UNIVERSITY OF CAPE COAST

A STUDY ON THE FISHERY, ASPECTS OF THE BIOLOGY AND CULTURE OF THE WEST AFRICAN MANGROVE OYSTER, *CRASSOSTREA TULIPA* IN THE DENSU DELTA, GHANA

BY

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DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature..... Date..19th June 2020

Name:..ISAAC KOFI OSEI.....

Supervisor's Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

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ABSTRACT

The study investigated the oyster fishery, aspects of the biology and the culture of *Crassostrea tulipa* in the Densu Delta, Ghana, from May 2017 to October 2018. Almost all the oyster fisherfolk sampled were females, mainly between the ages of 35 to 44 years, with many dependants. The annual catch was estimated to be 295 tonnes, with an appraised value of USD 65,559. The total annual cost of fishing, gross annual income and total annual profit were estimated at USD 11,897, USD 39,993 and USD 28,097, respectively. Generally, the oysters exhibited negative allometry. Oysters in the shallow waters (0.61 m depth) were depleted within six months, but the deep water (2.13 m depth) oysters were underexploited. Generally, the monthly sex ratios of the oysters did not deviate from unity. Unlike the deep water oysters, those from the shallow beds exhibited continuous spawning. None of the physico-chemical parameters predicted breeding. However, oyster condition index was significantly influenced by salinity, pH and phosphate concentrations. Growth and survival of oysters were better when cultured in suspension than at the bottom. Biofouling had no deleterious effect on the growth and survival of oysters cultured on coconut-shell and oyster-shell cultches. Proximate analysis revealed that cultured oysters had a significantly higher composition of carbohydrate and moisture than in wild oysters, while protein, lipids, ash and fibre were comparable in both treatments. Oyster consumers preferred the taste of cultured oyster meat to wild oyster meat. Regulation of the fishery, large-scale cultivation and value-addition are recommended to create jobs, maximise income and to meet both local and international demands.

KEY WORDS

Biofouling

Crassostrea tulipa

Oyster culture

Reproduction

Socioeconomics

TropFishR

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DEDICATION

To my family:

Samuel, Beatrice, Hellen, Christiana, Alice, Rebecca and Aaron

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LIST OF ACRONYMS

AOAC	Association of Official Analytical Chemists
BOD	Biological Oxygen Demand
BPR	Biomass per Recruit
CI	Condition Index
CS	Coconut-shell
DAA	Development Action Association
DO	Dissolved Oxygen
ELEFAN	Electronic Length Frequency Analysis
EPA	Environmental Protection Agency (United States)
FAO	Food and Agriculture Organisation
FAO/FiSAT	FAO ICLARM Fish Stock Assessment Tool
GI	Gonad Index
GR	Growth Rate
GSS	Ghana Statistical Service
GVF	Gamete Volume Fraction
MI	Morphological Index
MoFAD	Ministry of Fisheries and Aquaculture Development (Republic of Ghana)
NERR	National Estuarine Research Reserve

NOAA	National Oceanic and Atmospheric Administration (United States)
NRC	National Research Council
NTU	Nephelometric Turbidity Unit
OS	Oyster-shell
PDST	Professional Development Service for Teachers
SDG	Sustainable Development Goals
SH	Shell Height
SL	Shell Length
SW	Shell Width
SFMP	Sustainable Fisheries Management Project
USD	United States Dollar
VBGF	von Bertalanffy Growth Function
YPR	Yield per Recruit

CHAPTER ONE

INTRODUCTION

In the face of a near-collapsed marine fish stocks off Ghana, it is prudent to promote aquaculture by focusing on increasing the number of culture species and scaling up the culture systems to offset the deficit in fish protein as well as revamping the overexploited capture fisheries. Aside from the cultured finfish in Ghana (i.e., Nile tilapia, *Oreochromis niloticus* and mudfish, *Clarias gariepinus*), shellfish (bivalves) especially oysters have been reported by Obodai and Yankson (2000) and Yankson (2004) to exhibit cultivable potential on a large scale. Though information on some oyster fisheries in Ghana and elsewhere are available (e.g., Ansa & Bashir, 2007; Asare, Obodai & Acheampong, 2019), there is no information on the assessment of the oyster fishery, its biology and culture potentials in the Densu Delta, despite its high yield. Owing to the possibly different environmental conditions of the Densu Delta, there is a need to undertake this current research to guide stakeholders to make informed decisions on the sustainable exploitation and development of the oyster fishery and its culture to optimize yield as well as the promotion of the oyster resource.

1.1 Background of the Study

In literature, the West African mangrove oyster has been referred to by two species names, *Crassostrea tulipa* (Lamarck, 1819) and *C. gasar* (Dautzenberg, 1891). A study on the genetic analysis of the mitochondrial DNA of these two species by Lapegue et al. (2002) indicated that the two scientific names referred to the same organism. On the decision of which specific name to adopt, *C. tulipa* is preferred to *C. gasar* due to the precedence of the former

to the latter in literature. Yankson (1991) addressed the earlier confusion on the nomenclature of the species by giving a comprehensive discussion on the matter, which ended with the recommendation of referring to the West African mangrove oyster as *C. tulipa*. Given this, the species name *C. tulipa* was used in this document.

Bivalves (oysters, scallops, mussels and clams) are of immense importance, notably are their use as a source of food, rendering of ecological services and diverse use of the shells. According to Galtsoff (1964), irrespective of the taxonomic group to which an animal belongs, the greatest mass of materials that form the tissues and organs comprises three major groups, i.e., proteins, carbohydrates and lipids. Aside from the major groups, *C. tulipa* populations in Ghana have been found by Obodai (1990) and Yankson, Plahar and Obodai (1994) to provide a year-round rich source of calcium, iron and phosphorus. The National Research Council [NRC] (2010) listed several bivalve ecological services as turbidity decrease by filtration, biodeposition of nutrients and organic carbon, provision of structural habitat for epibionts, finfish, and shellfish as well as shoreline stabilisation. On the usage of shells, Obodai (1990) and Yankson (1977) reported on the local use of bivalve shells in some coastal communities in Ghana, as a source of calcium in poultry feed, paint production, base for footpaths, concrete for building, source of lime in agriculture and medicinally for treatment of burns and asthma.

Some fish production policies and regulations geared towards revamping collapsed and dwindling fisheries, developing fish stocks as well as improving on the yield of aquaculture have been enacted both globally and locally. At the global level, in line with the Food and Agriculture Organisation

Code of Conduct for Responsible Fisheries (FAO, 1995), the 2030 Agenda for Sustainable Development aims at the "contribution and conduct of fisheries and aquaculture towards food security and nutrition, and the sector's use of natural resources, in a way that ensures sustainable development in economic, social and environmental terms" (FAO, 2018a, p. 18). Moreover, particularly, as presented by FAO (2017), the Sustainable Development Goal (SDG) 14 focuses on conservation and rational use of the oceans, seas, and marine resources for sustainable development. The implementation of the SDGs is to be carried out by countries through the application of scientific information. At the local level, the Ghana Fisheries Act 625 (2002) stipulates that Ghana's fisheries resources and aquaculture are regulated and well managed. According to the Ghana Fisheries Act 625(2002, p.16), PART IV – Fisheries Management and Development, Sub-Part – fishery Plans, "A fishery plan prepared by the Commission for the management and development of fisheries shall (a) be based on the best scientific information available; (b) ensure the optimum utilization of the fishery resources but avoid overexploitation; and (c) be consistent with good management principles." As part of the content of a fishery plan, fishery resources and their characteristics are to be identified; assessed to ascertain the current state of exploitation based on relevant social, economic and biological factors to determine potential average annual yields; and the measures taken to promote the development of the resources specified.

The reduction of natural fish stocks is a problem related to social welfare and global food security, according to King (2007). Pillay and Kutty (2005) highlighted the overfishing and depletion of fish stocks as a living reality. They pointed out the recognition by management bodies in appreciating the necessity

to recover or create new stocks by human intervention. Based on FAO (2018a), it is clear that there is a steady surge in aquaculture production. The continual increase in the world's aquaculture production stands to reason that the culture of fish has the potential to feed the increasing population of humans in the face of dwindling capture fisheries production.

The following are some key statistics on global fisheries and aquaculture from FAO (2018a): (a) in the year 2016, the total global fisheries and aquaculture (food fish) productions in weight was estimated at about 171 million tonnes, valued at USD 362 billion, of which capture fisheries and aquaculture contributed about 53 % (91 million tonnes, valued at USD 130 billion) and 47 % (80 million tonnes, valued at USD 232 billion), respectively; (b) a breakdown of aquaculture production was given as 54.1 million tonnes of finfish (USD 138.5 billion), 17.1 million tonnes of molluscs (USD 29.2 billion), 7.9 million tonnes of crustaceans (USD 57.1 billion) and 938,500 tonnes of other aquatic animals (USD 6.8 billion) such as turtles, sea cucumbers, sea urchins, frogs and edible jellyfish; (c) in Africa, the marine and coastal aquaculture production (live weight) of finfish, molluscan, crustacean and other aquatic organisms contributed about 17,000 tonnes, 6,000 tonnes, 5,000 tonnes and none, against the world's production of 6.6 million tonnes, 16.8 million tonnes, 4.8 million tonnes and 407, 000 tonnes, respectively; and, (d) bivalves contributed about 29 % in value and 58 % by live weight of the total world trade of molluscan production (11.0 % and 11.1 % of value and weight respectively, of the world trade of fish and fish products). The proportions of selected dominant shellfish that contributed to the world's production in terms of both wild and cultivated bivalves in percentage were given as oysters 54 %, scallops

24 %, mussels 18 % and clams 4 % (FAO, 2018b). In Ghana, according to MoFAD (2017), aquaculture contributed about 11 % (57,405 tonnes) to the total fish production, which compares unfavourably with capture fisheries, 89 % (419,181 tonnes). Moreover, there is lack of data on the annual capture shellfish production in the marine, coastal and inland waters coupled with no reported commercial shellfish aquaculture production in Ghana.

The FAO (2017) and Vakily (1989) have indicated that the alarming decrease in some of the traditional finfish fisheries and the increasing demand for food production have necessitated the development of commercial bivalve farming in many parts of the world. The most farmed and traded bivalves globally, as presented by FAO (2018a) and Yankson (2004), are oysters, mussels, clams and scallops, which among their many benefits are food security, job creation and a lucrative commercial venture. Despite the above benefits, the culture of bivalves in Ghana remains an untapped potential (Yankson, 2004). Bivalves are highly promoted as healthy and sustainable food fish and in recent years, its demand is on the hike as reported by FAO (2018a). In West Africa, there is a surge in the interest of oyster culture, which is compelled by its potential to provide jobs for coastal dwellers. In Ghana, among the bivalve shellfish species that occur, *C. tulipa* is the most studied and can be cultured for mass production, according to Obodai (1997), Yankson (2004) and Yankson et al. (1994). Nevertheless, there is currently no recognised commercial cultivation of oysters in Ghana.

The oyster fishery in the Densu Delta can be described as open access and unregulated resource. However, the fisherfolk have built strong relationships through many years of exploiting the resource, which has led to

the formation of the Densu Oyster Pickers Association (DOPA) and the Development Action Association spearheaded by the Sustainable Fisheries Management Project (SFMP) to assist in the management of the oyster fishery. These institutions have been working supportively with the individual oyster fisherfolk to develop management strategies for the sustainability of the resource and to optimise yield. Notable of the initial efforts towards the sustainable management of the valuable resource was the quest for scientific understanding of the oyster fishery; this necessitated the current study. As the oyster fishery develops by the recruitment of new harvesters because of its increasing popularity, coupled with the low marine fish catches in recent times, the fishing effort is expected to intensify which might lead to the collapse of the fishery. Though the Densu Delta was designated as a wetland of international importance (Ramsar site) in the year 1992 to facilitate the conservation and sustainable use of the wetland, there was no strategy for the rational exploitation of the oysters in the management plan by Oteng-Yeboah (1999).

1.2 Statement of the Problem

There is limited information on the socioeconomic aspect of the oyster fishery in the Densu Delta. In the West African sub-region, *C. tulipa* fishery has been reported to have considerable economic potential, yet exploitation of the resource is limited to wild populations (Ajana, 1980; Yankson, 2004). Even though Janha, Ashcroft and Mensah (2017) reported on a participatory rural appraisal of the oyster fishery at the Densu Delta, where a preliminary assessment was made on aspects of the socioeconomics of the fishery, there is a dearth of detailed information on the demography of the resource users, its yield (value) as well as the profitability of the fishery.

For the rational management and development of the oyster fishery as well as its culture, there is a need to acquire scientific knowledge on the environment and aspects of the biology of the species. Physico-chemical factors may impinge on the growth, reproduction and survival of bivalves (Gosling, 2015). For a thriving oyster culture in the Densu Delta, information on the temperature, dissolved oxygen, salinity, pH, turbidity, nitrate and phosphate levels as well as bulk density of the sediment must be acquired to guide the choice of culture methods.

Information on aspects of the biology bordering on the growth, mortality, recruitment, exploitation rates and reproduction of the oysters in the Densu Delta is lacking. Some reproductive biology of bivalve populations have been studied in Ghana, including, *C. tulipa* (Obodai, 1990; Yankson, 1996), *Perna perna* (Krampah, Yankson & Blay, 2016), *Etheria elliptica* (Ampofo-Yeboah, Owusu-Frimpong & Yankson, 2009) and *Galatea paradoxa* (Adjei-Boateng & Wilson, 2011). However, owing to the possibly unique environmental conditions of the populations as well as the peculiarity at the species level, it is prudent to evaluate the sex ratio and the spawning pattern of the oyster population in the Densu Delta.

In some parts of the world, including Asia and Europe, commercialisation of oyster culture is far advanced (FAO, 2018a). This development was realised by the acquisition of requisite knowledge on the culture species as well as the medium of culture. Despite the awareness of the economic potential of *C. tulipa*, the cultivation of the species is virtually at the experimental level in the West African sub-region (Adite, Abou, Sossoukpe & Fiogbe, 2013; Ajana, 1980). The oyster population in the Densu Delta lacks

information that will inform the cultivation of the species. Hence the need to investigate the suspension and bottom culture methods as well as the effects of biofouling on the growth and survival of oysters with respect to different cultches. Aside from the direct application of the above study in the Densu Delta, the outcome will push the frontiers of knowledge concerning the growth and survival performance of oysters cultivated by suspension and bottom culture methods or cultured on biofouled and cleaned cultches of coconut-shells and oyster-shells.

