopnarine, P. D. (2010). The Half Shell: A Sclerochronological Investigation of a Modern Biological Invasion in San Francisco Bay, United States. Palmos, 743-745. Https://doi: 10.21 10/Palo. 2010.Plo-015r Q.

Goodwin, D., Gillikin, D. & Roopnarine, P. (2012). Preliminary evaluation of potential stable isotope and trace element productivity proxies in the oyster *Crassostrea gigas*. Palaeogeogr. Palaeoclimatol. *Palaeoecol.* 373, 88–97.

Gordon, S. E., Ngaluafe, P., Wingfield, M. & Southgate, P. C. (2017). Morphometric relationships and shell form of cultured winged pearl oysters (Pteria penguin) in Tonga. *Journal of Shellfish Research, 36*(3), 677-682.

Gosling, E. (2015). Bivalve Molluscs: biology, ecology and culture. CEUR Workshop Proceedings (Volume 1542). https://doi.org/10.1017/CBO9781107415324.004.

Gosling, E. (2004). Bivalve molluscs biology ecology and culture. Oxford.Blackwell Science.

Gregory P. J., Ingram, J. S. & Brklacich, M. (2005). Climate change and food security. Philosophical Trans Royal Societyc London B. *Biological Science, 360* (1463), 2139–2148.

Grimmes, D. J. (1991). Ecology of Estuarine Bacteria Capable of Causing Human Disease: A Review. *Estuaries.* 14(4),345-360.

Hagan, G. B., Ofosu, F.G., Hayford, E. K., Osae, E.K. & Oduro-Afriyie, K. (2011). Heavy Metal Contamination and Physico-Chemical Assessment of the Densu River Basin in Ghana. *Research Journal of Environmental and Earth Sciences, 3:* 385-392.

Hamby, D. M. (1994). A review of techniques for parameter sensitivity analysis of environmental models. *Environmental Monitoring Assessment 32* 135–154.

Harley, S. J., Myers, R. A. & Dunn, A. (2001). Is catch-per-unit-effort proportional to abundance? Canadian *Journal of Fisheries and Aquatic Sciences, 58*1760 – 1772.

Harper, D., Kemp, J., Vogel, B. & Newson, M. (2000). Towards an assessment of 'ecological integrity' in running waters of the United Kingdom. *Hydrobiologia.* 422-423. Https://doi.133-142. 10.1023/A:1017072906760.

Hassard, F., Gwyther, C. L., Farkas, K., Andrews, A., Jones, V., Cox, B., Brett, H., Jones, D., McDonald, J. & Malham, S. (2016). Abundance and Distribution of Enteric Bacteria and Viruses in Coastal and Estuarine Sediments—a Review. Frontiers in Microbiology. Https;// doi: 10.3389/fmicb.2016.01692.

Helton, J. C., Garner, J. W., Marietta, M. G., Rechard, R. P., Rudeen, D. K. & Swift, P. N. (1993). Uncertainty and sensitivity analysis results obtained in a preliminary performance assessment for the waste Isolation Pilot *Plant. Nuclear Science and Engineering. 114* , 286-331.

Hoegh-Guldberg, O. & Bruno, J. F. (2010). The impact of climate change on the world's marine ecosystems. Science, 328, 1523-1528 No 2010/535. http://www.fish.wa.gov).

Hofmann, E.E., Klinck, J.M. & Kraeuter, J.N. (2006). Population dynamics model of the hard clam, Mercenaria mercenaria: development of the age- and length-frequency structure of the population. *Journal of Shellfish Resources, 25,* 417–444.

Hollowed, A. B., Beamish, R. J., Okey, T. A. & Schirripa, M. J. (2008). Reports of PICES/NPRB workshops on forecasting climate impacts on future production of

commercially exploited fish and shellfish. PICES Scientific Report, North Pacific Marine Science. Organization (PICES), Sidney, British Columbia, Canada.pp

Holt, E. A. & Miller, S. W. (2010). Bio indicators: Using Organisms to Measure Environmental Impacts. *Nature Education Knowledge, 3(*10) 8-12.

Hoggarth, M. A. (1987). Determination of anterior-posterior orientation of glochidia by the examination of 68 Y. B. Akiyama & Y. Natuhara glochidial valves present within the umbos of juvenile unionid clams. *Ohio Journal of Science, 87* 93-95.

Huang, P.C., Su, P.H, Chen, H.Y, Huang, H.B., Tsai, J.L, Huang, H.I. & Wang, S.L. (2012). Childhood blood lead levels and intellectual development after ban of leaded gasoline in Taiwan: a 9-year prospective study. *Environment International, 40* 88-96.

Hughes-Games, W. L. (1977). Growing the Japanese oyster (Crassostrea gigas) in subtropical seawater fishponds. I. Growth rate, survival and quality index. *Aquaculture, 11*, 217229.

Howland, R.J.M, Tappin, A., Uncles, R., Plummer, D. & Bloomer, N. (2000). Distributions and seasonal variability of pH and alkalinity in the Tweed Estuary, The Science of the total environment. 251-252. 125-38. 10.1016/S0048-9697(00)00406-X.Https://doi// 10.4314/wajae.v10i1.45701.

Hyslop, E. J. (1980). Stomach contents analysis: A review of methods and their application. *Journal of Fish Biology, 17*, 411 – 429.

ICES (2008). Report of the Workshop on Cod and Future Climate Change (WKCFCC), 17–20 June 2008, ICES, Copenhagen. ICES Document CM 2008/OCC: 09. 98p.

IDRC (2015). Vulnerability and adaptation to climate change in semi-arid areas in West Africa. International Development Research Centre working group 22. International Food Policy Research. http://www.start.org/download/2015/ WestAfrica-RDS.pdf. (Accessed on 7/11/2016).

Iman, R. L. & Conover, W. J. (1980). Small sample sensitivity analysis techniques for computer models, with an application to risk assessment. *Commun. Stat. A Theory., 9* 1749–1842.

Iman, R. L., Helton, J. C. & Campbell, J. E. (1981). An approach to sensitivity analysis of computer models: part II – ranking of input variables, response surface validation, and distribution effect. *Insight, 45*, 32–35.

Intergovernmental Panel on Climate Change. IPCC, (2009). Climate Change: The Physical science basis. Summary for policy Cambridge. Cambridge University Press.246pp.

Intergovernmental Panel on Climate Change. IPCC (2007). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104p.

Jiang, G. B., Shi, J. B. & Feng, X. B. (2006). Mercury pollution in China. *Environment, Science and Technology, 40*, 3672–3678.

Johnson, J., Cook, J, Chin, A, Moore, B. R., Pratchett, M., Welch, D. J.,Williams, A., & Bell, J. (2018). Effects of Climate Change on Fish and Shellfish Relevant to Pacific Islands, and the Coastal Fisheries they Support. Pacific Marine Climate Change Report Card: Science Review, 74–98.

Karikari, A. Y., Asante, K. A. & Biney, C. A. (2006). Water quality characteristics at the estuary of Korle Lagoon in Ghana. *West African Journal of Applied Ecology, 10*, 73-85.

Kampa, M. & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution, 151* 362-367.

Karikari A. Y & Ansa-Asare O. D. (2006). Physico-Chemical and microbial water quality assessment of Densu River of Ghana. *West African Journal of Applied Ecology. 10* (1) 9-15.

Kasim, Ma'ruf & Mukai, H. (2009). Food sources of the oyster (Crassostrea gigas) and the clam (*Ruditapes philippinarum*) in the Akkeshi-ko estuary. Plankton and Benthos Research. 4. 10.3800/pbr.4.104.

Katikiro, R. E. & Macusi, E. D. (2012). Impacts of Climate Change on West African Fisheries and its Implications on Food Production. *Journal of Environmental Science and Management, 15*(2) 83-95.

King, M., (1995). *Fisheries biology, assessment and management.* Fishing News Books, Blackwell Science Ltd, Oxford, 341 p.

Kirby, M. F. Blackburn, M. A, Thain, J. E & Waldock, M. J. (1998). Assessment of water quality in estuarine and coastal waters of England and Wales using a contaminant concentration technique. *Marine Pollution Bulletin, 36*, 631-642.

Koehn, J., Alistair, H., Pratchett, M. & Gillanders, B. (2011). Climate change and Australian marine and freshwater environments, fishes and fisheries: Synthesis and options for adaptation. *Marine and Freshwater Research, 62*, 1148-1164.

Kouakou K. F, Aman J.B, Karamoko, M. & Otchoumou, (2019). A Study of the diet of

Crassostrea gasar in the lagoon Ebrie Ivory Coast. *Journal of Research in Ecology, 7*(1), 2403-2416.

Krampah, E. A., Yankson, K. & Blay, J. (2016). Aspects of reproduction of the brown *Perna perna* at the Iture rocky beach near Cape Coast, Ghana. African Journal of *Marine Science, 38*(4), 503-512. Https:// doi: 10.2989/1814232X.2016.1247751.

Laudien, J., Brey, T. & Arntz, W. E., (2003). Population structure, growth and production of the surf clam, *Donax serra* (Bivalvia, Donacidae) on two Namibian sandy beaches. *Estuarine Coastal Shelf Science, 58,* 105-115.

Laakkonen, K. S. (2014). *Effects of salinity and other stressors on eastern oyster (Crassostrea virginica) health and a determination of Restoration potential in Naples bay, Florida.* Master's thesis, 78p.

Lawrence, D. & Scott, G. (1982). The Determination and Use of Condition Index of Oysters. *Estuaries and Coasts, 5,* 23-27. 10.2307/1352213.

Levinton, J., Doall, M., Ralston, D., Starke, A. & Allam, B. (2011). Climate change, Precipitation and Impacts on an Estuarine Refuge from Disease. Plos One. Https://doi:10.1371/journal.pone.0018849. 6(4).

Lodeiros, C., Marquez, A., Revilla, E., Rodriguez, P. D. & Sonnenholzner, S. (2017). Spat Production of the Rock Oyster *Striostrea prismatica* (Gray, 1825). *Journal of Shellfish Research*. 36, 729-735.

Lowe, M. R., Sehlinger, T., Soniat, T. M., & Peyre, M. K. L. (2017). Interactive effects of water temperature and salinity on growth and mortality of eastern oysters, *Crassostrea virginica*: A meta-analysis using 40 years of monitoring data. *Journal of Shellfish Research*, 36(3), 683–697. https://doi.org/10.2983/035.036.0318

Loret, P., Pastoureaud, A., Bacher, C., Bruno & Delesalle, B. (2000). Phytoplankton composition and selective feeding of the pearl oyster Pinctada margaritifera in the Takapoto lagoon (Tuamotu Archipelago, French Polynesia): in situ study using optical microscopy and HPLC pigment analysis. *Marine ecology progress series*. 199 55-67.

Mahu, E. (2010). *Geochemistry of Estuarine Sediments of Ghana: Provenance, Trace Metal Accumulation Trends and Eco toxicological Risks*. Department of Marine and Fisheries Sciences University of Ghana. PhD Thesis.275pp.

Mahu, E. Nyarko E, Hulme, S. & Coale, K.H. (2015). Distribution and enrichment of trace metals in marine sediments from the Eastern equatorial Atlantic, off the coast of Ghana in the Gulf of Guinea. *Marine Pollution Bulletin*, 98, 301-307.

Markert, B. N., Breure, A. M. & Zeichmeister, H. G. (2003). *bio indicators and Biomonitoing. Principles, Concepts and Applications*. Elsevier Science Ltd. 265p.

Margalef, R. (1968). *Perspectives in ecological theory*. University of Chicago Press, Chicago. 111 p.

McGlade, J. M., Cury, P., Koranteng, K. A. & Hardman-Mountford, N. J. (2002). *The Gulf of Guinea Large Marine Ecosystem: Environmental Forcing and Sustainable Development of Marine Resources*. Elsevier.11, 428 pp.

McLusky, D. S. (1989). *The Estuarine Ecosystem* (2nd ed.). Glasgow: Blackie Academic and Professional Ltd.223pp.

Mekawy, M.S & Madkour, H. (2013). Oxygen and carbon stable isotope analysis on some Egyptian Tridacna maxima as an environmental and climatic indicator. *Egyptian J ournal of Paleontology, 13*(1), 173-183.

Mendo, J. & Jurado. E. (1993). Length-based growth parameter estimates of the Peruvian scallop, *Argopecten purpuratus*. *Fishery Research, 15*, 357- 367.

Metian, M., Pouil, S. Dupuy, C., Teyssié, J. & Michel Warnau, et al. (2020). Influence of food (ciliate and phytoplankton) on the trophic transfer of inorganic and methyl-mercury in the Pacific cupped oyster *Crassostrea gigas.* Environmental Pollution, Elsevier, 257, 113503.ff10.1016/j.envpol. 2019.113503ff.ffhal-02561065f.

Meynecke, J. O. Lee, S. Y., Duke, N. C. Warnken, J. (2006). Effects of rainfall as a component of climate change on estuarine fish production in Queensland, Australia. *Estuarine Coastal and Shelf Science. 69,* 491-504.

Mildenberger, T. K., Taylor, M. H. & Wolff, M., (2017). TropFishR: an R package for fisheries analysis with length-frequency data. Methods in Ecology and Evolution, 8, 1520-1527. http://onlinelibrarywileycom/doi/101111/2041-210X12791/epdf.

Mildenberger, T. K., (2017). Single-species fish stock assessment with TropFishR. https://cranrprojectorg/web/packages/TropFishR/vignettes/ tutorial html.

Mielke, H.W., Gonzales, C.R., Powell, E., Jartun, M. & Mielke Jr., P.W. (2007). Nonlinear association between soil lead and blood lead of children in 202 metropolitan New Orleans, Louisiana: 2000-2005. *Science of the Total Environment, 388*, 43-53.

Ministry of Fisheries and Aquaculture Development and Fisheries Commission (2020).

Densu estuary Community Fisheries Management Plan, Greater Accra Region, Ghana. Accra: Ministry of Fisheries and Aquaculture Development, Fisheries Commission. 59pp.

Mok, T.K. (1973). Studies on spawning and setting of the oyster in relation to seasonal environmental changes in Deep Bay, Hong Kong. *Hong Kong Fish. Bull.* 3: 89-101.

National Estuarine Research Reserve (1997). In North Carolina National Estuarine Research Reserve in cooperation with NOAA – Washington, DC (Ed.). Estuary-net: A Water Quality Monitoring Project – Estuarine Ecology (92 pp). Beaufort, North Carolina.

National Oceanic and Atmospheric Administration (NOAA) (2013). Tides and Currents, Mean Sea level Trend 9432780 Charleston, Oregon. http://tidesandcurrents.noaa.gov/sltrends/sitrends_station.shtml ?stnid=9432780

Ndanu, T. A. (1998). Heavy Metal Pollution of Fish and Fish Oils from some Coastal and Inland Waters of Ghana. Departmentof Nutrition and Food Science. University of Ghana. Masters Thesis.115pp.

NOAA/EPA (1988). Susceptibility and concentration status of Northeast estuaries to nutrient discharges: Northeast Case Study. Part 3: Strategic Assessment of near Coastal Waters. United States. National Oceanic and Atmospheric Administration & United States. Environmental Protection Agency. 50 pp..

Nunoo, F. K. E., Asiedu, B., Kombat, E.O. & Samey, B. (2015). Sardinella and other small pelagic value and supply chain of the fishery sector, Ghana. The USAID/Ghana Sustainable Fisheries Management Project (SFMP). Narragansett, RI, Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island and Netherlands Development Organisation. GH2014_ACT044_SNV. 98 pp. (also available at http:// www.crc.uri.edu/download/GH2014_ACT044_SNV_FIN508.pdf.

Nunoo, F. K. E., Quansah, E. E. K. & Ofori-Danson, P.K. (2016). Preliminary studies on impacts of ocean acidification on diversity of fish species landed by artisanal and semi-industrial fisheries in Ghana. *International Journal of Marine Science, 6(*27), 1– 22.