Oyster meat is tagged in the Western world as a first-class food that contains high quality protein, rich in valuable lipids and essential minerals, which are all vital for a balanced diet (Ajana, 1980; FAO, 2018a). Communities around the Densu Delta utilise shellfish as a cheaper source of protein compared to finfish and other forms of animal protein. There is a necessity to undertake this study to inform stakeholders on the nutritional value of wild and cultured oysters, to promote the culture of the *C. tulipa* as well as to enhance the popularity of the food fish in the coastal communities of Ghana and West Africa as a whole, and subsequently enhance the profitability.

It is highly probable that the lack of information on taste analysis of wild and cultivated *C. tulipa* could be one of the reasons why the culture of the species is unpopular in the coastal communities, despite its cultural potential. In an attempt to promote the cultivation of *C. tulipa* in the Densu Delta and coastal communities of Ghana at large, it is essential to undertake a taste evaluation of wild and cultured oysters to ascertain if cultured oysters are comparable with wild oysters.

Hence the necessity to investigate the fishery, aspects of the biology and the culture methods to be employed for sustainable management, development and culture of the species in Densu Delta.

1.3 Purpose of the Study

The study seeks primarily to furnish stakeholders with the necessary information on the oyster fishery, aspects of the biology and the right culture techniques to implement for the optimisation and sustainable management of the resource as well as to stimulate the extensive cultivation of oysters at the Densu Delta and other oyster populations in Ghana, at large.

1.4 Research Objectives

The overarching goal of this study was to investigate the oyster fishery, aspects of the biology, the right culture methods to implement in the cultivation of *C. tulipa* in the Densu Delta, Ghana.

The specific objectives of the study were to:

1. Assess the socioeconomic aspect of the oyster fishery.
2. Monitor some physico-chemical factors and their possible influence on the breeding pattern and condition of the oyster population.
3. Assess the population parameters of the oyster fishery.
4. Determine aspects of the reproduction and condition index of the oyster population.
5. Conduct a comparative study on the growth and survival of oysters grown by suspension and bottom culture methods in the wild.
6. Assess the impact of sedentary fouling organisms on the growth and survival of oysters.

7. Compare the proximate composition and taste of wild and cultured oysters.

The following hypotheses guided the study:

1. The individual physico-chemical factors at the Densu Delta do not directly influence oyster breeding pattern and condition.
2. The sex ratio of the oysters at the Densu Delta is not 1:1.
3. Growth and survival of oysters do not vary when cultivated on different surfaces of coconut-shell and oyster-shell cultches.
4. Fouling organisms do not affect the growth and survival performance of oysters on the surfaces of coconut-shell and oyster-shell cultches.
5. Wild oysters do not have higher nutritional value than cultured oysters.
6. Wild oysters do not have better taste than cultured oysters.

1.5 Significance of the Study

Detailed socioeconomic information are fundamental to the formulation of fisheries policies and management plans to optimise yield, increase profitability and ensure the sustainability of the fisheries (FAO, 2006). Social information, including gender roles, age structure and alternative livelihoods of the fishers, are necessary to strengthen both operational and strategic management decisions. Such information and its implementation in management strategies could circumvent the extermination of the oyster population in the Densu Delta.

The application of scientific knowledge in the development of rational management strategies to regulate a fishery is founded on the understanding of the fish's biology. The above sets the basis to enhance a given environment. Principally, information on the physico-chemical factors, population

parameters, reproduction and knowledge gained from the culture experiments will be useful in the choice of appropriate culture technique to be adopted, site selection and when to commence the cultivation of oyster seed in the Densu Delta. The physico-chemical factors like temperature, DO, salinity, turbidity, nitrate and phosphate concentrations as well as bulk density of sediments, will assist in the discussion of other components of the study.

Even though bivalves contribute about 2 % to the global capture fishery landings, their generally high unit price compensates for the smaller landed weight when compared with the combined categories of fish, crustaceans and other molluscs according to Gosling (2015). For sustainable exploitation of bivalves, efficient approaches to the conservation, management and development of wild populations must be established. To strategically plan and manage bivalve fisheries, knowledge of growth and mortality parameters as well as the exploitation level of the population is pertinent. Upon establishing the status of a particular fishery, the right management plans and regulations can be formulated for optimal utilisation of the resource.

Sex ratio and spawning pattern as well as the condition of fish provide essential information for the conservation and sustainable fisheries management as well as optimising yield (da Costa et al., 2012). Knowledge of the seasonal fatness (plumpness) cycle is of utmost importance for market purposes since changes in the meat size affects the financial returns. Furthermore, knowledge of timing and intensity of spawning events could offer valuable information for the prediction of spatfall.

Suspension and bottom culture as well as biofouling study on the growth and survival performance of cultivated oysters are needed where bivalve culture

is being developed, to guide the necessary culture techniques to employ. Thus, whether to adopt the suspension or bottom culture method or the need for getting rid of fouling organisms on cultches (Quayle & Newkirk, 1989). The use of different cultches (i.e., coconut-shells and oyster-shells) will bring to the fore the material which supports growth and survival better. The choice of using coconut-shell and oyster-shell as suitable collectors for the current study was based on a recommendation by Obodai (1990) in investigating into the efficiency of different types of collectors, their availability and cost of acquiring the cultch materials. Growth and survival performance of bivalves could be influenced by the depth of rearing structures (Glasby & Connell, 2001; Lacoste & Gaertner-Mazouni, 2015), hence, the premise for the study to cover suspension and bottom cultures as well as top 2-collectors and bottom 2-collectors of cultches held in suspension with respect to biofouling. Besides, it has been reported that spat prefer the undersurface (concave side) of collectors to the upper surface, convex side (Obodai, 1990; Quayle, 1980). Hence the need to ascertain the growth and survival performance of oysters on these surfaces over time.

A study on the proximate and taste analyses of cultured and wild oysters will sensitise fishers to consider the cultivation of oysters to aid in bridging the gap in the protein demand. Moreover, such knowledge could also form the basis to facilitate the promotion of the food fish (oysters), which will eventually improve on the returns of fishers in Ghana and the West African sub-region, where coastal communities mainly patronise it as a source of protein.

1.6 Delimitations

The study was carried out on the *C. tulipa* population at the Densu Delta in the Greater Accra Region of Ghana to draw some information on the fishery, physico-chemical factors, biology, culture methods to adopt and proximate and taste analysis for the promotion of the oyster business. Moreover, oyster fisherfolk from Bortianor/Tsokomey and Tetegu communities around the Densu Delta were interrogated by the use of an interview guide to elicit information on the socioeconomic aspect of the fishery.

1.7 Limitations

Sampling of oysters at Station 3 (out of the three oyster sampling sites) was impractical from May to November 2017 and July to October 2018 because of the extermination of oysters at the station. Individuals involved in the oyster harvesting, processing and marketing were drawn from Bortianor/Tsokomey and Tetegu. Inhabitants of Faana (the community on the dunes, see Fig. 1) who exploited the oyster fishery were captured in the Bortianor/Tsokomey group. This is because most of the inhabitants of Faana partly live in Bortianor/Tsokomey in order to access some social amenities. Besides, inhabitants of Faana occasionally resettle in Bortianor/Tsokomey when the Faana community gets inundated. This is the reason why Faana was not captured as a sampling community in this study.

1.8 Definition of Terms

Biofouler/ Fouling organism/ Epibiont – nuisance organism that grows around and/or on the desired species.

Collector – a unit material used as a substrate for the setting of oysters

Cultch – strung collectors used as substrates for the setting of oysters

Culture – to grow organisms under suitable conditions

Larval setting/Settlement – the attachment of oyster larvae to a substrate

Migrant – a person who settles at another location other than his/her place of origin for economic gains

Native/Indigene – an original inhabitant of a place

Settler – a person who travels to live in a new place permanently

1.9 Organisation of the Study

This study is structured into six chapters. The first chapter consists of a background to the study, statement of the problem, the purpose of the study, research objectives and hypothesis, significance of the study, delimitation, limitations and the organisation of the study. Review of literature is presented in Chapter Two, which borders on socioeconomic assessment, physico-chemical factors, population parameters, reproduction, culture methods as well as proximate and taste analyses to establish the theoretical basis. Chapter three is about the materials and methods of the study with a focus on the study area, data collection and data analyses to mainly address the research objectives. The findings are presented in Chapter Four, which comprised figures and tables with statistical analyses as well as comments of the results. Chapter Five is a discussion of the results with reference to relevant literature. Chapter Six presents the summary, conclusions of the findings and recommendations of the study.

CHAPTER TWO

LITERATURE REVIEW

This study borders on the fishery, aspects of the biology and culture of *Crassostrea tulipa* to inform policies and strategies for the optimisation of yield, sustainable management and cultivation of oysters in the Densu Delta. Chapter Two presents a review of the literature covering the subject under investigation. The literature review is organised under the following thematic areas: general oyster biology and ecology, socioeconomic assessment of oyster fisheries, physico-chemical parameters, population parameters and dynamics, reproductive biology of oysters, suspension and bottom culture, biofouling, nutritional value and taste evaluation of oysters. Again, the thematic areas are structured by way of introduction, body (background to methodology, theories/concepts and past and current research) and conclusion (literature gaps) except for general oyster biology and ecology as well as physico-chemical parameters.

2.1 General Oyster Biology and Ecology

Researchers have given the biology and ecology of bivalves immense attention due to their high commercial value and cultivation potential. Oysters are arguably the most studied invertebrates, according to Angell (1986). Their biology and ecology have been extensively studied.

Oysters belong to Kingdom Animalia, Phylum Mollusca, Class Bivalvia and Order Ostreida. Earlier, the living oysters were grouped under the families Ostreidae and Gryphaeidae. However, according to Quayle (1980), most members of Gryphaeidae are extinct and the extant species have been reassigned to Family Ostreidae. There are many genera of living oysters that exist in

literature but the genera *Crassostrea*, *Saccostrea* and *Ostrea* contain the most commercially important species (Angell, 1986).

Oysters occupy coastal marine and brackishwater systems, spanning from temperate, subtropics to tropical latitudes worldwide (Gosling 2015; Ruesink et al., 2005). According to Angell (1986), like the *Ostrea* spp., *Crassostrea* spp. inhabit all tropical seas except Polynesia and Melanesia, while *Saccostrea* spp. are confined to the Indo-Pacific waters. Currently, due to the invasion of new habitats or the introduction of foreign oyster species, extermination and increased research on oyster populations around the globe, there is a possibility of some changes in the geographical distribution of oyster species. Gosling (2004) reported that the black-bordered oyster, *Saccostrea echinata* and the Indian rock oyster, *S. cucullata* have a wide distribution, with the latter species spanning from the shores of East coast of Southern Africa through the Indian Ocean to the coast of the Philippines.

Regionally, Bayne (2017) describes oysters to be principally coastal, inhabiting the intertidal and or shallow subtidal areas of estuaries, lagoons, marshes and bays. Locally in Ghana, oysters (*C. tulipa*) are found in clusters on mangrove roots, shells, rocks and any hard or firm substrates in lagoons and estuaries. *C. tulipa* dwells in coastal water bodies from Senegal to Angola and is known to be one of the essential commercial bivalves in the world (Gosling, 2004; Yankson, 2004).

Generally, bivalves are sexually monomorphic, dioecious and sex ratio is unity. On sexual development and spawning mode of oysters, both *Crassostrea* spp. and *Saccostrea* spp. according to Angell (1986) and Galtsoff (1964), are dioecious and oviparous, while species of *Ostrea* are hermaphrodite

and larviparous. Oysters, like most bivalves, acquire food by filtering suspended particles in the water. Food particles for oysters consist mainly of phytoplankton and detritus.

2.2 Socioeconomic Assessment of Oyster Fisheries

According to Pinello, Gee and Dimech (2017), socioeconomic information is a vital constituent of the scientific guidance needed for the evidence-based management of fisheries. However, this information is limited in many cases. FAO (2002) reported that fish and fisheries form a significant part of societies around the world and make vital contributions to the economic, social health and well-being of people. Detailed socioeconomic information is fundamental to the formulation of fisheries policies and management plans to ensure the sustainability of the fisheries, optimise yield and increase the profitability of the business (FAO, 2006).

The sampling approach, as opposed to census, has been used extensively in this kind of study due to time and financial constraints. Moreover, due to the sensitivity and complexity of some information, respondents may not grant an interview, hence the difficulty in undertaking the census approach. Sampling in social research has been carried out by two broad approaches, namely probability and non-probability. Probability sampling, according to Levine, Weber, Park and Hullett (2008), is the selection of sampling subjects based on known probabilities, which permits mathematically sound and unbiased inferences about the population of interest. These include simple random sampling, stratified sampling and systematic sampling.

On the other hand, in non-probability sampling, the sample subjects are selected without any knowledge of their probabilities. The literature indicate

that the types of non-probability approach consist of snowball sampling, quota sampling, convenience sampling and purposive sampling. Battaglia (2011) showed that the non-probability techniques are used extensively for their advantages of low cost, convenience, speed and for populations that are less defined. Snowball or chain-referral sampling is defined as a technique for finding research subjects where a subject gives the researcher the name of another subject, who in turn provides the name of a third, and so on (Vogt, 1999). Among the many reasons for using the snowball sampling technique are its cost-effectiveness, the difficulty in accessing subjects, sampling hesitant subjects and having an undefined target population.

Etikan, Alkassim and Abubakar (2016) presented three types of snowball sampling as linear, exponential discriminative and exponential non-discriminative snowball approaches. These are explained as (a) linear snowball approach, sampling by starting with one subject, and the subject provides only one referral and so on until the required number is attained; (b) exponential discriminative snowball approach, samples are obtained by multiple referrals from a subject but only one is sampled; whereas (c) exponential non-discriminative snowball approach, samples are obtained by engaging all multiple referrals from a subject and so forth until the required number is attained. Several researchers, like Abarike, Alhassan and Alipi (2015) and Cinner and McClanahan (2006), used the snowball sampling method to elicit socioeconomic information of fisheries. However, a simple random stratified sampling was used by Asare et al. (2019) in investigating the socioeconomic aspect of the Nakwa oyster fishery. In the present study, snowball sampling (i.e.,

exponential non-discriminative) was used, mainly because of the hesitant subjects and the cost-effectiveness of the approach.