Nunoo, F. K. E & Asiedu, B. (2013). An investigation of fish catch data and its implications for management of small-scale fisheries of Ghana. International *Journal of Fisheries and Aquatic Sciences, 2*(3), 46 – 57.

Nunoo, F. K. E., Asiedu, B. & Amador, K., Dyhia, B. (2014). Reconstruction of Marine Fisheries Catches for Ghana, 1950 -2010 Working Paper #2014 – 13. Https:doi:10.13140/RG.2.1.2632.9762.

Obodai E.A, Boamponsem L.K., Odokoh, C.K., Essumang, D. Villawoe, E.A., Aheto, D. & Sefah Debrah, J. (2011). Concentration of heavy metals in two Ghanaian Lagoons. *Advances in Applied Science Research., 3*, 177-187.

Obodai, E. A. (1997). *Studies of culturing of mangrove oyster, Crassostrea tulipa, in Ghana.* Department of Zoology, University of Cape Coast.Unpublished PhD thesis. 201pp.

Obodai, E. A., Nyarko, H.D., Amponsah, S.L. (2010). Effect of depuration on microbial content of mangrove oyster (*Crassostrea tulipa,* L) from Benya Lagoon, Ghana. *Ethiopian Journal of Environmental Studies and Management, 3*(2). 47-53.

Obodai, E. A. (1990). *Aspects of ecology and biology of the West African mangrove oyster, (Crassostrea tulipa),* Lamarck occurring in some coastal waters of Ghana, West Africa. Department of Zoology, University of Cape Coast, Ghana.Unpublished Masters thesis, 198pp.

Obodai, A. A. (1999). The present status and potential of the oyster industry in Ghana

Journal of Ghana Science Association, 2(2). 66-73.

Obodai, E. A. (2000). Performance of oyster (Crassostrea tulipa) spat cultured at different densities. *Journal of the Ghana Sciences Association, 2*(3), 129-135.

Obodai, E. A. & Yankson, K. (2000). Effects of fouling organisms on cultured Crassostrea tulipa, in three Ghanaian lagoons. *Journal of Ghana Science Association, 2(*2), 36-53.

Ofori-Danson, P. K. & Kwarfo-Apegyah, K. (2008). An assessment of the cichlid fishery of the Bontanga Reservoir, Northern Ghana. *West African Journal of Applied Ecology*, *14*, 88 - 97.

Ofori-Danson, P. K. & Amoah, C. (2013). The habitat, fisheries and aquaculture of the Volta dam, *Galatea paradoxa* in the lower Volta river in Ghana: An example of the worldwide importance of brackishwater clams. Fisheries and Aquaculture.329341URI: Http://ugspace.ug.edu.gh/handle/123456789/28830.

Ofori-Danson, P. K., Asiedu, B., Amponsah, S. K. K. & Crawford, B. (2019). Assessment of the Socio-Economic, Food Security and Nutrition Impacts of the 2019 Canoe Fishery Closed Fishing Season in Ghana. USAID/Ghana Sustainable Fisheries Management Project. Narragansett, RI: Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island. GH2014_SCI076_CRC. 109p.

Okyere, I. (2019). Implications of the deteriorating environmental conditions of River Pra estuary (Ghana) for marine fish stocks. *Journal for Fisheries and Coastal Management, 1*, 15-9.

Okeyere, I, Nortey, D. D. (2019). Assessment of ecological health status of river Pra estuary and adjoining wetlands using physicochemical conditions and macroinvertebrate indicators. *West African Journal of Applied Ecology*.26 (2).44-55.

Okyere, I., Blay, J. & Aheto, D. (2011). Composition, Diversity and feeding habit, of the Fish Community of a Tropical Coastal Wetland in Ghana. *Journal of Environment and Ecology. 2*, 15-23.

Osei, I., Yankson, K. & Obodai, E. (2020). Demographic and profitability analyses of the West African Mangrove Oyster (*Crassostrea tulipa*) fishery in the Densu estuary,Ghana. Journal of Fisheries and Coastal Management. 2, 12-18.DOI 10.5455/jfcom.20190528122752.

Osei, K. I. (2019). *A study on the fishery, aspects of the biology and culture of the West African mangrove oyster, Crassostrea tulipa in the Densu delta, Ghana.* Department of Fisheries and AquaticSciences University of Cape Coast, Ghana. PHD thesis.237pp.

Osei, I. K. (2015). *Aspects of the biology of Sardinella aurita and Sardinella maderensis (Clupeidae) in the coastal waters of the Central Region, Ghana*. Department of Fisheries and Aquatic Sciences, University of Cape Coast.Masters thesis.150 pp

Osei, A., Newman, M., Mingle, J.A.A., Ayeh-Kumi, P. & Mubarak, K. (2013). Microbiological quality of packaged water sold in Accra, Ghana. Food Control. 31. 172–175. 10.1016/j.foodcont.2012.08.025.

Oteng-Yeboah, A. A. (1999). Development of a Management Plan for the Densu estuary Ramsar Site for Wildlife Division of Forestry Commission Ministry of Lands and Forestry. 100pp.

Otchere, F. A. (2003). Heavy metals concentrations and burden in the bivalves (*Anadara (Senilia) senilis*, *Crassostrea tulipa* and *Perna perna* from lagoons in Ghana: Model to describe mechanism of accumulation/excretion. *African Journal of Biotechnology, 2 (9)*, 280-287.

Oliveira, L.F.S., Ferreira, M.A.P., Juen, L., Nunes, Z.M.P., Pantoja, J.C.D., da Paixão, L.F., De Lima, M.N.B. & Da Rocha, R.M. (2018). Influence of the proximity to the ocean and seasonality on the growth performance of farmed mangrove oysters (*Crassostrea gasar*) in tropical environments. *Aquaculture, 495*, 661-667. Https://doi: 10.1016/j.aquaculture.2018.06.049.

Owusu, K., Obour, P. B. & Asare-Baffour, S. (2015). Climate Variability and Climate Change Impacts on Smallholder Farmers in the Akuapem North District, Ghana. 10.1007/978-3-642-38670-1_111.

Pace, M. L. (2001). Prediction and the aquatic sciences. *Canadian Journal of Fisheries & Aquatic Science, 58*, 63–72.

Pandey, P. K., Kass, P. H., Michelle, L., Soupir, S. B. & Singh, V. P. (2014). Contamination of water resources by pathogenic. AMB Express 2014, 4:51 http://www.amb-express.com/content/4/1/51MINI.

Parker, L. M., Ross, P. M., O'Connor, W. A., Portner, H. O, Scanes, E. & Wright, J. M. (2013). Predicting the response of Shellfish to the impact of ocean acidification. *Biology (Basel). 2(*2), 651-692.Https:// doi: 10.3390/biology2020651.

Pauly, D. & Greenberg, A. (2013). ELEFAN in R: a new tool for length frequency analysis. University of British Columbia Fisheries Centre Research Reports, 21(3), 52.

Pauly, D., Christensen, V., Guenette, S., Pitcher, T., Sumaila, R., Walters, C., Watson, R. & Zeller, Dirk. (2002). Towards sustainability in world fisheries. *Nature. 418*, 68995. 10.1038/nature01017.

Pauly, D. (1979). Theory and management of tropical multispecies stocks: A review, with emphasis on the Southeast Asian demersal fisheries. ICLARM Stud. Rev.9 pp.

Pauly, D. (1984). Fish populations dynamics in tropical waters: a manual for use with programmable calculators. ICLARM Studies and Reviews 8, ICLARM, Manila. 289pp.

Pauly, D. & David, N. (1980). An objective method for determining growth from lengthfrequency data. ICLARM Newsletter, 3(3), 13-15.

Pecl, G. T., Ward, T., Briceño, F., Fowler, A., Frusher, S., Gardner, C., Harmer, P., Hartmann, K., Hartog, J.,Hobday, A.,Hoshino, E., Jennnings, S., Linnane, A.,Marzloff, M., Mayfield, S. , Mundy, C. Ogier, E., Sulivan, A. Tracey, S. Tuck, G. & Wayte, S. (2014). Preparing Fisheries for Climate Change: Identifying Adaptation Options for Four Key Fisheries in South Eastern Australia. Project 2011/039, Hobart, TAS: Fisheries Research and Development Corporation, Project 2011/039. 80pp.

Plagányi É. E. Punt,. Hillary, A. E. Morello, R., Thébaud, E. B., Hutton, O. & Pillans, R. D. (2012). Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. *Fish and Fisheries,2(*1),213-218.

Pratchett, M. S., Munday, P. L., Wilson, S. K., Graham,S. K., Cinner, N. A. J., Bellwood, D. R., Polunin, N. V. C. & Mcclananan, T. R. (2008). Effects of climate-induced coral bleaching on coral-reef fishes: ecological and economic consequences. Oceanography and Marine Biology: *An Annual Review, 46,* 251–296.

Pierterse, A. (2013). *Growth, condition, survival and feeding rate of the Pacific oyster (Crassostrea gigas,* Thunberg*) cultured in three distinct South African environments.* Department of Zoology. University of Stellenbosch.189pp.

Pogoda, B., Buck, B. & Hagen, W. (2011). Growth performance and condition of oysters (*Crassostrea gigas* and *Ostrea edulis*) farmed in an offshore environment (North Sea, Germany). *Aquaculture, 319*,484-492.

Pollack, J. B., Kim, H. C., Morgan, E. K., & Montagna, P. A. (2011). Role of flood disturbance in natural oyster (*Crassostrea virginica*) population maintenance in an estuary in South Texas, USA. *Estuaries and Coasts 34*, 187–197.

Quayle, D. B. (1980). *Tropical Oysters*: Culture and Methods. Ottawa, IDRC. 150pp.

Quayle, D. B. (1989). *Tropical Oysters:* Culture and Methods. International Development Research Centre, Ottawa, Canada, TS17e. 80pp.

Quayle, D. B. & Newkirk, G. F. (1989). Farming Bivalve Molluscs: Methods for Study and Development. The World Aquaculture Society and the International Development Research Centre, Baton Rouge, Louisiana, USA.199 pp.

Randall, P.M. & Chattopadhyay, S. (2013). Mercury contaminated sedimentites- An evaluation of remedial options. *Environmental Research*, 125, 131–149.

Renaud, M. L. (1986). Hypoxia in Louisiana coastal waters during 1983: Implications for fisheries. Fisheries Bulletin (Washington, DC) 84: 19 – 26.

Rhodes M.W. & Kator H. I. (1990) Effects of sunlight and autochthonous microbiota on Escherichia coli survival in an estuarine environment. *Current Microbiology 21*(1),65–73.

Ritchie, T. P. (1977). Fiji oyster culture.Aquaculture Development Project. Food and Agriculture Organization Report No. F1:DP FU/73/016/2. 501pp.

Rocha, R. R. A., Thomas, S. M., Carvalho, P. & Gomes, L. C. (2009). Modelling chlorophyll a and dissolved oxygen concentration in tropical floodplain lakes (Parana River, Brazil). *Brazilian Journal of Biology. 69*, 491–500.

Rosa, M. & Padilla, D. (2020). Changes in Food Selection through Ontogeny in *Crassostrea gigas* Larvae. The Biological Bulletin.Https:// doi:10.1086/706821.

Rouillon, G. Guerra rivas, J. Ochoa, N. & Navarro, E. (2005). "Phytoplankton composition of the stomach contents of the mussel *Mytilus edulis* l. From two populations: comparison with its food supply," *Journal of Shellfish Research*. 24 (1), 5-14, Retrieved from https://doi.org/10.2983/07308000 (2005)24 [5:PCOTSC]2.0.CO;2.

Sakuda, H.M. (1966a). Condition of American oyster *'Crassostrea virginica'* in West Loch, Pearl Harbor, Hawaii. *Trans. Am. Fish. Soc. 95*(4), 426-429.

Schwamborn, R. (2018). How reliable are the Powell-Wetherall plot method and the maximum-length approach? Implications for length-based studies of growth and mortality. Reviews in Fish Biology https://doi.org/10.1007/s11160-018-9519-0.

Shannon, E. C. & Wiener, W. (1963). The Mathematical theory of communication. University of Illinois Press, Urbana. 117 pp.

Shiel, R. J. (1995). A guide to identification of rotifers, cladocerans and copepods from Australian waters. Cooperative Research Centre for Freshwater Ecology. Albury, Australia. 144 pp.

Shumway, S. E. (1996). *Natural environment factors*. In V. S. Kennedy, Newell and

Eble, R. I. E., editors. The eastern oyster *Crassostrea virginica* Maryland Sea Grant College, University of Maryland, College Park, Maryland. 467- 513.

Solitoke, H. D.,Afiademanyo, K. M., Ouro-Sama, K., Tanouayi, G.,Badassan, T. E. & Gnandi, K. (2020). Aspects of population dynamics of the mangrove oyster, Crassostrea gasar, Dautzenherg (1891) (Ostreida: Ostreidae) from the lake ZowlaAneho lagoon system in Togo. *Journal of Fisheries and Aquaculture Research. 5(*1), 93-106.

Sparre, P. & Venema, S. C. (1998). Introduction to tropical fish stock assessment. Part Manual, FAO Fisheries Technical Paper 306/1, Rome, Italy. 407 pp.

Staunton-Smith, J., Robins, J. B., Mayer, D. G., Sellin, M. J. & Halliday, I. A. (2004). Does the quantity and timing of freshwater flowing into a dry tropical estuary affect year-class strength of barramundi (Lates calcifer)?. *Marine and Freshwater Research*. 55, 787-797.

Strickland, J. D. H. & Parsons, T. R. (1972). A practical handbook of seawater analysis. Fisheries research board, Canada. Bulletin 167.328pp.

Shepard,C., Brenner, J., Kathleen, L., Goodin, K. & Ames, W. (2019). Ecological Resilience Indicators for Five Northern Gulf of Mexico Ecosystems Chapter 5. Ecological Resilience Indicators for Oyster Reefs. The Nature Conservancy, Gulf of Mexico Program, Punta Gorda, FL, U.S.A.

Singaraja, K.V. (1980a). Some observations on spat settlement, growth rate, gonad development and spawning of a large Brazilian oyster. *Proc. Natl. Shellfish. Assoc. 70(*2): 190-200.

Singaraja, K.V. (1980b). On the taxonomy, ecology and physiology of a giant oyster, *Crassostrea paraibanensis*, new species. *Bulletin. Marine Science. 30*(4), 833-841.

Smith, E. M., Gerba, C.P. & Melnick, J. L. (1978). Role of sediment in the persistence of enteroviruses in the estuarine environment. *Applied Environmental Microbiology, 35*(4), 685–689.

Sonke, J.,Lars-Eric, S., Heimburger, L.E., & Dommergue, A. (2013). Mercury biogeochemistry: Paradigm shifts, outstanding issues and research needs. C. R. *Geoscience, 345*,213–224.

Stankovic, S. & Stankovic, R. A. (2013). Bio indicators of toxic metals. In: Lichtfouse E et al (eds) Environmental chemistry for a sustainable world, 2, 8pp.

Stankovic, S., Kalaba, P. & Stankovic, A.R. (2014). Biota as toxic metal indicators. *Environmental Chemistry Letters, 12*,63–84. Https://doi.org/10.1007/s10311-0130430-6.

Strayer, D. L. (2008). Freshwater mussel ecology: a multifactor approach to distribution and abundance. University of California Press, Berkeley, California. Freshwater Ecology Series, Volume 1, 2008. 204 pp.

Sutton, A. E., Yankson, K. & Wubah, D. A. (2012). The Effect of Salinity on Particle Filtration Rates of the West African Mangrove Oyster. *Journal for Young Investigators, 24* (4), 55-59.

Tait, R. V. (1981). *Elements of Marine Ecology* (3rd ed.). London: Butterworth Heinemann Ltd .356.pp.