Fisheries regulation and management have traditionally focused on the acquisition and implementation of biological data, fisheries data and sometimes economic data (cost and profit). A review of literature on the socioeconomics of fisheries by Charles (1988) indicated that there is a recognition that socioeconomic factors are vital in understanding the modern fisheries dynamics, hence its inclusion in the quest to gather data for sustainable management of a fishery. Since then series of international reports like FAO (1995 & 2006) and Pinello et al. (2017) have advocated for social information including age structure, gender roles and livelihoods of the fishers to strengthen both operational and strategic management decisions. According to Charles (1988), the effectiveness of a proposed fishery regulation strategy depends on, in part, the behavioural response of fishers and the community, which is also influenced by their socioeconomic conditions and the property right structure of the fishery. Currently, many vital fisheries have moved from the open resource fishery to a well-managed resource, where access is regulated.

Generally, the fishery sector all over the world has contributed immensely to food security, employment as well as foreign exchange. In Ghana, some studies on socioeconomic aspects of bivalve fisheries have been undertaken. Adjei-Boateng, Agbo, Agbeko, Obirikorang and Amisah (2012) in reporting on the Volta clam (*Galatea paradoxa*) fishery documented that the fishery has been an essential source of protein and employment to neighbouring communities. The authors observed 251 fishing canoes and 503 fishers engaged in the clam fishery with an estimated mean daily catch per canoe of 130 kg, an

annual yield of 7700 tonnes worth GHS 4,620,408. On the same clam fishery, Abarike et al. (2015) concluded that the fishery supported the livelihood of poor women aged between 30 and 35 years with a low level of education and a high number of dependants. Asare et al. (2019) also reported on an oyster fishery at Nakwa, where again, women dominated the fishery with low educational background. It was reported that oysters were available all year-round and 60 % of the fishers exploited the oyster for sale, subsistence purpose or both. By studying the socioeconomics of the general fisheries at Kpong, Ayisi (2015) reported male dominance in the fisheries with the majority of fishers between 24 – 29 years. The Kpong fishers who were mainly married had a low level of education. Detailed socioeconomic information on the *C. tulipa* fishery are lacking in the Densu Delta and West Africa as a whole.

In Ghana, there is a need to capture the bivalve shellfish production in its national fisheries production to ascertain its significance in the overall fishery to draw the necessary management intervention for their sustainable exploitation.

2.3 Physico-chemical Factors

It is known that the distribution, growth, reproduction and survival of bivalves are impinged on by some physico-chemical parameters. Temperature and salinity were mentioned by Gosling (2015) as the two most important factors that control the spatial distribution and abundance of bivalves as well as influencing all aspects of their biology. This section reviews literature mainly on the effects of temperature, dissolved oxygen, salinity, pH, turbidity, nutrients (nitrate and phosphate) and bulk density of sediment on oysters in particular and bivalves in general.

2.3.1 Temperature

McLusky and Elliot (2004) indicated that temperature values are highly variable in estuaries than in nearby waters because of its shallowness; this exposes the water to rapid heating and cooling. Temperature is known to have a significant influence on aquatic organisms as well as other physico-chemical parameters, including dissolved oxygen (DO), salinity and pH.

According to the National Estuarine Research Reserve [NERR] (1997), temperature is a critical factor in the determination of an organism's habitat and its survival. Dame (1996) stated that many studies support the notion that water temperature affects metabolism and activities such as growth, reproduction and larval development in most marine invertebrates. When it comes to the feeding of bivalves, it has been reported that filtration rate depends on the temperature of the water body, aside from the speed of water current (Ward, Sanford, Newell, & MacDonals, 2000). Dame (2012) observed that the impact of temperature on marine invertebrates might be altered by the changes in the intensity of other concurrent physical and chemical factors, principally light, salinity and dissolved gases.

Oysters can tolerate water temperatures ranging from 1 to 36 °C, according to Galtsoff (1964). This probably explains the absence of oysters in the Polar Regions. Ajana (1980) mentioned that *C. tulipa* survives a temperature range of 23 - 31 °C in the Lagos lagoon, Nigeria while in Ghana, Obodai (1997) reported temperature ranges of 27 - 34 °C, 24 - 32 °C and 27 - 36 °C for the same species in Jange, Benya and Nakwa lagoons respectively in Ghana. Moreover, Yankson (1990) found the temperature range of 25 – 30 °C as optimal for fertilisation and larval growth of *C. tulipa* in the laboratory. Ward

et al. (2000) noted that the temperature regime of a water body has an impact on the growth and survival of oysters by regulating the rate of water transport, feeding, respiration, gonad formation and spawning. Narasimham (2005) used the periodic variations of temperature to estimate the percentage of time during which oysters in any given locality continue to feed and reproduce.

2.3.2 Dissolved oxygen (DO)

Aquatic organisms obtain oxygen through diffusion of atmospheric oxygen into water, primary production in the water and influx of water. High biological oxygen demand (BOD) from decaying organisms as they get rid of phytoplankton blooms and other organic waste resources may deprive living aquatic organisms of DO.

According to NERR (1997), DO is a vital chemical parameter for the survival of aquatic organisms through the process of respiration. Quayle and Newkirk (1989) noted that the presence of bivalves in a locality could be an indication of a sufficient amount of dissolved oxygen. Angell (1986) and Molnar, Gamboa, Revenga and Spalding (2008) observed that DO impacts on the population and individual growth of oysters. Oysters are tolerant of low DO and survive at concentrations as low as 1 mg/l, as noted by Andrews (1982). Concentrations of DO of Jange, Benya and Nakwa lagoons with *C. tulipa* populations in Ghana were estimated to range from 8.44 – 10.03 mg/l, 2.19 – 9.94 mg/l and 5.62 – 13.17 mg/l, respectively (Obodai, 1997). The lower concentration of DO in Benya was attributed to a high level of putrefaction of organic matter.

2.3.3 Salinity

The average salinity of the ocean is 35 ‰, while that of freshwater is less than 0.5 ‰. Estuarine salinity varies greatly between that of seawater and freshwater due to its location, tidal fluctuations and the volume of freshwater runoff (NERR, 1997) as well as precipitation (Dame, 2012). Though there have been instances where the salinity of estuarine systems can be more than 37 ‰ (Obodai, 1997), it is known that salinity changes in coastal systems may affect the concentration of dissolved gases.

Though temperature is generally documented as the primary factor at large biogeographical scales, salinity is a key influential factor in the distribution of coastal and estuarine bivalves and impinges on many physiological activities (Dame, 2012; Gosling, 2015). Bivalves inhabit a wide range of salinities, including freshwater and hypersaline areas characteristic of tropical zones (Dame, 1996; Gosling, 2004).

Oysters are described as osmoconformers meaning that the osmotic concentration of their extracellular fluid fluctuates with variations in the salinity of the medium (Bayne, 2017). However, oyster species can tolerate the physiological stress posed by the ambient salinity variations within certain limits. According to Angell (1986), the salinity tolerance status of *Ostrea* and *Saccostrea* spp. could be described as stenohaline, while that of *Crassostrea* is euryhaline. In Ghana, Obodai (1997) reported salinity ranges of 0 – 35 ‰, 5.0 – 38.0 ‰ and 0 - 35 ‰ of *C tulipa* populations in Jange, Benya and Nakwa lagoons respectively. Obodai ascribed the low salinity levels to rainfall in Jange and massive freshwater inflow in Nakwa. A recent salinity profile estimation by Asare et al. (2019) in Nakwa lagoon was similar to the observation of Obodai

(1997). *C. tulipa* larvae were found to thrive best in a salinity range of 20 - 30 ‰ (Yankson, 1990). Salinity variation is known to influence many biological activities like reproduction, feeding, growth rate, condition and respiration. Besides, as reported by Dame et al. (2002) and Obodai (1990), low salinities have been directly linked to high mortalities in oysters.

2.3.4 Hydrogen ion concentration (pH)

A pH value of 7 is said to be neutral, but acidic and basic when it is lower and above 7, respectively. The presence of dissolved carbonate ions in saline water buffers the changes in pH by reacting with the free ions, hence estuarine pH values are fairly constant.

Variations in pH may be caused by reduced salinity. Quayle and Newkirk (1989) observed that a drastic change in pH over a long period could be harmful to bivalves. A large number of aquatic organisms can tolerate pH values between 5.0 and 9.0, as reported by NERR (1997).

For thriving oyster culture and good condition, Zhong-Qing (1982) stated pH values ranging from 7.9 – 8.4, whereas Arakawa (1990) indicated 6.2 – 8.7 as being ideal for larval development. Obodai (1997) reported pH values between 7.20 – 8.19, 7.14 – 8.05 and 6.95 – 8.05 for Jange, Benya and Nakwa lagoons, respectively. Obodai attributed the lower pH for Benya to a higher rate of decomposition of organic matter in the water body.

2.3.5 Turbidity

According to Fincham (1984), estuaries are relatively more turbid than the adjacent water bodies; this could be ascribed to the suspended materials in estuaries originating from the river and the sea as well as the resuspension of

particles by currents and tides. The seston include suspended organic matter, soil particles and plankton.

According to Lloyd, Koenings and LaPerriere (1987), turbidity values ranging from 5 - 25 NTU could have a negative impact on the primary productivity of estuaries due to the reduced light penetration in the water column. Consequently, there is less or no food for the suspension feeders. High turbidity also impacts on the feeding efficiency of bivalves since more energy is expended in selecting food and discharging unwanted particles (Bilotta & Brazier, 2008; Quayle & Newkirk, 1989).

Angell (1986) noted that high turbidity might hinder setting, growth and cause mortality of oyster larvae. Also, prolonged high turbidity regimes may result in high mortality of adult oysters.

2.3.6 Nutrients (nitrate and phosphate)

Studies by Howarth and Mariano (1990) and Nixon (1992) have pointed out that nitrogen and phosphorus are the two main nutrients that drive primary productivity in the aquatic ecosystems and critical water quality parameters. The concentration of bio-available forms of these nutrients (i.e., nitrates, nitrites, ammonium and phosphates) in estuaries could serve as an indication of the amount of phytoplankton (Howarth, 1988; Nixon, 1995), therefore food for filter-feeding bivalves. However, primary productivity may be hindered when there is a high turbidity regime even with ample nutrients, sunlight and other vital factors. Of the bio-available forms of nitrogen, Neill (2005) stated that nitrate is widely used in estimations because ammonium and nitrites are generally present in low concentrations in less polluted waters. As reported by Redfield (1958), primary producers approximately assimilate nutrients of

nitrogen and phosphorus in the ratio of 16 N: 1P. It is said that primary production is nitrogen-limited when the ratio of available nitrogen to phosphorus is less than 16:1 and vice versa. Smith (1984) acknowledged that nutrient limitation is a restriction to the growth rate of phytoplankton populations. In the temperate region, it has been reported that nitrogen is mainly the limiting nutrient in estuaries and coastal marine systems for primary production (Howarth, 1996; Nixon, 1992; Vitousek & Howarth, 1991). To a lesser extent, some estuaries were found to be phosphorus limited, while others seasonally switch between the two (Howarth, 1988). Comparatively, the tropical coastal aquatic systems are less studied as compared to their temperate counterparts. In the tropics, there have been reports by Howarth (1988) and Smith (1984) that many estuarine systems may be phosphate limited. Howarth (1988) listed three primary factors that could determine whether an aquatic system is likely to be nitrogen or phosphorus limited. These are the ratio of nitrogen to phosphorus in external nutrients inputs, the preferential loss of nitrogen or phosphorus in the photic zone (for example, through denitrification and absorption of phosphorus) and the extent to which any relative insufficiency in nitrogen accessibility is compensated for through nitrogen -fixation.

2.3.7 Bulk density of sediment

As reported by McLusky and Elliot (2004), estuarine sedimentary materials are assembled from tidal contribution, river influx and land runoffs. The sediments include gravel, sand, stilt and clay particles. Dunn, Zigic, Burling and Lin (2005) reported that the type of sediment at a given location within the estuary varies with the speed of the bottom current as well as the size and density of suspended particles.

Bivalves have adapted to a wide range of substrate types from rocky to fine soil particles to optimise their chance of survival (Gosling, 2015). Oysters cement their shells on hard substrates, mussels use byssal threads to hold fast on firm substrates while clams, cockles and scallops burrow into soft sediments. In Ghana, Obodai (1990) documented that bottom substrates impacts on the distribution and abundance of oysters

In the literature, hard, rocky bottoms and semi-hard muds have been reported extensively to support oyster setting and growth more than sandy substrates. Soft muds tend to smother oysters. According to Quayle and Newkirk (1989), the type of sediment has an impact on the shape of the oyster, in that, oysters grown on soft mud may have elongated and smooth shell whereas the ones grown on the hard bottom may have circular and deeper left valve with fluted shells.

The combined effect of the physico-chemical properties might impinge on the biological processes of bivalves and for that matter, oysters. As documented by Dame (2012) as well as Quayle and Newkirk (1989), most bivalves close their shells tightly during harsh environmental conditions to avoid physiological stress for a manageable period.

2.4 Population Parameters

As documented in a review by Gosling (2015), it appears that the majority of the world's essential fisheries have attained their maximum potential, with most of the fish stocks fully exploited. To continually reap the benefits of fisheries resources, international, regional and state bodies advocate for the discovery of new stocks, rebuilding of collapsed fisheries and to sustainably exploit existing stocks. There have been several attempts at defining

a fish stock in literature. However, the definition by Gayanilo, Sparre and Pauly (2005) is well accepted. Thus, "fish stock is a sub-set of one species having the same growth and mortality parameters, for which the geographical limits can be defined." Moreover, fish stocks are said to be discrete groups of fish that show little mixing with adjacent groups. The overarching aim of fish stock assessment is to establish the current levels of exploitation of the fishery as well as determining the levels of sustainable exploitation to inform management strategies.

The significant contribution of bivalve fisheries and its potential globally calls for efficient methods of assessment to safeguard rational production over time. Gosling (2015) noted that the current assessment and management practices used for shellfish are established methods that have been utilised for finfish stocks. These methods hinge mainly on length -based or age-based procedures. In the tropics, length-based procedures have been employed extensively in the assessment of fish stocks (Ofori-Danson & Kwarfo-Apegyah, 2008; Osei, 2015; Pauly, 1984) owing to the reported difficulty in ageing tropical fish.