Thangavelu, R. (1988). Settlement of Spat of the Brackishwater Oyster, *Crassostrea madrasensis* in Pulicat Lake. *Bulletin of the Central Inland Fisheries Research Institute, 42,* 318-323.

The World Fish Centre (WFC) (2009). The World Fish Centre. Penang. 10pp.

Thommai, D., Devaraj, T., Arockia G., Lakshman, G. (2014). Water Quality Parameters of Thamirabarani Estuary. *Limnology and Oceanography, 380*-386.

Taylor, M. H. & Mildenberger, T. K. (2017). Extending electronic length frequency analysis in R. *Fisheries Management and Ecology, 24*(4), 230-238. https://doi.org/10.1111/fme.12232.

Turner, R.E., Rabalais, N. N., Swenson, E.M., Kasprzak, M. & Romaire, T. (2005). Summer hypoxia in the northern Gulf of Mexico and its prediction from 1978 to 1995. *Marine Environmental Research, 59,* 65 – 77.

U. S. AID, B C. (2016). The Importance of Wild Fisheries for Local Food Security: Ghana.2 pp.

U.S. Environmental Protection Agency (U.S. EPA) (2014a) Protocol for Developing Pathogen TMDLs. National Summary of Impaired Waters and TMDL Information. http://iaspub.epa.gov/waters10/ attains_nation_cy.control?p_report_type=T.

U.S. Environmental Protection Agency (U.S. EPA) (2014b) Cyanobacterial Harmful Algal Blooms., http://www2.epa.gov/nutrient-policy-data/cyanobacterial- harmful-algalblooms-cyanohabs.12pp.

U.S. Environmental Protection Agency (U.S. EPA) (2014c) Hypoxia., http://water.epa. gov/type/watersheds/named/msbasin/hypoxia101.cfm.

United States Environmental Protection Agency (2011). Exposure Factors Handbook 2011 Edition (Final Report). Environmental Protection Agency, Washington, DC, EPA/600/R-09/052F, 2011.

Ukwade, I. M. (1990). Microbiological studies of the mangrove oyster Crassostrea gasar (Adanson 1757) from an experimental fish farm of the Lagos lagoon, Nigeria.

http://hdl.handle.net/1834/2485.

Ullrich, S.M., Tanton, T.W., and Abdrashitova, S. A. (2001). Mercury in the aquatic environment: a review of factors affecting *methylation. Critical Reviews in Environment, Science and Technology, 31*, 241–293.

UNEP (United Nations Environmental Programme) (2008). Draft final review of scientific information on lead. UNEP Chemical Branch, DTIE. 99pp.

United States Environmental Protection Agency (EPA) Report on the (2013). U.S. International Decontamination Research and Development Conference., Research Triangle Park, NC, November 05 - 07, 2013. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/210, 2014.

USEPA (United States Environmental Protection Agency), (2004). Aquatox (Release 2). Modeling Environmental Fate and Ecological Effects in Aquatic Ecosystems, Technical Documentation. Environmental Protection Agency, Washington, DC. 2: 10pp.

USEPA. (1976). Quality Criteria for Water (The Red Book). U.S. Environmental Protection Agency, Washington DC.533pp.

Vance, D. J., Staples, D. J. & Kerr, J. D. (1985). Factors affecting year to year variation in the catch of banana prawns (*Penaeus merguinensis*) in the Gulf of Carpentaria, Australia. *Journal Conseil International pour IiExploitation de la Mer 42*, 8397.

Vanderpuye, C. J. (1984). Fisheries and limnology of Volta Lake. In: Status of African reservoir fisheries. (Kapetsky, J.M. and Petr, T., eds). pp. 261-320. CIFA Tech. Pap.10.

Valavanidis, A. & Viachogianni, T. (2010). Metal Pollution in Ecosystems. Ecotoxicology

Studies and Risk Assessment in the *Marine Environment.Science advances on Environment, Toxicology and Ecotoxicology issues,* 1-14.29-33.

Virabhadra, R. & Nayar, K. N.(1956). Rate of growth of spat and yearlings of the Indian Backwater oyster, *Ostrea madmsensis* Preston. *Indian Journal of Fisheries 3*(2), 231260.

von Bertalanffy, L. (1938). A quantitative theory of organic growth (Inquiries on growth laws. II). In: Sparre, P. and Venema, S. C., Introduction to tropical fish stock assessment. Part 1. Manual, FAO Fisheries Technical Paper 306/1, Rome, Italy. 407 pp.

Wallace, R. B.,Baumann, H. Grear, J. S.,Aller, R. C. & Gobler, C. J. (2014).Coastal ocean acidification. The other eutrophication Problem. *Estuarine, Coastal Shelf Science. 148,* 1-13. Https://doi:10.1016/j.eces2014.05.027.

Walker, J. L., Younos, T. & Zipper, C. E. (2007). Nutrients in lakes and reservoirs-A literature review for use in nutrient criteria development (Special Report No. 34).40pp. Virginia Polytechnic institute and state University of Blacksburg.

Water Resources Commission (2018). Water Resources Commission Annual Report. Accra.11pp.

Watters, K.W. & T.E. Prinslow (1975). Culture of the mangrove oyster *Crassostrea rhizophorae* Guilding, in Puerto Rico. Proc. *World Mariculture Society*. 6, 221-233.

Wedler, E. (1970). Experimental spat collecting and growing of the oyster *Crassostrea rhizophorae* Guilding in the Cienaga Grande de Santa Marta, Columbia. *Aquaculture 21*, 251-259.

Wetzel, R. G. (2001). *Limnology: Lake and River ecosystem. Benthic algae and nutrient in lentic Freshwater ecosystems*. Elsevier Science & Technology.12pp.

Wickham, H., Hester, J. & Chang, W. (2018). devtools: Tools to make developing R Packages easier. R Package Version 2.0.1. Retrieved from https://cran.r-project.org/package=devtools.

Wilson, J. G. (1994). The Role of bio indicators in Estuarine Management. Estuaries, vol. 17, no. 1, 1994, pp. 94–101. JSTOR, www.jstor.org/stable/1352337.

Wood, E. J. F. (1967). *Microbiology of Oceans and Estuaries*. Amsterdam: Elsevier Publ.90.

World Bank (2017). CO2 emissions (metric tons per capita). https://data.worldbank. org/indicator/ EN.ATM.CO2E.PC.

Wright, J., Ross, P., Parker L. & O'Connor, W. (2011). Predicting the physiological response of oysters to climate change. 4th International Oyster Symposium, Hobart, Tasmania. Retrieved from https://www.dpi.nsw.gov.au/content/ research/areas/aquaculture/outputs/2011/1967.

Xu, Q. & Hongsheng Y. (2007). Food sources of three bivalves living in two habitats of jiaozhou bay (qingdao, china): indicated by lipid biomarkers and stable isotope analysis," *Journal of shellfish research* *26*(2), 561-567. Https://doi.org/10.2983/0730-8000(2007)26[561:fsotbl]2.0.co;2.

Yankson, K. (1977). *Some aspects of the biology of the West African bloody cockle (Anadara senilis L.) occurring in some coastal lagoons in Ghana*. Department of Cape Coast, University of Cape Coast.Masters thesis.177pp.

Yankson, K. (1986). Reproductive cycles of *Cerastoderma glaucum* (Bruguiere) and C. edule (L.) with special reference to the effects of the 1981–82 severe winter. *Journal of Mollusca Studies, 52*, 6-14.

Yankson, K. (1990). Preliminary studies on the rearing of the West African mangrove oyster, *Crassostrea tulipa,* in the laboratory. *Discovery and Innovation, 2*, 45-51.

Yankson, K. (1991). A note of the nomenclature of the West African mangrove oyster. In D. Wilson (Ed.). Proceedings of the 17th Biennial Conference (pp. 109-112). Legon, Ghana: Ghana Science Association.

Yankson, K. (1991). Certain aspects of the culture of the local mangrove oyster (*Crassostrea tulipa*) in Ghana. *Oceanography, 3,* 9-14.

Yankson, K. (1996). Sexual differentiation of Crassoatrea tulipa in two contrasting brackish water environments. *Journal of Molluscan Studies, 62*, 135-137.

Yankson, K. & Obodai, E. A. (1999). An update of the number, types and distribution of coastal lagoons in Ghana. *Journal of Ghana Science Association (Special edn), 3*, 26 31.

Yankson, K. (2004). Fish from the shell: its potential in the quest for adequate protein in Ghana: An inaugural lecture delivered at the University of Cape Coast. Accra, Ghana: Media Graphics & Press LTD. 220.

Zuma, B. S. (2010). Microbial Ecology of the Buffalo River in Response to Water Quality Changes.http://www.books.google.com/Microbial_Ecology_of_ the Buffalo_Riveri.ht on. Rhodes University, South Africa.Master's thesis. 265 pp.

APPENDICES

Appendix A: Monthly Means of Physicochemical Parameters in The Densu estuary, 2019

Month	pH	DO (mg/L)	CONDUCTIVITY (µs/cm)	TEMPERATURE (^{0}C)	SALINITY (ppt)	TDS (mg/L)	DI (m
March	7.95 ± 1.99	5.85±1.46	43.26 ± 10.82	31.21 ± 7.80	27.71 ± 6.93	18773.80 ± 5.41	1.6
April	8.20 ± 2.12	6.65 ± 1.72	37.77 ± 9.75	32.98 ± 8.52	23.72 ± 4.85	10444.00 ± 16.12	0.6
May	8.03 ± 2.23	3.79 ± 1.05	40.13 ± 11.13	27.76 ± 7.70	25.54 ± 7.08	8801.92 ± 5.11	0.4
June	9.01 ± 1.37	6.29 ± 1.06	17.80 ± 32.07	27.55 ± 4.57	11.47 ± 1.07	6627.71 ± 32.07	0.5
July	8.01 ± 1.41	6.21 ± 0.78	187.05 ± 7.54	26.67 ± 4.67	6.22 ± 2.82	5361.45 ± 386.50	0.8
August	7.90 ± 1.30	2.21 ± 0.36	2377.73 ± 60.17	27.85 ± 4.57	9.93 ± 1.63	256187.11 ± 413.27	0.6
September	7.52 ± 1.29	5.00 ± 0.33	283.48 ± 52.33	28.61 ± 1.43	4.34 ± 0.33	468.58 ± 331.11	0.6
October	7.52 ± 1.28	5.00 ± 0.67	283.48 ± 5.89	28.61 ± 4.91	4.34 ± 0.74	468.58 ± 24.52	0.6
November	7.60 ± 1.27	3.36 ± 0.56	561.22 ± 4.57	29.70 ± 4.95	13.81 ± 2.30	48116.42 ±532.19	0.6
December	7.59 ± 1.87	4.26 ± 1.11	1700.55 ± 1.99	28.91 ± 0.11	2.27 ± 1.90	918.57 ± 97.88	0.5

Appendix B: Monthly means of Physicochemical parameters in the Densu estuary, 2020

Month	PARAMETER					
	pH	DO (mg/L)	CONDUCTIVITY (µs/cm)	TEMPERATURE (^{0}C)	SALINITY (ppt)	TDS (mg/L)
Feb	7.94 ± 1.89	3.41 ± 0.97	34.52 ± 2.39	30.72 ± 0.99	20.42 ± 3.23	25197.89 ± 73.33
March	8.00 ± 2.98	3.70 ± 1.66	36.00 ± 9.11	30.00 ± 2.11	21.00 ± 9.12	25221.11 ±11.28
April	7.90 ± 2.33	4.20 ± 1.10	35.00 ± 9.88	31.00 ± 7.22	20.45 ± 13.33	21880.20 ± 19.78
May	8.20 ± 1.77	6.00 ± 0.97	40.00 ± 0.99	32.00 ± 8.90	24.00 ± 1.98	10001.00 ± 90.11
June	8.00 ± 1.34	5.00 ± 0.50	16.00 ± 0.77	28.00 ± 6.33	25.00 ± 4.56	8501.00 ± 11.22
July	8.90 ± 1.78	6.70 ± 1.17	188.00 ± 10.33	28.00 ± 0.55	12.00 ± 5.43	65001.00 ± 92.89

August	7.90 ± 0.90	6.20 ± 0.18	2300.00 ± 7.78	26.00 ± 0.77	6.00 ± 2.33	52310.00 ± 111.12

Appendix C: Monthly means of microbes and metals in the Densu estuary, 2020

MONTH	**PARAMETER**				
	TOTAL VIABLE MESOPHILE COUNTS (CFU/ml)	**faecal COLIFORM (CFU/ml)**	***E. COLI* (CFU/ml)**	**LEAD (mg/L)**	**CADI (mg/L**
March	80.00 ± 5.65	0.00 ± 0.00	0.00 ± 0.00	0.05 ± 0.03	0.03 ±
April	87.50 ± 6.10	0.00 ± 0.00	0.00 ± 0.00	0.05 ± 0.01	0.05 ±
May	34.50 ± 4.39	2.00 ± 1.41	1.00 ± 0.02	0.01 ± 0.00	0.05 ±
June	32.50 ± 3.43	20.50 ± 4.14	34.00 ± 3.89	0.03 ± 0.02	0.08±
July	61.50 ± 0.99	27.50 ± 9.80	39.00 ± 2.33	0.04 ± 0.01	0.03 ±
August	73.00 ± 1.90	37.50 ± 11.23	34.00 ± 0.77	0.05 ± 0.02	0.03 ±
September	98.50 ± 10.23	45.00 ± 9.87	16.00 ± 0.74	0.05 ± 0.03	0.03 ±
October	89.00 ± 11.89	43.00 ± 2.12	19.00 ± 1.22	0.05 ± 0.01	0.05 ±
November	73.00 ± 6.78	34.50 ± 1.41	22.00 ± 0.10	0.00 ± 000	0.05 ±
December	72.00 ± 11.27	40.50 ± 4.49	15.50 ± 0.11	0.03 ± 0.01	0.08 ±

APPENDIX D:Monthly Means Microbes and Metals in The Densu estuary, 2020

	PARAMETER					
MONTH	**TOTAL VIABLE MESOPHILE COUNTS (CFU/ml)**	**faecal COLIFORM (CFU/ml)**	***E. coli* (CFU/ml)**	**LEAD (mg/L)**	**CADMIUM (mg/L)**	**MERCURY (mg/L)**
March	48.00 ± 9.89	0.00 ± 0.00	0.50 ± 0.35	0.05 ± 0.03	0.03 ± 0.01	0.00 ± 0.00
April	70.00 ± 10.23	3.00 ± 1.77	1.50 ± 0.50	0.05 ± 0.01	0.03 ± 0.01	0.00 ± 0.00
May	71.00 ± 9.88	2.00 ± 0.33	0.01 ± 0.00	0.05 ± 0.02	0.05 ± 0.01	0.00 ± 0.00
June	58.50 ± 2.56	20.50 ± 3.77	1.50 ± 0.40	0.00 ± 0.00	0.05 ± 0.01	0.01 ± 0.00
July	32.50 ± 9.56	27.50 ± 3.10	34.00 ± 7.53	0.03 ± 0.01	0.08 ± 0.03	0.00 ± 0.00
August	61.50 ± 3.33	37.50 ± 1.44	39.00 ± 4.01	0.04 ± 0.02	0.03 ± 0.01	0.00 ± 0.00