Ages of fish populations have been estimated indirectly by statistically analysing length-based data, especially when there are no regular laid down growth rings in their hard parts. The electronic length-frequency analysis (ELEFAN), as first described by Pauly and David (1980), is a collection of fishery assessment tools that uses length-frequency data. The FAO developed the system as a separate programme and 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 and David (1980). In part, due to the cost-effectiveness of length data and the insufficiency of catch data. Lately, Pauly and 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, 2017; Mildenberger, Taylor & Wolff, 2017); fishmethods (provide functions for the application of fisheries stock assessment methods, Nelson, 2018); devtools (provide functions that simplify and facilitate commands, Wickham, Hester & Chang, 2018); ks (kernel smoothing for confidence contours, Duong, 2019) and fishboot (a tool for the study of fish stocks and aquatic resources, Schwamborn, Mildenberger & Taylor, 2018). The new optimisation algorithms which are packages built for the R software (R Core Team, 2019), according to Taylor and Mildenberger (2017), have the capability of optimising the search for a combination of four parameters (asymptotic length (L_∞), growth coefficient (K), summer point (t_s) and strength oscillation (C)) at a reduced computation time, where FiSAT II software fall short. These modern tools were used in this study.

2.4.1 Population density

According to King (1995), organisms are mainly controlled by density-dependent factors like competition for food and living space when environmental factors are stable. This, in turn, results in stable population density. In harsh environmental conditions, bivalve stock abundance fluctuates over time.

In literature, several approaches for surveying the distribution and density of bivalve fisheries exist. These include the use of quadrats, dredger, benthic corers and underwater visual vehicles. The efficiency of a given method relies on the type of bivalve species, nature of the bottom, clarity of the water, the extent of the area and the distribution and density of the species. According to Bayne (2017), the use of oyster dredge or tongs requires a carefully calibrated gear to maintain its catchability, which has been found to vary over time and between reefs. Also, underwater visuals may be less useful in highly turbid waters. Quadrat sampling is widely used, Gosling (2015) indicated that this method could be employed by counting individuals within the quadrat or by subjectively assigning a score based on the coverage of specimens. In the case of deeper water, divers have estimated population density by randomly placing quadrats on populations and counting the individuals within the quadrat. Quadrats come in different sizes and these are guided by the density of the target population.

Population density estimates have informed restoration programmes of bivalves, globally. According to Gaines, White, Carr and Palumbi (2010), measuring the performance of oyster populations has helped in assigning and evaluating the efficacy of "no-take" reserves. Others have also reported on the influence of population density on the growth and survival performance of bivalves (Maccacchero, Ferreira & Guzenski, 2007; Obodai, 2000). The literature indicate that the influence of high population density on growth can be variable, especially in oysters.

2.4.2 Growth

For bivalves, growth is said to be an increase in the longest dimension of the shell, according to Gosling (2003). The longest dimension of the shell is the length for mussel, clam and cockle while that of oyster and scallop is the height. However, the use of only shell dimensions in growth studies may not yield satisfactory results as Lee (1986) pointed out, in the sense that faster increment in shell dimension may not positively correlate with meat production. Hence the need to combine linear shell measurements with weights in the study of the growth of bivalves.

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. Bailey suggested that the use of directional terminologies should be based on knowledge of the anatomy of the species. Moreover, in fossil groups, where the anatomy may be inconspicuous, the use of anterior and posterior terms should be discouraged.

The confusion in shell dimension, where a given dimension is given different names abounds in the literature. Particularly in oysters, the distance between the hinge and the opposite shell margin has been labelled as height (Galtsoff, 1964; Gosling, 2015; Spencer 2002) while the same dimension has

been termed length (Gordon, Ngalouefe, Wingfield & Southgate, 2017). However, per the conventional shell dimensions according to Gosling (2015), the height is the distance from the hinge line to the opposite shell margin; length is the widest part across the shell at 90 degrees to the height; width is measured at the thickest part of the two shell valves. The above agrees with the description given by Galtsoff (1964) in his elaborate study on the American oyster, *C. virginica*. Galtsoff's description, which is consistent with the conventional use of oyster shell dimension was adopted in this study.

In growth studies of bivalves, Quayle and Newkirk (1989) presented four methods of assessing shell growth, namely: measurements of shell dimension of randomly sampled specimens, sequential measurements of tagged individuals, measurements of growth rings (upon validation) and acetate peels of cut shells. Besides, Bayne (2017) highlighted the use of changes in stable isotope ratios within the shell growth. Given the procedures above, the measurement of individual sizes (particularly the untagged procedure) has been widely used in assessing tropical bivalve fish stocks (Laudien, Brey & Arntz, 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.

In literature, growth rate has been investigated by relating the size of an organism to age (i.e., over a given time) or on the population basis, by following the modal progression of time-series length data (Gulland, 1969; Pauly, 1980) and by determining the relationship between growth rates of one variable to the other, allometry (Gordon et al., 2017; Hemachandra, 2008; Newell & Hidu, 1982; Vakily, Tuaycharoen & Nugranad, 1988). A lot of scientists (Lodeiros &

Himmelman, 1996; Pit & Southgate, 2003) have used individual growth rates to investigate the influence of both biotic and abiotic factors on growth in experimental set-ups.

The development of the special, generalised and seasonalised von Bertalanffy Growth Function (VBGF) among others (like Richards, Logistic, Gompertz, Power) make it possible to estimate population parameters like asymptotic length (L_∞, the theoretical length a fish will approach if it grows indefinitely) and growth coefficient (K, the rate at which the L_∞ is approached) by the progression of length-frequency modes over time (Urban, 2002). The special VBGF is the original growth model described by von Bertalanffy, the generalised and seasonalised forms were developed later on to tackle particular needs as the names suggest. The seasonalised VBGF (soVBGF) has been used mainly to fit the growth of fish populations from the temperate regions (Dridi, Romdhane & Elcafsi, 2007; Tsikliras, Koutrakis & Stergiou, 2005). It is currently recommended that seasonality is factored in tropical fish stock analysis (Morales-Nin & Panfili, 2005), although seasonality is not as striking as in the temperate and polar regions (Fischer et al., 1988; Fowler, 1995).

Moreover, it has been established by Longhurst and Pauly (1987) and Pauly and Ingles (1981) early on that winter-summer temperature change as low as 2°C in the tropics, induces significant seasonal growth oscillations in tropical fish. Although the VBGF is the most used model for fitting the growth curve of fish populations, authors have recounted several shortfalls. As pointed out by Pilling, Kirkwood and Walker (2002), von Bertalanffy parameters are estimated means of the population derived from individual sizes, and there may be bias especially dealing with populations of highly variable growth, like oysters.

Also, Ricker (1975) indicated the difficulty in fitting the growth curve of juveniles using the VBGF since they seem to have a faster growth rate than the adults.

The Powell Wetherall Plot (P-W plot) coupled with the K-scan has been used to fit growth curve in length-frequency data by estimating the asymptotic length first (P-W plot) followed by the search of K using the K-scan routine (Gayanilo et al., 2005; Pauly & David, 1981). Another fit algorithm which is more popular is the Response Surface Analysis (RSA) incorporated in ELEFAN I, which attempts to optimise the unrestricted search of VBGF parameters (mainly K and L_∞) to obtain the best combination (Gayanilo et al., 2005; Schwamborn, Mildenberger & Taylor, 2019). Similar to the RSA, Mildenberger et al. (2017) recently developed unconstrained search algorithms, namely ELEFAN_GA and ELEFAN_SA (both a part of the TropFishR) but, these can search highly dimensional parameter space (four parameters as compared to the two in the RSA). All three types of fit algorithms named above have a different set of mathematical computations used to fit the best growth curve.

Schwamborn et al. (2017) described ELEFAN_GA as a composite and refined VBGF curve fit procedure, which is based on a genetic or evolutionary algorithm (Scrucca, 2013) while the ELEFAN_SA uses computer-generated annealing, a normal randomized algorithm for estimating an absolute optimum (Xiang, Gubian, Suomela & Hoeng, 2013). Like the RSA, the ELEFAN_GA and ELEFAN_SA procedures estimate a single optimum combination of VBGF parameters without giving a 95 % confidence intervals. However, Schwamborn et al. (2018; 2019) noted that the ELEFAN_GA provides a higher precision than the ELEFAN_SA. According to the above authors, to resolve the pitfall of

inadequate data for most fisheries, the bootstrapping analysis was introduced into the stock assessment. In comparing the partial bootstrapping (PBoot) and full bootstrapping (FBoot) VBGF estimates, Schwamborn et al. (2019) documented that FBoot routines are very robust, replicable and accurate, hence its recommendation in the estimation of growth parameters.

The use of allometry is popular among a wide range of disciplines in biology. With respect to the study of growth in bivalves, allometry is defined as the relationship between the growth rate of one part of an organism and that of another or between one part and the whole organism. The above techn ique has been employed extensively in the growth rate studies of bivalves including oysters (Gordon et al., 2017; Grizzle et al., 2017) mussels (Hemachandra, 2008; Vakily et al., 1988) and clams (Obirikorang, Adjei-Boateng, Madkour, Amisah & Otchere, 2013; Newell & Hidu, 1982), probably because of its reliability.

The allometry in bivalves is investigated by determining the relationship between the dimensions of the shell (height, length and width) and its whole weight or (wet or dry) meat weights. Morphometric indices like elongation index, compactness index and convexity index have been used (Holopainen & Kuiper, 1982) to describe the shape of bivalves. It abounds in literature that the morphological characteristics of bivalves are greatly modified by some local environmental factors despite their genotypic makeup. Notable among the environmental parameters are population density (Quayle, 1980), depth (Claxton, Wilson, Mackie & Boulding, 1998), predation (Reimer & Harms-Ringdahl, 2001), nature of sediment (Newell & Hidu, 1982), degree of exposure to tide (Steffani & Branch, 2003) and physico-chemical parameters (García-March, Pérez-Rojas & García-Carrascosa, 2007).

2.4.3 Mortality and exploitation

In fish population dynamics, mortality assessment of exploited stock is vital (Gayanilo et al., 1989; Pauly, 1984). Mortality in fish is caused by many factors, including predation (Manning & Lindquist, 2003), unfavourable environmental conditions (Dame 1976; Galtsoff, 1964), fishing and old age (King, 2007) and parasites and diseases (Perkins, 1993; Quayle & Newkirk, 1989).

Total mortality (Z), is the sum of the instantaneous rate of natural mortality (M, which is the totality of all causes of death except fishing) and the instantaneous rate of fishing mortality (F) caused by the fishing operation (King, 1995). Gosling (2015) indicated that the loss of fish could be assessed by the percentage of individuals that survive over a particular period or the percentage that die. Indirectly, Gayanilo et al. (2005) and Pauly (1983) noted that the total mortality rate could be estimated by plotting the natural logarithms (Ln) of survivors by age, this is referred to as a catch curve. The above analysis gives a sound output when samples are representative of the population. It also assumes a constant recruitment and mortality rates among various age groups selected for the analysis. Alternatively, the catch-per-unit-effort (CPUE) data, age information and mark-recapture data could be used in estimating the total mortality rate. However, these approaches are less employed compared to length-converted catch-curve (Pauly, 1983). This is due to the adherence to many assumptions and a large amount of catch data required by the two approaches.

The instantaneous natural mortality rate of fish populations, M, can be computed indirectly, commonly using Pauly's (1980) empirical (M) equation,

which requires the use of the temperature of the water body, L_∞ and K in its estimation. Also, Rikhter and Efanov's method is used in estimating M; this relates natural mortality to the age at which 50 % of the stock reaches the age of sexual maturity (Gayanilo et al., 2005). In bivalve fisheries, a direct method of assessing the natural mortality rate could be done by the analysis of cluckers (dead shells) as described by Caddy (1989) and Orensanz, Parma and Iribarne (1991). It is estimated as the ratio of cluckers to live animals of a particular age group or cohort, with the assumption that the empty shells held by a ligament (before it degenerates) suffered only natural mortality. The above technique is more applicable to bivalves that can be aged by the shells. This implies that the approach is less relevant to *C. tulipa* populations since its shell has no regular growth rings, according to Gosling (2015).

Indirectly, by simple arithmetic, the instantaneous fishing mortality rate, F, is calculated as total mortality rate (Z) minus natural mortality rate (M), given that these estimates are available (Pauly, 1980; Ricker, 1975). The above method is the most used in the field of fish stock assessment, perhaps because of its combined usage with the length-converted catch curve approach of estimating Z. Alternatively, F could be determined directly by obtaining pre- and post-harvesting densities or by the use of swept-area methods, as indicated by Gosling (2015). The challenge with the swept-area approach in estimating the fishing mortality is that the exploitation of bivalves, where fishing is localised defies the assumption of random fishing.

For a sustainable fishery, Pauly (1983) recommended that the instantaneous natural mortality and fishing mortality rates should be equal. It is upon this basis that the exploitation rate becomes an index of estimation of the

level of utilisation of a fish resource. The exploitation ratio is given by the instantaneous fishing mortality rate divided by the total mortality rate (Pauly, 1980; Ricker, 1975; Sparre & Venema, 1992). The length-based yield-per-recruit predictive models (Thompson and Bell model and Beverton and Holt model) are used in evaluating the status of the fishery with respect to reference levels and forecasting the consequences of different fishing efforts on the yield of fish stocks. These predictive cohort models connect stock assessment with fisheries management. Unlike the Beverton and Holt model, the Thompson and Bell model does not assume a steady stage condition. Gayanilo et al. (2005) noted that the latter model is preferred over the former because of its non-steady condition predictions.

FiSAT II software has been employed in the population dynamics of *C. virginica* and *C. madrasensis* by Amin, Zafar and Halim (2006) and Amin, Zafar and Halim (2008) in Bangladesh. Moreover, Yapi, Ble, Etchian, Kadjo and Yao (2017) used the length-based software to assess the stock of mangrove oyster, *C. gasar* (= *tulipa*) in the Ebrie and Aby lagoons in Cote d'Ivoire.

There is scarce information on the population dynamics of the West African mangrove oyster, *C tulipa*. Information on the stock assessment of the oyster fishery at the Densu Delta will be valuable in making an informed decision on the rational exploitation of the fishery.

2.5 Reproductive Biology of Oysters

Potts and Wootton (1984) assert that fish species develop reproductive strategies and traits that safeguard their existence under variable and often unfavourable conditions. Some of these strategies and traits are the frequency of spawning, sex ratio, mode of fertilisation and sex-changing abilities.

Knowledge of the reproductive strategies and traits will guide the development of management strategies and regulations. In this section, the main highlights of the literature review on reproduction will cover the distribution of sexes and gametogenic cycle and spawning in oysters and bivalves

For a detailed reproductive study, observations must be made at the cellular or tissue level. Many authors have studied the sex ratio of bivalves by the use of gonadal histology and squash due to the lack of macroscopic sexual dimorphism. The use of smears or squash method is less laborious and reasonably satisfactory for females; however, according to Quayle and Newkirk (1989), it may be challenging in the identification and staging of males. Furthermore, the use of a simple colourimetric test by the observation of one of two chromophores formed on heating the mantle tissue has been used by Jabbar and Davis (1987) in *Mytilus edulis*. The colour difference has been attributed to the disparity in the energy reserves between eggs and sperm.