Appendix Monthly of

APPENDIX E:Monthlymeans Estuarine Acidification Factors in the Densu estuary

YEAR/MONTH 2019	TOTAL ALKALINITY (µmol/kgSW)	SILICA ALKALINITY (Si Alk)	HYDROXYL IONS (OH) (µmol/kgSW)	PARTIAL PRESSURE OF CARBON DIOXIDE (P CO_2)	CO_3
March	1029.07 ± 11.22	19.50 ± 0.99	12.16 ± 0.77	172.19 ± 0.99	114.21 ± 4.23
April	349.68 ± 9.86	15.00 ± 1.55	3.36 ± 1.23	146.33 ± 1.22	9.48 ± 1.22
May	99.91 ± 9.91	7.85 ± 2.86	10.02 ± 4.33	-14.50 ± -12.11	-12.75 ± -11.11
June	1298.83 ± 8.83	7.78 ± 1.78	32.00 ± 3.45	0.08 ± 0.18	91.58 ± 0.87
July	1508.64 ± 8.64	18.53 ± 2.53	10.12 ± 3.33	201.91 ± 0.12	183.55 ± 3.55
August	1039.07 ± 9.07	10.03 ± 7.03	10.34 ± 3.22	127.12 ± 2.77	120.74 ± 10.74
September	1118.99 ± 8.99	12.72 ± 5.43	6.67 ± 1.23	248.38 ± 0.99	96.81 ± 9.88
October	509.54 ± 9.54	11.28 ± 3.45	4.17 ± 1.55	247.57 ± 2.33	33.15 ± 11.22
November	979.12 ± 9.12	10.00 ± 5.40	5.39 ± 0.44	404.76 ± 3.33	72.90 ± 0.29
December	1288.84 ± 8.84	9.90 ± 1.33	5.73 ± 1.22	463.04 ± 4.44	103.92 ± 7.88
2020/ Feb	1178.94 ± 8.94	10.00 ± 2.45	1.23 ± 0.11	2640.54 ± 2.33	23.47 ± 4.30
March	99.92 ± 9.92	14.00 ± 5.60	0.42 ± 0.10	697.49 ± 4.33	0.60 ± 0.30
April	1278.85 ± 8.85	15.00 ± 1.22	4.27 ± 0.27	840.14 ± 5.22	64.12 ± 4.12
May	1468.68 ± 8.68	13.00 ± 1.44	0.08 ± 0.001	18952.57 ± 2.57	1.22 ± 0.22
June	99.91 ± 9.91	8.00 ± 3.22	0.32 ± 0.01	10612.63 ± 2.63	10.47 ± 0.46
July	1298.83 ± 8.83	7.00 ± 2.11	8.29 ±1.22	169.88 ± 8.99	207.73 ± 7.70
August	1508.64 ± 8.64	12.00 ± 3.44	13.47 ± 2.33	138.68 ± 8.68	223.80 ± 3.80

APPENDIX F:Monthly meansof Estuarine Acidification Factors in the Densu estuary

YEAR/MONTH	CARBON DIOXIDE $C0_2$	MINERAL SATURATION STATES FOR ARAGONITE (ΏAr)	MINERAL SATURATION STATES FOR CALCITE (Ώcalcite)	REVELLE FACTOR
2019/March	180.23 ± 0.23	171.68 ± 2.68	1.64 ± 0.22	2.44 ± 0.11
April	153.67 ± 0.67	145.90 ± 10.90	0.18 ± 0.03	0.31 ± 0.02
May	-15.05 ± -12.33	-14.46 ± -11.12	-0.14 ± -0.11	-0.23 ± -0.33
June	0.08 ± 0.01	0.08 ± 6.55	0.81 ± 0.02	1.39 ± 0.31
July	209.00 ± 9.00	201.28 ± 12.87	2.58 ± 0.13	3.91 ± 0.91
August	131.58 ± 3.78	126.72 ± 8.88	1.70 ± 0.70	2.57 ± 0.57
September	257.11 ± 5.71	247.60 ± 7.89	1.41 ± 0.41	2.12 ± 0.12
October	257.43 ± 7.43	246.82 ± 6.85	0.38 ± 0.03	0.60 ± 0.06
November	421.69 ± 3.99	403.54 ± 4.50	0.93 ± 0.01	1.42 ± 0.42
December	481.53 ± 2.88	461.64 ± 6.78	1.35 ± 0.03	2.07 ± 0.07
2020/ Feb	2752.55 ± 51.33	2632.61 ± 10.61	0.31 ± 0.11	0.47 ± 0.11
March	728.94 ± 8.94	695.43 ± 10.43	0.01 ± 0.00	0.01 ± 0.00
April	880.43 ± 8.22	837.68 ± 7.66	0.94 ± 0.03	1.40 ± 0.40
May	19685.28 ± 11.22	18894.26 ± 4.26	0.02 ± 0.01	0.04 ± 0.11
June	10987.23 ± 7.88	10579.59 ± 5.11	0.16 ± 0.01	0.20 ± 0.10
July	175.16 ± 4.33	169.34 ± 9.34	1.98 ± 0.20	3.36 ± 0.01
August	143.59 ± 1.90	138.25 ± 8.25	3.02 ± 0.23	4.61 ± 1.12

APPENDIX G: Monthly mean of Estuarine Acidification Factors in the Densu estuary, 2019-2020

YEAR/MONTH 2019	MINERAL SATURATION STATES FOR CALCITE (ΩCalcite)	REVELLE FACTOR	BICARBONATES ($HC0_3$) (µMOL/KGSW)	BUFFER ALKALINITY (BALK)
March	1.64 ± 0.22	2.44 ± 0.11	648.97 ± 0.97	137.59 ± 5.77
April	0.18 ± 0.03	0.31 ± 0.02	321.23 ± 11.23	4.75 ± 0.75
May	-0.14 ± -0.11	-0.23 ± -0.33	-54.45 ± -0.35	166.17 ± 7.14
June	0.81 ± 0.02	1.39 ± 0.31	8.51 ± 3.51	742.92 ± 2.90
July	2.58 ± 0.13	3.91 ± 0.91	972.82 ± 2.82	149.27 ± 4.93
August	1.70 ± 0.70	2.57 ± 0.57	626.02 ± 6.01	151.70 ± 1.70
September	1.41 ± 0.41	2.12 ± 0.12	811.37 ± 11.57	103.36 ± 3.39
October	0.38 ± 0.03	0.60 ± 0.06	361.31 ± 6.23	76.25 ± 6.25
November	0.93 ± 0.01	1.42 ± 0.42	739.92 ± 10.92	85.81 ± 6.87
December	1.35 ± 0.03	2.07 ± 0.07	980.19 ± 80.13	92.61 ± 2.67
2020/ Feb	0.31 ± 0.11	0.47 ± 0.11	1109.37 ± 12.78	20.98 ± 1.98
March	0.01 ± 0.00	0.01 ± 0.00	91.93 ± 3.33	6.61 ± 0.61
April	0.94 ± 0.03	1.40 ± 0.40	1091.08 ± 9.89	54.42 ± 1.91
May	0.02 ± 0.01	0.04 ± 0.11	1466.28 ± 6.23	0.14 ± 0.01
June	0.16 ± 0.01	0.20 ± 0.10	1440.56 ± 0.56	7.08 ± 0.08
July	1.98 ± 0.20	3.36 ± 0.01	687.53 ± 7.53	181.77 ± 1.77
August	3.02 ± 0.23	4.61 ± 1.12	851.39 ± 1.39	190.38 ± 2.33

APPENDIX H: Tidal changes in physicochemical parameters of Densu estuary for the two seasons during the study period (2019-2020)

Parameter	Mean ± S.E. Dry Season			Mean ± S.E. Wet Season		
	High Tide	Low Tide	Overall	High Tide	Low Tide	Overall
Temperature (^{O}C)	30.96 ± 0.32	33.28 ± 1.12	30.78 ±	28.02 ± 0.79	27.97 ± 0.44	27.49 ± 0.25
Depth (m)	0.64 ± 0.15	0.17-0.65	4.34 ±	0.72 ± 0.50	0.52 ± 0.06	5.29 ± 0.25
Total Dissolved Substances(mg/L)	25356 ± 1573.33	51.40-3080	30837.45 ±	186538 ± 10.81	1964 ± 62.81	1087.07 ± 15.90
Salinity (ppt)	30.29 ± 0.42	0.36-23.50	19.27 ±	18.09 ± 4.23	10.04 ± 3.21	11.02 ± 1.05
Dissolved Oxygen (mg/L)	5.55 ± 0.09	1.85-24.27	4.74 ±	15.41 ± 6.75	7.31 ± 2.91	17.16 ± 6.46
pH	8.01 ± 0.06	7.43-9.18	7.82 ±	8.19 ± 0.23	7.91 ± 0.23	7.94 ± 0.04
Conductivity (µs/cm)	46.82 ± 0.67	1.92-2867.67	307.80 ±	454.36 ± 24.21	688.96 ± 39.10	939.10 ± 14.3
Silicates (mg/L)	3.92 ± 0.52	12.5 ± 3.55	8.21 ± 2.50	11.42 ± 3.36	17.51 ± 3.60	14.47 ± 2.77
Chlorophyll a	3.13 ± 0.89	3.12 ± 0.36	3.12 ± 0.58	4.11 ± 0.54	4.08 ± 0.87	3.66 ± 0.40
Total ViableCounts (CFU/ml)	92.50 ± 1.50	74.01 ± 2.80	83.25 ± 5.96	69.50 ± 18.5	61.51 ± 7..50	65.59 ± 10.90
faecal coliform bacteria (CFC/ml)	0.50 ± 0.11	1.01 ± 0.01	0.88 ± 0.22	24.00 ± 0.99	41.500 ± 10.50	32.75 ± 8.70
Escherichia coli (CFC/ml)	0.51 ± 0.01	1.50 ± 0.01	1.00 ± 0.05	32.10± 0.29	18.01 ± 0.61	25.28 ± 6.81
Arsenic (mg/L)	0.07 ± 0.01	0.05 ± 0.02	0.04 ± 0.01	0.09 ± 0.00	0.08 ± 0.01	0.06 ± 0.01
Lead (mg/L)	0.058 ± 0.01	0.031 ± 0.00	0.05 ± 0.01	0.038 ± 0.01	0.02 ± 0.00	0.03 ± 0.01
Cadmium (mg/L)	0.05 ± 0.00	0.038 ± 0.00	0.04 ± 0.01	0.04 ± 0.01	0.07 ± 0.01	0.05 ± 0.01
Mercury (mg/L)	<0.001	<0.001	<0.001	<0.001	0<0.001	0.001 ± 5.27E-05

Total alkalinity (µmol/kg)	559.96 ± 46.00	1263.63 ± 74.33	911.79 ± 27.8	1143.97 ± 59.44	1086.67 ± 214.91	1115.32 ± 104.69
Total carbon dioxide (TCO_2),	437.19 ± 44.00	1069.36 ± 129.80	753.27 ± 26.1	1161.40 ± 134.65	999.63 ± 196.10	1080 ± 118.45
Carbon dioxide fugacity ($fC0_2$)	128.24 ± 11.23	228.708 ± 10.23	178.47 ± 72.75	5701.13 ± 48.70	211.61 ± 32.39	2956.37 ± 27.25
Carbon dioxide fugacity ($fC0_2$)	128.24 ± 11.23	228.708 ± 10.23	178.47 ± 72.75	5701.13 ± 48.70	211.61 ± 32.39	2956.37 ± 27.25

APPENDIX I: Monthly ranges in physicochemical parameters of Densu estuary(2019-2020)

Parameter	**Range**	**Mean** ± S.E.
Temperature (^{O}C)	24.04-34.74	28.83 ± 6.43
Depth (m)	0.54-1.00	0.61 ± 0.07
Total Dissolved Substances(mg/L)	51.40-8801	3550.58 ± 790.24
Salinity (ppt)	0.36-35.11	16.41 ± 3.65
Dissolved Oxygen (mg/L)	1.85-24.27	6.09 ± 1.36
pH	7.43-9.47	8.07 ± 1.80
Conductivity (µs/cm)	1.92-2867.67	453.14 ± 94.27
Silicates (mg/L)	3.00-19.90	11.79 ± 3.65
Chlorophyll a	1.26-11.49	4.45 ± 1.04
Total Viable Counts (CFU/ml)	19.00-99.00	64.36 ± 10.58
faecal coliform bacteria (CFC/ml)	0.00-55.00	22.89 ± 3.76
Escherichia coli (CFC/ml)	0.00-50.00	17.08 ± 2.81
Arsenic (mg/L)	0.001-0.088	0.05 ± 0.01
Lead (mg/L)	< 0.0001-0.068	0.03 ± 0.01
Cadmium (mg/L)	0.043-0.088	0.05 ± 0.01
Mercury (mg/L)	<0.0001	< 0.001
Total alkalinity (µmol/kgSW)	99.91 -1511.01	936.42 ± 104.61
Total carbon dioxide (TCO_2) (µmol/kg SW)	67.53 – 2052.73	834.62 ± 111.57
Carbon dioxide fugacity ($fC0_2$) (µatm)	0.08-18894.27	1657.67 ± 948.23
Seawater partial pressure of carbon dioxide (pC02), (µatm)	-14.50-10612.63	4746.72 ± 88.01
Carbon dioxide concentration ($C0_2$) (µmol/kg SW)	-0.34—585.23	140.90 ± 32.23
Mineral saturation states for calcite (Ώcalcite)	-0.23-4.61	1.39 ± 0.32
Mineral saturation states for aragonite (ΏAr)	-0.144-4.61	0.90 ± 0.21
Revelle factor	0.28-16.36	3.50 ± 0.80
Bicarbonates ($HC0_3$) (µmol/kgSW)	-54.45-1440.56	430.32 ± 98.00

Carbonates ($C0_3$) (µmol/kg SW)	-12.75-183.55	70.62 ± 16.20
Hydroxyl ions (OH) (µmol/kgSW)	0.32-322.69	7.18 ± 1.64
Buffer alkalinity (BalK) (µmol/kg SW)	0.140-742.92	161.90 ± 37.15

Appendix J: Monthly variations in CPUE of commercial and experimental oyster fishing in Densu estuary in 2019 and 2020

Month	**Experimental (kg/hr/fisher/day)**	**Commercial (kg/hr/fisher/day)**
March_2019	30.88 ± 3.11	18.11 ±0.11
April_2019	33.57 ± 6.00	16.79 ± 3.00
May_2019	79.67 ± 10.00	39.84 ± 2.50
June_2019	132.5 ± 15.00	66.25 ± 9.33
July_2019	52.50 ± 4.90	26.25 ± 5.00
August_2019	43.20 ± 5.00	21.60 ± 5.30
Sep_2019	10.00 ± 1.30	3.00 ± 1.30
Oct_2019	10.00 ± 3.00	5.00 ± 2.00
Nov_2019	52.50 ± 4.90	26.25 ± 5.00
Dec_2019	43.20 ± 5.00	21.60 ± 5.30
Jan_2020	16.00 ± 1.30	10.00 ± 1.00
Feb_2020	15.00 ± 3.00	8.00 ± 2.00
March_2020	32.50 ± 3.90	26.25 ± 3.00
April_2020	60.00 ± 7.10	30.00 ± 1.20
May_2020	85 .00 ± 8.30	42.50 ± 8.30
June_2020	200.00 ± 5.00	100.00± 11.00
July_2020	105.00 ± 8.00	52.50 ± 6.00

August_2020	126 .00 ± 12.00	63.00 ± 16.00

Appendix K: Descriptive statistics of biological parameters of the mangrove oyster in Densu

Biological parameter	**Range**	**Mean ± S. E**
Shell Width (cm)	1.00-3.00	3.53 ± 0.178
Shell Height (cm)	3.44-8.24	6.11 ± 0.28
Shell Weight (g)	7.70 -66.70	19.17 ± 4.16
Shell Length (cm)	2.24-5.13	2.24 ± 5.13
Relative Abundance (kg/hr/fisher/day)	15.00-500.00	15.00-500.00
Condition factor	30.00-300.00	30.00-300.00

Appendix L: Exposure parameters used for the health risk assessment USEPA (2004)

Value parameter	**Child**	**Adult**
Body weight (BW)	15	70
Exposure Frequency (EF)	6	30
Exposure Time (ET)	1	0.58
Ingestion Rate (IR)	1	2
Skin Surface Area (SA)	6600	18,000
For carcinogenic	365 *70	365 *70
For non-carcinogenic	365 * ED	365 * ED