Moreover, Fraser et al. (2016) compared eight mussel sex determination methods to establish an efficient sex determination protocol by covering the reproductive cycle. The methods were mantle colour, fresh smear, stained smear, histology, chemical colouration, spectrophotometric analysis and male associated polypeptide. Others have suggested that squash preparations from fine-needle extracts of mantle tissue are a preferred technique because it can be done on live bivalves as compared to the sacrificial and expensive method of histology (Burton, Johnson & Davidson, 1996). Histological and squash preparations have been touted as the most reliable methods for sex determination (Quayle & Newkirk, 1989). However, histological and squash preparations may fail to differentiate between sexes in post-spawning bivalves

or during the sexual rest stage when gametes are absent (Fraser et al., 2016). These authors recommended the use of histological procedure before the sex-specific gene method, which is employed during the sexual rest and post-spawned stages. In the tropics where bivalves hardly go through the sexual rest stage, histological and squash preparations have been reported to give appreciable results, according to Krampah et al., 2016 and Yankson (1996).

The cycle of gametogenesis and spawning of bivalves have been assessed directly by visual observation and histological procedures. And indirectly by the observation of relative abundance of larvae or the recruitment of spat/juvenile over time. The periods of relatively high abundance of larvae or spat could indicate major spawning. However, it could be challenging to ascertain the origin of the planktonic larvae in the case of several populations with varying environmental conditions within a locality, as larval forms typically disperse widely by the currents. Moreover, in the literature, condition index and biochemical composition have been used indirectly to study seasonal gonadal development of bivalves. Condition index (CI) is a quantitative method for indirect assessment of the reproductive stage of bivalves, according to Barber and Blake (1991) and Gosling (2003).

The practice of gross visual observation of gonads (concerning its relative size, shape and colour) is simple, and it has been adopted widely in scallops due to its conspicuous and anatomically distinct gonad from the visceral mass. However, there may be difficulty in identifying a specific stage with less expertise (Quayle & Newkirk, 1989).

Gosling (2003) reported that histological preparation is the most consistent method in assessing the gametogenic state of molluscan gonads. It

enables the various proportions of developmental stages of the gonad of individuals to be estimated at regular intervals throughout the year. Even though gametogenesis is a continuous process in the tropics, generally, many researchers have staged the process into various phases based on gonad morphology. The number of developmental stages describing the gametogenic cycle as presented in literature includes three stages (Obodai, 1979 for an oyster), five stages (Krampah et al., 2016 for a mussel; Yankson, 1977 for a cockle) and eight stages (Powell, Wilson-Ormond & Choi, 1993 for an oyster). The criteria for the classification of bivalve gonads are highly subjective. King, (2007) argues that whichever classification is used, there is some merit in defining as few stages as possible as the main interest in fisheries studies is in determining the time when the majority of the population is in the final spawning stage. An analysis of percentage stacked frequency distribution of the various proportions of developmental stages of gonads over time has been used widely to represent the gametogenic cycle. Stereological methods and index of gonad maturation (GI or GSI) are the two primary quantitative approaches used in assessing reproductive conditions of bivalves (Krampah et al., 2016; Yankson, 1986).

A gonad or gonadosomatic index (GI or GSI) expresses gonadal mass as a proportion of total body mass to follow the reproductive cycle of fish species at regular intervals (Barber & Blake, 1991; King, 2007). This index assumes that gonads increase in size with increasing development and compares the mass of the gonad with the total mass of the organism. Generally, the mean GI for a month is calculated by multiplying the number of individuals at each developmental stage by the numerical ranking of that stage and dividing the sum

by the total number of individuals in the sample. As indicated by Gosling (2015), GI works for all bivalves while GSI applies to scallops due to its discrete gonad from the visceral mass, hence the possibility of weighing the gonad wholly. Increasing GI or GSI has been attributed to gonadal development while a decline denotes major spawning. Stereological techniques quantify changes in the volume fractions of different components of the gonad, which involve gametes, nutritive storage cells and connective tissue from point counts on test grids applied to random thin sections of the gonad. This method, employed by Yankson (1986) for two European cockles, is less subjective than the index of gonad maturity scheme as the later does not fully recognise intermediate stages of gonadal development (Roger et al., 1982). It has been indicated in the literature that there is good agreement between GI calculated from histological examination and gamete volume fraction (GVF) estimated by stereology. This agreement implies that GI can be reliably used to describe the gametogenic cycle and spawning of bivalves in the absence of a graticule for the estimation of GVF.

2.5.1 Sex ratio

Sex in oysters can be identified during the reproductive periods by microscopic examination of gonads. The proportion of males and females are equal for most populations of bivalves.

Oviparous oysters, such as the species of *Crassostrea*, are dioecious with a rare occurrence of hermaphroditism as compared to the larviparous oysters, including *Ostrea edulis* and *O. lurida* which are hermaphrodites with functional male and female gonads (Galtsoff, 1964). Researchers have reported sex reversal in oysters of the genera *Crassostrea* (Asif, 1979; Thompson,

Newell, Kennedy & Mann, 1996), Ostrea (Galtsoff, 1964; Gosling, 2004) and Saccostrea (Asif, 1979). However, the larviparous oysters undergo a regular change of sexual phases in a defined rhythm, while their counterpart exhibits a relatively rare condition of alternation of sexes. Yankson (1996) concluded that *C. tulipa* undergoes protandric sexual development with an overall 1:1 adult sex ratio by studying populations from Pra estuary and Benya lagoon in Ghana. Galtsoff (1964) emphasised that the *Crassostrea* spp. are bisexual, in a sense that the primary gonads contain germinal cells of both sexes; hence the difference between both groups is not as explicit as it appears. Some investigators have maintained that after breeding, the gonad of *C. virginica* retains its bisexual potencies, and its sex may alternate in either direction (Galtsoff, 1964). However, it has been demonstrated that sex in *C. gigas* is determined by a single gene locus with dominant maleness (M) allele and an allele for protandric femaleness (F) (Guo, Hedgecock & Hershberger, 1998), where MF genotypes are true males that do not change sex, while FF genotypes are protandric females that mature as males at the juvenile stage but can change sex in later years.

2.5.2 Reproductive cycle and spawning

The reproductive cycle of bivalves comprises gamete formation, spawning, fertilisation, larval development, settlement, metamorphosis and growth to sexual maturity. Roger, Hilbish, Koehn and Newell (1982) indicated that to enhance reproductive success, bivalve species demonstrate a variety of adaptations, both genetic and non-genetic to coordinate these reproductive events with the environment. It was also reported widely that different populations show different reproductive strategies to enhance survivability.

Newell, Hilbish, Koehn and Newell (1982) documented that depending on the species and prevailing environmental conditions, the reproductive cycle of marine bivalves can occur annually, semi-annually or continuously. Krampah et al. (2016) observed continuous gonad development throughout the year with two major peaks in the brown mussel, *Perna perna* at the Iture rocky beach, Ghana. In studying the body and gametogenic cycle of *Galatea paradoxa* population in the Volta River estuary, Adjei-Boateng and Wilson (2011) found that the species exhibited an annual reproductive cycle with a single spawning event between June and October peak. Reporting on oysters, Pouvreau, Jonquieres and Buestel (1999) documented a continuous gametogenic activity of the blacklip pearl oyster, *Pinctada magarifitifera* throughout the year with increased activity during the warm season in the Takapoto atoll, France. In Ghana, Obodai, Yankson and Blay (1994) reported on the breeding of oysters from Benya lagoon and Pra estuary, where the former population spawned year-round, while the latter exhibited seasonal spawning from February to May.

2.6 Suspension and Bottom Culture

The global aquaculture outlook is favourable as depicted in the literature. The growth, survival and reproduction of oysters are influenced by the variations in environmental factors such as water temperature, salinity, pH, dissolved oxygen, turbidity and phytoplankton as well as the culture systems or techniques (Quayle, 1980; Quayle & Newkirk, 1989). According to Quayle and Newkirk (1989), there are few fundamental ways of culturing oysters. However, there are several variants. The basic kinds are bottom and suspension types (rack, raft/longline and stake). Quayle (1980) indicated that the suspension and bottom culture techniques are the two major types in use.

Performance of culture techniques have been assessed in the field based on the growth and survival rates of the experimental subjects (Obodai, 2000; Obodai & Yankson, 2000). Growth of cultured oysters could be assessed by the changes in size over time, while survival could be determined by the proportion of live oysters at a given time to the initial stocking number. The culture technique that supports the oysters best from the spat stage through to its desired market size is the preferred one.

Angell (1986) indicated in a study and review of the biology and cultivation of tropical oysters that oyster culture consists of four elementary operations, namely spat collection, nursery, grow-out and harvest. A cultch, which is synonymous to a collector, is a material used to collect oyster spat and growing them to market size. Examples of types of oyster spat collectors reported in the literature are bamboo, coconut-shells, oyster-shells, tiles and ropes. According to Angell (1986) and Quayle and Newkirk (1989), spat collected on materials are grown for some time (nursery phase) and later transferred to a grow-out system until the oysters grow to market size. However, in many culture systems, oysters are left to grow to the desired size at the very place the spat were collected. During grow-out, the oysters are frequently cleaned of silt and biofoulers and their densities are regulated to optimise growth (Gosling, 2015).

Existing literature on *C. tulipa* in Ghana indicate that the species is suitable for mass cultivation (Obodai & Yankson 2000; Yankson, 2004) and in other West African countries like Nigeria (Ansa & Bashir, 2007), Senegal (Afinowo, 1975) and the Gambia (Njie & Drammeh, 2011). Despite the cultural

potential of the species, its mass cultivation has not been realised in Ghana and to some extent in Africa.

Based on the conditions in a given water body, the suspension and bottom culture methods may come in varied forms like the use of rafts and racks as frameworks with oysters grown on trays, strings and sticks, among others. According to Quayle (1980), the bottom culture method may not be suitable for tropical estuaries and lagoons due to their typically soft muddy bottoms. Obodai and Yankson (2000) experimented on oyster culture in three coastal water bodies in Ghana, where suspension culture performed better in Benya lagoon, both methods had similar performance in Nakwa lagoon while in Jange lagoon better growth and survival rates were seen in oysters cultivated in suspension. The variance in results was attributed to the difference in sediments of the three water bodies. Lodeiro, Pico, Prieto, Narvaez and Guerra (2002) found that pearl oysters (*Pinctada imbricata*) cultivated in suspension had better growth as well as a seeming higher survival rates than their bottom counterpart in the Golfo de Cariaco, Venezuela. However, in a similar study by Urban (2002) on the same species in the Colombian Caribbean, the results indicated that there was no difference between the growth rates of oysters cultured by suspension and bottom methods. Obodai and Yankson (2000) asserted that the choice of culture method hinges mainly on the depth of the water at low tide and the nature of bottom sediments. There is, therefore, a need to experiment on oyster culture systems at the Densu Delta to inform the right culture technique.

2.7 Biofouling of Oysters

It has been documented widely that growth and survival of cultivated bivalves are influenced by environmental factors, including fouling organisms

(Pit & Southgate, 2003; Quayle, 1980; Villarroel, Buitrago & Lodeiros, 2004). Biofouling, as defined by Quayle and Newkirk (1989), is the attachment of marine organisms, either plant or animal to the object of interest, whether it be oyster cultch or a boat. Researchers like Arakawa (1990) have described fouling organisms as unwanted species that occupy the same ecological niche as the desired species, likely to cause harm by contesting for available food and space. Generally, there are three types of unwanted organisms associated with bivalve culture, namely organisms that grow around or on cultured species (biofoulers), disease-causing organisms and predators (Arakawa, 1990; Quayle & Newkirk, 1989). Barnacles, mussels, tube-dwelling polychaetes, tunicates and hydroids are the main reported tropical biofoulers (Obodai & Yankson, 2000; Quayle, 1980).

Angell (1986) showed that biofouling could be a severe problem in the tropics. Moreover, Watson and Shumway (2009) reported that biofouling (unwanted organisms) on cultured molluscs could be severe and at times, overwhelming. On the contrary and concerning oysters (genus *Crassostrea*), Quayle (1980) describes biofouling as more of a nuisance than a severe problem. This assertion is further strengthened by Quayle and Newkirk (1989) in explaining that biofoulers are generally stenohaline organisms hence their deleterious effect on the euryhaline *Crassostrea* spp. may be absent when cultivated in an estuarine environment (Quayle & Newkirk, 1989).

Nonetheless, other literature show that biofouling may reduce growth rate and cause mortality (De Sá et al., 2007; Pit & Southgate, 2003). Other problems are reduced marketability due to biofouling, particularly for half-shell oysters, making the shells visually unappealing (Royer, Ropert, Mathieu &

Costil, 2006) and high operational cost incurred in taking control measures (Fitridge, Dempster, Guenther & De Nys (2012). In the Australian pearl oyster culture, about 30 % of the total operational costs were reported to be an estimation of additional expenditure on biofouling (De Nys, Steinberg, Hodson & Heasman, 2002).

Some studies have reported harmful (Daigle & Herbinger, 2009), no effect (Mallet, Carver & Hardy, 2009; Royer et al., 2006) or beneficial (Arakawa, 1990; Dalby & Young, 1993) impacts of biofouling on growth and survival of cultivated bivalves. Moreover, other biofouling works on bivalves showed a harmful impact on growth, no effect for survival (Lodeiros & Himmelman, 1996; Pit & Southgate, 2003) and no effect for growth, adverse implication for survival (Lopez, Riquelme & Gonzales, 2000). Also, in a review by Fitridge et al. (2012), it was concluded that the presence of biofouling in marine aquaculture is a significant management issue causing increased operational expenses and deleterious impacts on the cultured species.

Obodai and Yankson (2000) stated that biofouling has little effect on spatfall, growth and survival of *C. tulipa* in three water bodies in Ghana; however, biofouled oysters had better survival in Nakwa and Jange lagoons. Earlier work on the suitability of water bodies for oyster culture in Ghana by Obodai (1997) showed that the oyster population at Sakumo I lagoon (a part of the then Densu Delta) was highly fouled and cultivable. Nonetheless, the effect of fouling on the oyster was not investigated.

2.8 Nutritional Value of Oysters

Marine bivalves are known as a potential source of proteins, carbohydrates and lipids, which according to Grienke, Silke and Tasdemir

(2014), have been studied for their beneficial effects on human health aside from their culinary value. Oysters are highly valued seafood, which is extensively consumed globally (Yuasa et al., 2018). Asha, Anandan, Suseela and Lakshmanan (2014) indicated that the surge in the consumption of oysters comes at the back of increasing consciousness for more nutritious and healthy foods. Biochemical or proximate composition of a species helps to evaluate its nutritive and food value (Asha et al., 2014; Yankson et al., 1994). This further enhances the popularity among consumers and to authenticate its importance for future policy formulation and management. Information on the biochemical composition, as reported by Ndome, Oriakpono and Agnes (2010), will enable consumers to make a choice of consumption based on their nutritional needs. Moreover, it determines the conditions for marketable processing technique and storage, as specified by Alvarez, Moran, Keenam, Mullen and Delgado-Pando (2019).

The nutritional value or proximate analysis of animals has been conducted widely by employing the protocol of the Association of Official Analytical Chemists (AOAC). The standards contain internationally approved protocols used in the estimation of the various components of meat. The proximate composition of food organisms caught the attention of researchers around the world about a century ago. These studies have been carried out on fish, livestock, poultry and edible plants (both aquatic and terrestrial). Several researchers have reported on the meat composition of fish.

Shellfish, particularly oyster species, have also received immense attention from researchers. For instance, the seasonal variations in the biochemical composition of *C. rhizophorae* have been studied by Martino and

Maria da Cruz (2004). Asha et al. (2014) studied the biochemical profile of the oyster, *C. madrasensis* and its nutritional attributes, while Yuasa et al. (2018) also evaluated the taste characterisation and micronutrient content of rock oyster (*C. nippona*) and Pacific oyster (*C. gigas*). Moreover, a comparative study of the composition of meat and heavy metal concentration of shellfishes and finfishes has been undertaken by Marichamy, Shanker, Saradha, Nazar and Badhul-Haq (2011). In Ghana, Yankson et al. (1994) reported on the seasonal variations in the biochemical composition of *C. tulipa* from the wild to address the knowledge gap on the nutritional value of the species in West Africa. Others, like Asha et al. (2014), focused on the proximate analysis of cultured oysters. Oysters are a natural source of several minerals, including calcium, phosphorus, iron, zinc, selenium and an excellent source of vitamin B12 (Yankson et al., 1994).

In Africa, bivalve species are popular and consumed in coastal communities where they are exploited (Ansa and Bashir, 2007; Yankson, 2004). Yankson et al. (1994) assessed the seasonal changes in the biochemical composition of oysters occurring in two contrasting coastal water bodies in Ghana. However, to the best of my knowledge, there is no information on the comparative study of the biochemical composition of wild and cultured of *C. tulipa* and oysters as a whole.

2.9 Taste Analysis of Oysters

A consumer's fundamental concern for selecting and eating a food product is more of the palatability than the nutrition or its wholesomeness, according to Lawless and Heymann (2010). Given this, product developers invest vast resources into having a unique and delicious taste. Sidel and Stone

(1993) define sensory analysis as a scientific discipline used to evoke, measure, analyse and interpret responses to products as perceived through the senses of sight, smell, touch, taste and hearing. In describing taste analysis, Anand, Kharb, Kataria, Kukkar and Choudhury (2008) indicated that taste assessment is designed to analyse parameters like taste, flavour and texture. The tongue is the primary taste receptor. However, the palate and inner walls of the mouth are known to perceive sensations of food (Lawless & Heyman, 2010). The taste buds on the tongue can differentiate five sensations, namely sweet, salty, sour, bitter and umami.

According to Watts, Ylimaki, Jeffery and Elias (1989), the difficulty in designing an instrument for evaluating sensory characteristics of flavour and texture led to the engagement of human assessors as tools. Owing to the subjectivity and variability in human assessors, for a sensory evaluation to offer reliable and valid results, Lawless and Heymann (2010) indicated that the panel must be screened, calibrated and validated just as in scientific instruments. In the literature, methods of sensory evaluation have been categorised into two main groups, namely affective (preference) and analytical techniques. Affective methods involve consumer acceptance and preference, whereas the analytical techniques have to do with the evaluation of specific product parameters for discrimination and description (Watts et al., 1989). Moreover, affective methods employ a larger sample size of consumers ranging from 75 to 150, whereas the analytical methods use smaller sample sizes (< 50) but highly trained assessors (Lawless & Heyman, 2010). The use of large sample size in affective methods addresses the issue of variability among untrained consumers. It also enhances the confidence in the verdict of the untrained consumers. The

types of affective methods frequently used and their applications are presented in Table 1.

Table 1: *Types of Affective/Preference Test and their Applications (Adapted from Lawless and Heyman, 2010)*

Test	Number of Product Samples	Objective
Paired Preference Test	2	To ascertain the preferred item
Hedonic Rating Scale	1 or more	To determine how much a product is liked/disliked
Food Action Rating Test	1 or more	To ascertain attitude by indicating the extent of liking/disliking for a product
Preference Ranking Test	2 or more	To rank products in order of preference

The Professional Development Service for Teachers [PDST] (2017) documented that the practice of sensory evaluation became popular after the Second World War when food scarcity gave way to abundant and varied types of food products, hence the need for quality. This occasioned the formation of the British Standards Institute to develop techniques to assess food products, which in modern times is applied in product development, product matching and quality control.

Hamilton and Bennett (1984) used sensory evaluation to determine consumer preference of products made from two different fish species, where the consumers preferred none; this stands to reason that either of the species could be used in the product. However, there was a consumer preference for triploid oysters when a sensory evaluation was conducted on a diploid and

triploid *C. gigas* (Allen & Downing, 1991). There is no information on the sensory evaluation of cultured and wild *C. tulipa* as well as oysters in general, to the best of my knowledge.

CHAPTER THREE

MATERIALS AND METHODS

This chapter presents the description of the study area, sampling and culture stations on the field as well as sampling methods, data collection and analyses of the data.

3.1 Study Area

The research was conducted in the Densu Delta located between longitudes 0° 16' W - 0° 21' W and latitudes 5° 30' N - 5° 33' N. The Densu River originates from the Atewa Mountains in the East Akim Abuakwa District of Eastern Region of Ghana (Oteng-Yeboah, 1999) and supplies the Delta with freshwater. The river has been dammed at Weija (which supports the main water treatment plant for Accra in the Greater Accra Region) as seen in Fig. 1. The Densu Delta is greatly influenced by the water spillage from the Weija Dam during the rainy season. It is located 11 km South-West of Accra and under the Ga traditional authorities and Accra Metropolitan Authority (Dadson, 1995). The Densu Delta has a permanent opening at Station 4 and a temporary mouth, which is usually created between Stations 2 and 3 during periods of flooding as a result of spillage from the Weija Dam.

Aside from the oyster, other shellfish (crabs: *Uca tangeri*, *Cardiosoma armatum* and *Callinectes amnicola*. mud-flat periwinkle, *Tympanotonus fuscatus*), and shrimps) and finfish (typical freshwater, estuarine and marine fish) including flat sardinella and black-chinned tilapia are exploited in the Densu Delta. These fisheries are exploited by handpicking, castnet, 'acadja' (brush parks), drag-net and traps.

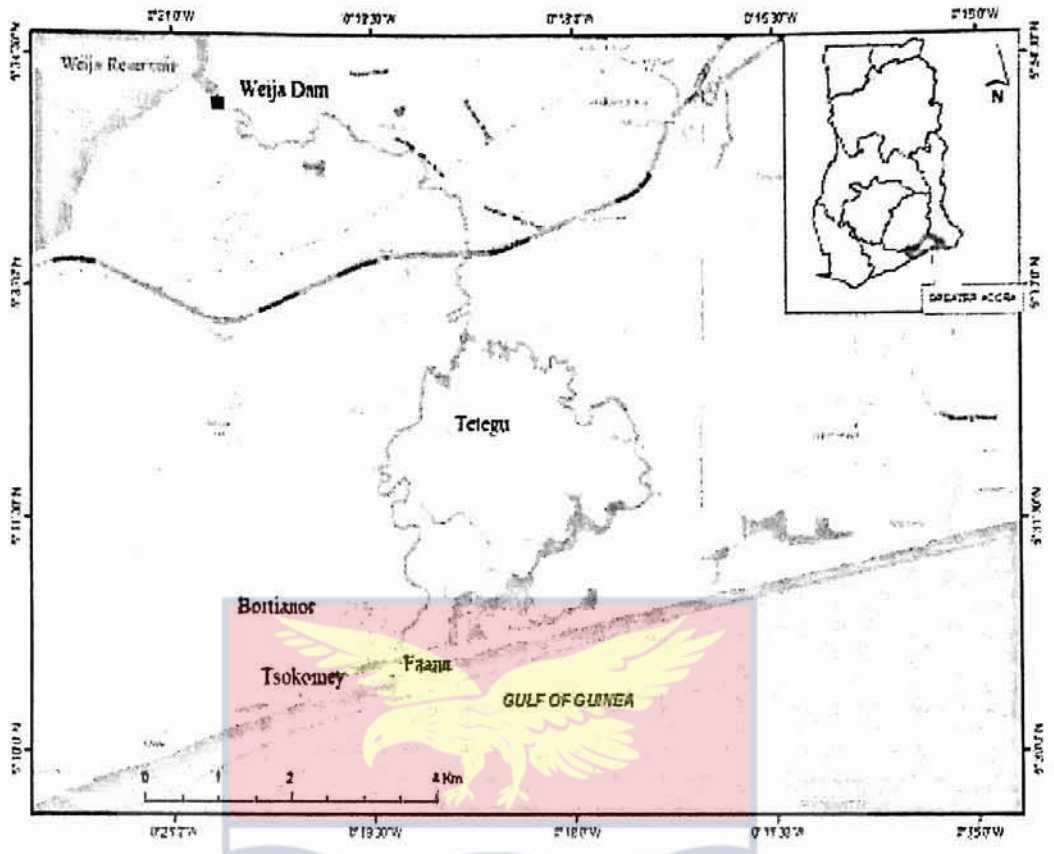

Figure 1: Map of Ghana, presenting the study towns Bortianor/Tsokomey and Tetegu as well as the Densu Delta and the Weija Reservoir

The water body is fringed landward by patchy mangrove species, namely red mangrove (*Rhizophora racemosa*) and white mangrove (*Avicennia africana*). Agricultural practices like animal husbandry, sugar cane plantation, and other crop cultivation are carried out in the catchment area of the Delta. Also, industries like quarrying, housing projects, salt production are situated around the water body. Moreover, the surroundings serve as a recreational hub, with several hotels dotted around the wetland.

The communities bordering the Densu Delta are Bortianor/Tsokomey, Tetegu and Faana (Fig. 1). The population of the local communities comprises about 54.8 % Gas, 32.7 % Ewes and 8 % other tribes, according to Dadson (1995). These people are prevalently engaged in fishery-related livelihoods.

3.2 Sampling and Culture Stations

The physico-chemical parameters were sampled at Stations 1, 2, 3, 4a and 4b as seen in Figure 2. Oysters were extinct at Stations 1 (where the landing quay is sited) and 2. Oyster samples were obtained at Stations 3, 4a and 4b. Stations 1, 2 and 3 are shallow, approximately 0.61 m deep at high tide (Fig. 2). Nonetheless, Kele has a shallow (0.61 m) and a deep portion (roughly 2.13 m at high tide) that were designated as Stations 4a and 4b, respectively (Fig. 2). Station 3 oysters were isolated from oysters at Stations 4a and 4b. The estimated distances from Stations 1 to 2, 2 to 3, 3 to 4a and 3 to 4b were approximately 792 m, 780 m, 807 m and 1042 m, respectively. Also, Stations 4a and 4b were sited about 1030 m and 1021 m, respectively, away from the permanent mouth. The selection of the stations was based on the availabi lity of oysters, depth and proximity to the permanent mouth. However, the rationale for the selection of stations with respect to the mouth of the water body was defeated by the temporary opening at Faana in June 2018 to ease the flow of water into the sea during the rainy seasons (Fig. 2). Areas of extinct oyster population in the Delta were studied to ascertain the prevailing conditions of the water body at these portions, which may not have supported oyster growth and survival. The distance from the artificial opening of the delta to Stations 3 and 4a was estimated as 808.20 m and 1664.50 m, respectively.

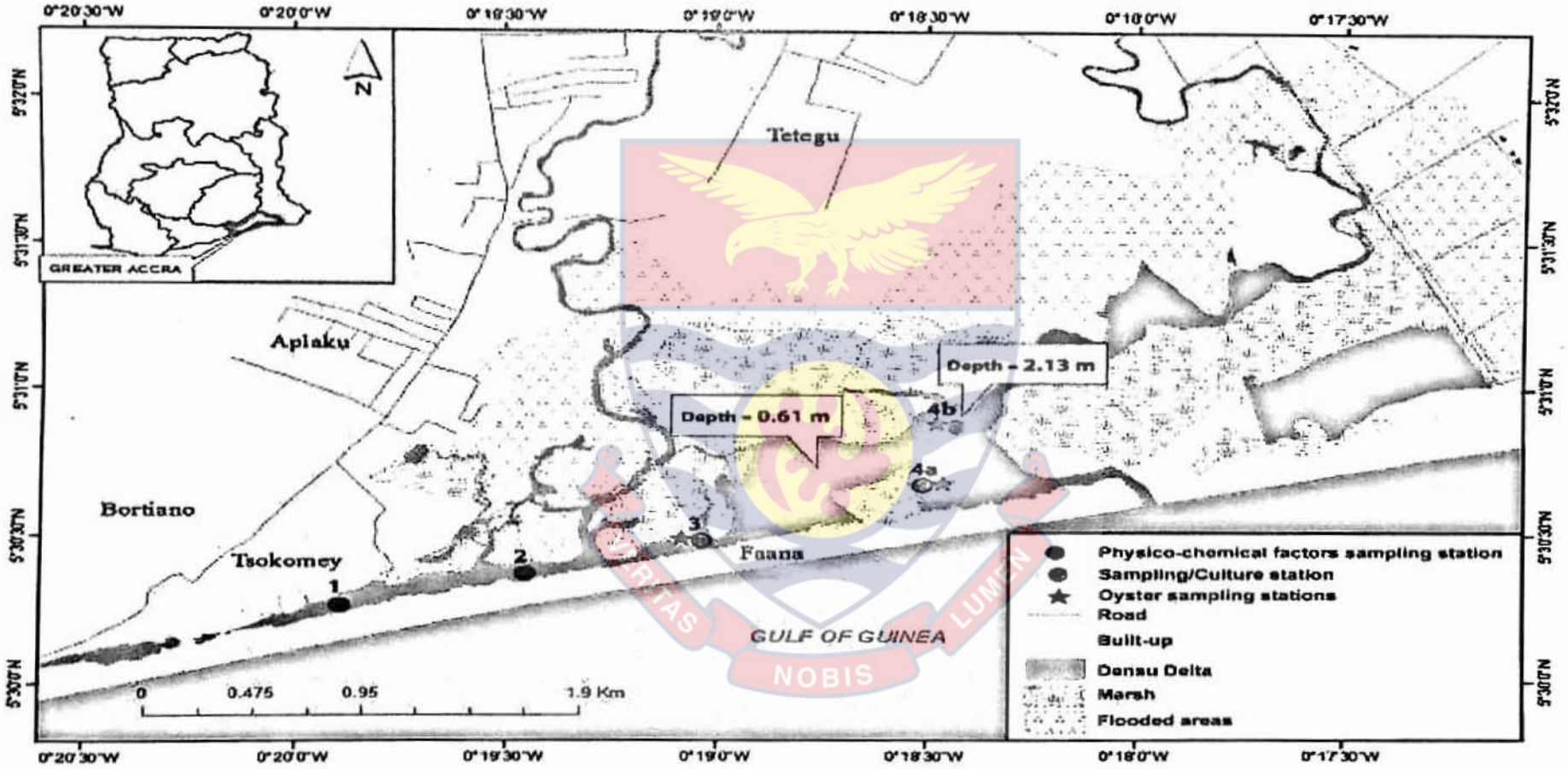

Figure 2: Map of the study area, showing the sampling and culture stations at the Densu Delta

3.3 Sampling, Data Collection and Analyses

3.3.1 Socioeconomic assessment

Ninety-eight (98) individuals involved in the oyster fishery were interviewed using a semi-structured interview guide (Appendix A) from May to July 2017 at Bortianor/Tsokomey and Tetegu. Members of the Densu Oyster Pickers Association (DOPA) indicated that the fishery had about 500 individuals. Due to the element of subjectivity in arriving at the population size, the sample size could not be reliably calculated. Therefore, 20 % of the assumed population size was taken as the sample size. An interview guide was used in this study because majority of the target group (harvesters, processors and traders) could neither read nor write. Moreover, the questions were rendered in Ga and Ewe (local dialects) for effective communication. The interview guide composed of both open and closed-ended questions. It elicited information bordering on the demography of individuals engaged in the oyster fishery, exploitation and economics of the oyster resource concerning harvesting, processing and marketing. The dollar exchange rate at the time of the study was USD 1 = GHS 4.3724 (Bank of Ghana, July 2017). Individuals involved in the fishery were sampled by exponential non-discriminative snowball sampling technique.

Responses from fishers, processors and traders were analysed by descriptive statistics to summarise the basic features of the data in the form of frequencies and percentages using Statistical Package for Social Sciences (SPSS). Reactions to open-ended questions were categorised into groups, coded and analysed as categorical data. A Chi-square test was carried out to determine the significance of the categories (e.g., Ethnicity and Origin).

3.3.2 Physico-chemical factors

Temperature, dissolved oxygen (DO), salinity, pH, turbidity, nitrate and phosphate concentrations were monitored monthly at low tide from May 2017 to October 2018. Each of these factors was estimated by taking the mean of three replicate measurements at each sampling station. Temperature (°C), DO (mg/l), and pH were measured using a multi-parametric water quality checker (HORIBA, Model U-5000) by immersing the probe into the water to a depth of about 30 cm from the surface. Salinity (‰) and turbidity (NTU) were measured with a hand-held refractometer (Eclipse 45 – 65) and turbidimeter, respectively. Nitrate and phosphate concentrations (mg/l) were determined in the laboratory by colourimetric procedures using Hach DR 900 Colourimeter and Reagent Powder Pillows (NITRAVER 5 & PHOSVER 3, respectively) after fixing water samples on ice on the field. Monthly distributions of each physico-chemical parameter were constructed using means with its associated standard errors of the three replicates at each sampling station. Also, the surface and bottom vertical distributions of temperature, DO, Salinity and pH were constructed. A one-way analysis of variance (ANOVA) and t-test unpaired 2-sample, assuming unequal variances were used to ascertain the statistical significance of estimates at months with distinct non-overlapping standard errors of the means among sampling stations and the vertical profiles, respectively. A Tukey's HSD (honestly significant difference) test was carried out when there was a significant 1-way ANOVA test to ascertain the difference.

Sediment bulk density was determined once in the course of the study by the use of a corer of known volume. The corer was driven into the sediment until the bottom of the corer went deeper than the surface of the substrate. The

corer was carefully retrieved without losing the trapped sediment sample. Distended sediment materials were cropped off to attain the actual volume of the corer. Three replicates of sediment samples were obtained from Stations 1, 2, 3 and 4 into labelled zip-lock bags. The sediment samples were then transferred to the laboratory and oven-dried at 105 °C until a constant weight was achieved. The bulk density of the samples was calculated according to Allen et al. (1974, as cited in Obodai, 1997) as follows: Bulk Density = Weight of oven-dry soil / Bulk volume of soil (Inner volume of corer)

A one-way ANOVA was used to compare the means of bulk density of the sediments for the various sampling stations. A Tukey's HSD test was carried out when the 1-way ANOVA was significant to ascertain the difference among the samples.

3.3.3 Population density

Oysters at Stations 3, 4a (Appendix B1) and 4b (Appendix B2) were sampled randomly using a 0.25 m^2 quadrat at monthly intervals during the lowest daytime tide from May 2017 to October 2018. Oyster samples at Station 4b were obtained by diving and picking within the quadrat. Three to five quadrats were taken, depending on the density of the population at each sampling station to collect enough samples for further analyses. The samples from each oyster sampling station were placed in separate labelled containers and transferred to the laboratory at the University of Cape Coast. The oyster specimens, which were cemented together (Appendix B3), were separated by the use of scalpel in conjunction with a shucking-glove, cleared of biofoulers using a knife and brushed, and after that washed individually to get rid of soil particles and debris. The population density of oysters at the various sampling

stations was estimated using the equation: Population density = Number of oysters counted / Area of quadrat (m^2). The difference in population densities between the sampling stations and the period (monthly) and station interactions were assessed by the use of repeated-measures ANOVA. Subsequently, a Bonferroni test (which is best suited for repeated measures ANOVA) was conducted to identify which sampling stations had statistically different population densities. The relative coverage of oyster beds at the various sampling stations was estimated by eye with the consideration of the extent of oyster coverage at the stations.

3.3.4 Size-frequencies and growth relationships

Individual oysters were washed and blotted dry with an absorbent paper prior to the measurement of their dimensions and weights. The shell dimensions were defined according to Gosling (2015): height is the distance from the hinge line to the opposite shell margin, length is the widest distance across the shell at 90° to the height and width is measured at the thickest part of the two shell valves. The shell height (SH), shell length (SL) and shell width (SW) of each specimen as seen in Figure 3, were measured with a pair of dividers in conjunction with a rule to the nearest 0.1 cm. The oyster size data were pooled to construct size-frequency distribution histograms for each of the three sampling Stations (3, 4a and 4b). The shell height was used for the size-frequency analysis because it has been reported to be the best predictor of soft tissue biomass in oysters (Edwards, 2014). The whole oyster (total weight) and the oyster meat, which was shucked with a knife and the water mobbed up with an absorbent paper, were weighed to the nearest 0.01 g with an electronic

balance. The epibionts on the oysters were identified using the online portal of WoRMS (World Register of Marine Species) and Schneider (1990).

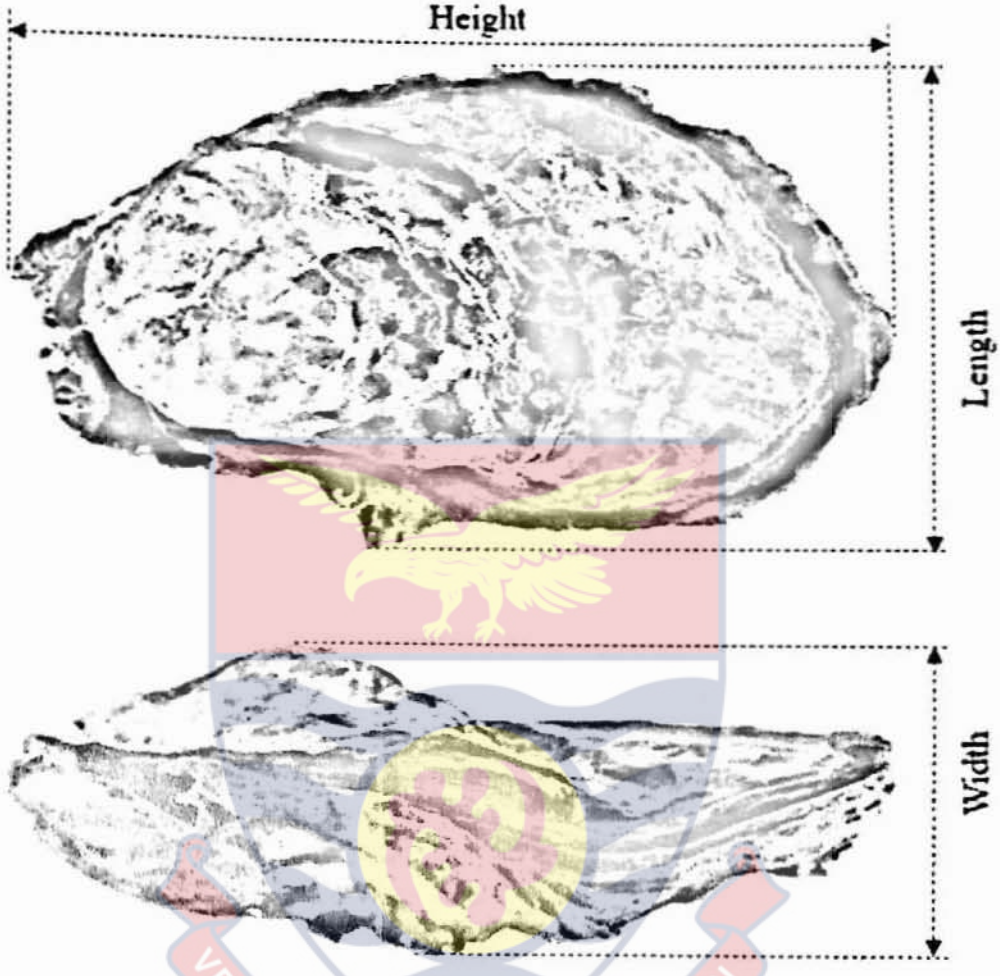

Figure 3: Definition of shell dimensions, height, length and width

Variations in oyster growth pattern among the sampling stations were investigated using relationships of shell dimensions (height-length and height-width) and shell height-weights (height-total weight, height-wet meat weight). Variables that were not homoscedastic (i.e., homogeneity of variances) and did not meet the normality assumption (using Kolmogorov-Smirnov and Levene's tests, respectively) were log-transformed to assume normality. Shell height-length/width relationships were estimated using a log-transformed linear equation (Pauly, 1983): $\log H = \log a + \log bL$ where H = shell height, L = shell length, a (intercept) and b (slope) are constants. The shell height-total

weight/wet meat weight relationships were determined using a non-linear equation: $W = aL^b$, where W = weight, L = length, a (intercept) and b (slope) are constants. The above equation was log-transformed into a linear equation expressed as Log W = Log a + b Log L. The slope and the intercept of the transformed data were estimated by regression analysis.

For height-length/width relationships, the slope b is said to be isometric when it is equal to 1. T-test (Ho, $b = 1$) was conducted to test the significance of the b values with a confidence level of 95%. A significant deviation from the isometric value ($b = 1$) indicates either a negative ($b < 1$) or positive ($b > 1$) allometric relationship. Also, height-weight relationships with b value of 3 are described as isometric. The deviation of the gradient (b) of the regression from the isometric value (Ho, $b = 3$) was verified using a t-test, which is given by the equation (Nagi, Shenai-Tirodkar & Jagtap, 2011): $t = b - 3$ / s. e., where t is t-test value, b is the gradient/coefficient of allometry and s. e. is the standard error of the gradient. A significant deviation from $b = 3$ indicates either a negative ($b < 3$) or positive ($b > 3$) allometric relationship. Biometric outputs among the three oyster sampling stations were compared.

3.3.5 Morphological index (MI) determination

The morphological indices (MI) of oysters from the various sampling stations were estimated by the equation (Imai & Sakai, 1961, as cited in Barillé, Haure, Cognie & Leroy, 2000) given below to ascertain the significant difference between the shell shapes. A one-way ANOVA was used to test the significance of the variation in shape among the sampling stations. MI = (height × 100)/ [(length + width)/2].

3.3.6 Estimation of population dynamics

The analytical packages used in analysing the monthly oyster size data were TropFishR (Taylor & Mildenberger, 2017), fishmethods (Nelson, 2018), fishboot (Schwamborn et al., 2018), devtools (Wickham, Hester & Chang, 2018) and ks (Duong, 2019) in addition to the base packages in the R software (R Core Team, 2019). The TropFishR was used to assess the oyster fishery by following the steps indicated by Sparre and Venema (1992).

Growth parameters

Growth was modelled by the seasonalised von Bertalanffy Growth Function (soVBGF) given by Somers (1988): $SH_t = SH_\infty [1-(\exp -K(t-t_o) + s(t) - s(t_o))]$, where SH_t is the oyster shell height at-age t, SH_∞ is the asymptotic shell height, K is the growth coefficient and t_o, the theoretical age at length zero (now t_{anchor}). Also, $S(t) = (CK/2\pi)$ sin 2π $(t - t_s)$, C is the intensity of the sinusoidal oscillation, which generally ranges from 0 to 1 (C value greater than 1 suggests periods of shrinkage in size dimension) and t_s is the fraction of a year, relative to the age of recruitment where the sine wave oscillation begins. The L_∞, K, t_o, C, Φ' (growth performance index) and t_{anchor} (i. e., portion of the year where annually repeating growth curves cross length equal to zero) were determined by modal progression analysis using the ELEFAN_GA full bootstrap approach (Mildenberger, 2019; Schwamborn et al., 2019; Scrucca, 2013) in the TropFishR package. The full bootstrap approach was employed to enhance the data due to some of the low monthly sample sizes at the various stations.

The settings for the ELEFAN_GA_boot algorithms for soVBGF were *popSize* = 100, *maxiter* = 50, run 10, *pmutation* = 0.2 and Bootstrap

runs/nresamp = 1000 (Mildenberger et al., 2017). The growth performance index (Φ') given by Pauly and Munro (1984) was estimated using the equation: $\Phi' = \text{Log10}\ K + 2\ \text{Log10}\ L_\infty$. The t_o value according to Pauly (1979) was calculated as: $\text{Log}_{10}(t_o) = 0.392 - 0.275\text{Log}_{10} L_\infty - 1.038\ \text{Log}_{10} K$. Longevity ($t_{max}$) of the oyster population was estimated according to the equation (Pauly, 1984): $t_{max} = 3/K$.

Mortalities and exploitation rates

The total mortality (Z) of the oysters from the various sampling stations were estimated by the length-converted catch curve (Pauly, 1983; Munro, 1984) while the instantaneous natural mortality (M) was estimated from Pauly's (1980) empirical equation: $\log_{10} M = -0.0066 - 0.279\ \log_{10} L_\infty + 0.6543\ \log_{10} K + 0.4634\ \log_{10} T$, with inputs from the growth parameters, where T is the mean annual water temperature (27 °C, mean surface temperature of the Densu Delta during the sampling duration). Fishing mortality (F) was obtained from the relationship: $F = Z - M$ (Gulland, 1971). The level of exploitation (E) of the oyster fishery was calculated by the relationship: $E = F/Z$ (Gulland, 1969).

Since the oysters at Stations 3 and 4a were virtually depleted by six months into the opening of the fishing season, samples from these stations were excluded from the yield/recruit (YPR) and biomass/recruit (BPR) estimates using Thompson and Bell model. The YPR and BPR of oysters at Station 4b were estimated by the utilisation of the growth and mortality parameters to construct the Thompson and Bell model (Sparre & Venema, 1992). The Thompson and Bell model estimated the current fishing mortality (F), fishing mortality ($F_{0.5}$) at which 50 % of the virgin biomass is exploited and the fishing mortality (F_{msy}) that gives the maximum sustainable yield.

Recruitment

The recruitment pattern of each sampling station was constructed using the pooled size-frequency data sets by backward projection onto the size axis. The routine determines the recruitment rhythm from a time series of the size-frequency data to determine the number of pulses per year and the relative strength of each pulse. The distribution of the recruitment pattern was determined by NORMSEP, which is available in FiSAT (Pauly & Caddy, 1985).

3.3.7 Histological preparation of oyster gonads

The sex and developmental state of the oyster gonads were determined by standard histological methods in conjunction with light microscopy. Monthly samples of twenty (20) adult oysters longer than 4.0 cm SH (exploited sizes) were obtained, each from Stations 3, 4a and 4b for this study. Oysters were shucked and their 'gonads' (Visceral mass) were cut at the dorsal and ventral ends with a surgical blade prior to fixing them in a Bouin's solution for 24 hours to enhance the infiltration of the fixative. The fixed oyster specimens were then washed thoroughly and preserved in 70 % ethanol.

The samples were subsequently processed by standard histological techniques involving dehydration with increasing concentrations of ethanol to absolute (100 %), clearing with chloroform and infiltration with molten paraffin wax using an automatic tissue processor (Shannon Elliot SE 400). Subsequently, the processed tissues were embedded in paraffin wax, and the blocks were then placed on wooden holders for sectioning with a rotary microtome (Bright 5040). Six 'serial' sections were made from each specimen. Thus, two successive sections from three different portions along the gonad were cut to get a good representation of the gonadal development. The sections were cut at 6 - 10 µm thickness, mounted on microscope slides and allowed to

dry on a slide warmer for about 24 hours. Duplicates of sectioned tissues on microscope slides were kept, should samples be damaged in the process of staining. The tissues were subsequently stained with Ehrlich's haematoxylin and counter-stained with eosin.

Well dried cover-slipped slides were examined microscopically at magnifications ranging from 50 - 400 (Yankson, 1996) using Motic BA310 Compound Microscope in conjunction with Motic Image Plus 2.0 software ran by a computer to make observations and take photographs.

Sex ratio

Twenty (20) specimens from each sampling station, prepared by the standard histological method were examined and sexed on monthly basis. Significant deviations from the expected sex ratio of 1:1 were determined by Chi-square (χ^2) analysis (Zar, 1996).

Gonadal index determination

Monthly gonadal indices of oysters from the various stations were calculated by a modified version of Chipperfield's (1953) index of gonad maturity scheme by ranking the different gametogenic stages as follows: Stage I (Developing) – 1; Stage II (Ripening) – 2; Stage III (Ripe) – 3; Stage IV (Spawning) – 2; Stage V (Reabsorption/ Redeveloping) – 1. Individual scores assigned to gonad conditions were used to estimate the monthly mean gonad index according to the equation: Mean GI = $\Sigma gn/ N$ (Krampah et al., 2016; Ndzipa, 2002), where g = rank of the stage, n = number of individuals assigned to a stage and N = sample size. The relationship between gonad indices (as a measure of the gonad development) of oysters from the various sampling

stations and the measured physico-chemical factors were assessed by multiple linear regression analysis.

3.3.8 Condition index determination

Condition indices of thirty (30) adult individuals (> 4 cm SH) from the various sampling stations were estimated monthly prior to the gonad fixation. The condition index was estimated by the displacement method adopted by Yankson (1986), given as CI = (Meat volume × 100) / (Whole volume - Shell volume), where the meat, whole and shell volumes were the water displacements (ml) by the meat, intact oyster with closed shells and empty shells, respectively. The relationship between the condition indices of oysters from the various sampling stations and the measured physico-chemical factors were assessed by multiple linear regression.

3.3.9 Suspension and bottom culture and biofouling experiments

Both experiments were undertaken simultaneously at Stations 3 and 4a (Fig. 2; Appendix E1) near oyster beds from December 2017 to July 2018, after the installation of bamboo racks in November 2017. In these studies, for convenience, a cultch will refer to a set of strung materials while a collector will be used for a unit material.

Coconut-shell and oyster-shell cultches were constructed using a ¼-inch nylon rope with 12 cm length between two collectors, as indicated in Figure 4. The cultches were installed in the middle of December 2017 when spatfall was observed to be high on the installed racks with the concave surfaces of the collectors facing downwards (Fig. 4). Each of the 5 unit coconut-shell or oyster-shell collectors were allowed to grow five spat at the concave and convex surfaces (by thinning-out, see Appendices C1 - C4), that is a cultch supported

50 spat. Each experiment was conducted by using 16 coconut-shell and 16 oyster-shell cultches, suspended vertically (for the biofouling experiment) and horizontally at the bottom on bamboo racks (suspension and bottom culture) of dimensions 1.5 m length x 1.0 m height x 1.0 m width as seen in Figure 5b). Hence, each experiment was started with 800 spat on the coconut-shell as well as 800 spat on the oyster-shell cultches. The fouling organisms on the fouled oysters were noted.

Growth of oyster spat was monitored by monthly measurements for both experiments and recorded on data sheets (Appendices D1 & D3 and Appendix E2) to ascertain the changes in size over time. The average values obtained for the shell height in January 2018 were used as the initial sizes of the spat. The field measurements were repeated in the middle of every month (January to July 2018). The monthly growth rate was calculated using the equation: Monthly growth rate = $H_2 - H_1 / t$, where H_2 is final shell height, H_1 is initial shell height in cm, and t is the number of days between sampling periods.

Oyster survival was determined by counting the number of live oysters on monthly basis (see Appendices E2 & E4) and expressing it as a percentage of the initial number stocked. The percentage of survival was calculated using the following equation: Survival = (Number of survivors / Number of spat stocked) ×100.

Suspension and bottom experiment

Out of the 16 coconut-shell and 16 oyster-shell cultches, eight of each type were suspended by tying the ends of the nylon ropes while the other eight sets were tightly tied horizontally to the bamboo rack at the bottom (Fig. 5).

Both suspension and bottom cultches were cleaned of fouling organisms, including oysters that settled latter.

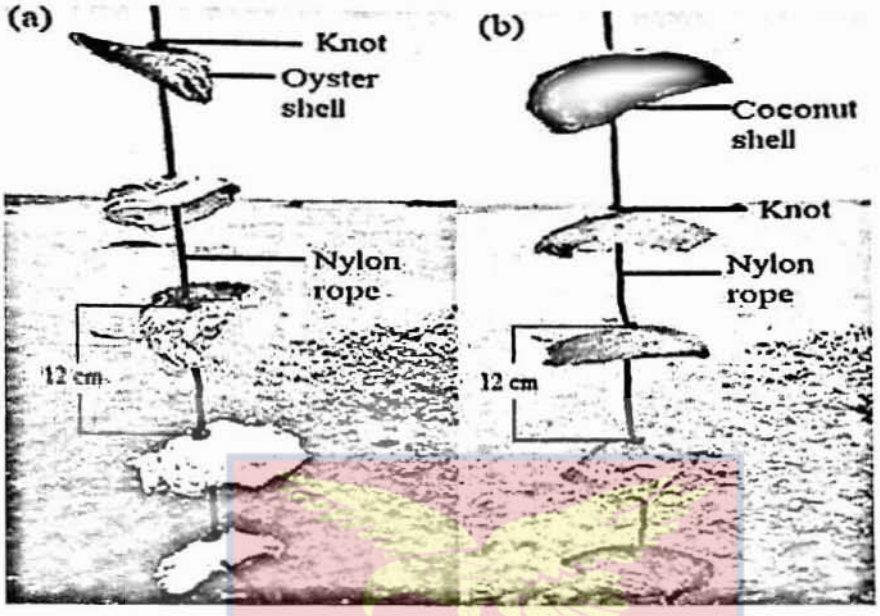

Figure 4: (a) Oyster-shell cultch and (b) Coconut-shell cultch

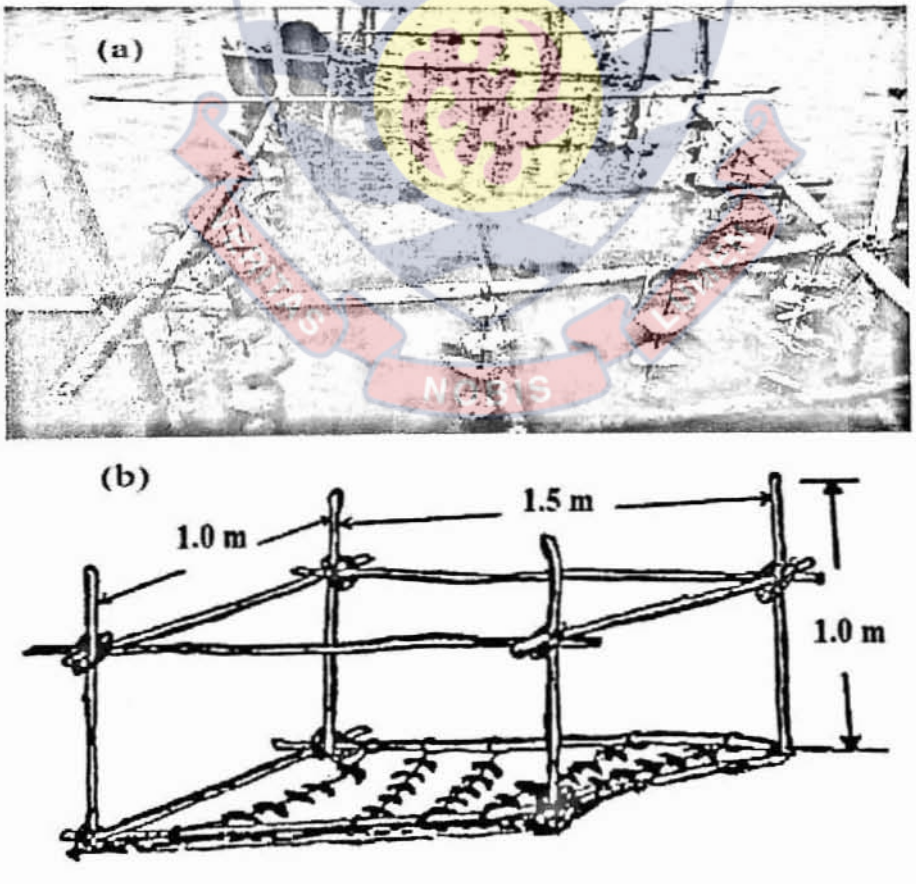

Figure 5: (a) Suspension and (b) Bottom culture set-ups (b is adapted from Obodai, 1997)

Cleaning was done on monthly bases by clearing fouling organisms using the tip of a knife as well as the removal of algae on the cultches and resetting them. Each of the suspended and bottom cultches was identified using different numbers of knots, ranging from 1 to 8, after the last unit collector for easy identification during the monthly assessments (see Appendix E3 for an example).

The efficiency of the suspension and bottom cultures was investigated by using coconut-shell and oyster-shell cultches as well as the surface of the collector (convex and concave) with respect to growth and survival of oysters. The above was assessed by comparing the monthly mean shell heights and survival. Thirty (30) oysters (specimens) cultured by suspension and bottom method on the convex and concave surfaces of both cultch types were randomly measured on monthly bases. Repeated measures ANOVA and Chi-square test of independence were used to compare the growth and survival performance.

Biofouling experiment

Of the 16 coconut-shell and 16 oyster-shell cultches, eight of each type were allowed to get fouled by organisms while the other eight sets were cleaned of biofoulers and reset on monthly basis. The biofouled cultches were tagged by two (2) knots above the first unit collector while the cleaned cultches had a knot. Each of the eight cultches tagged as biofouled or cleaned of a given type of cultch (i.e., coconut shell or oyster shell) was identified by a number of knots ranging from 1 to 8 after the last unit collector for easy identification. To avoid positional effect, the biofouled and cleaned cultches were alternated.

The effect of biofouling on the growth and survival of oysters cultivated on the convex and concave surfaces of coconut-shell and oyster-shell cultches

as well as oysters grown on biofouled and cleaned top and bottom 2 collectors of both cultches were assessed by comparing the monthly mean shell heights and survival of oysters on cleaned and biofouled cultches. Thirty (30) cultured oysters on the biofouled and cleaned convex and concave surfaces of both cultch types were randomly measured on monthly bases (Appendix E2). Measurements of oysters on the top and bottom two collectors (24) were obtained from the data above. Repeated measures ANOVA and Chi-square test of independence were used to compare the growth and survival of oysters on the convex and concave surfaces as well as on the top and bottom two collectors of biofouled and cleaned cultches (coconut-shell and oyster-shell).

3.3.10 Proximate analysis

Proximate analysis was undertaken a week after July's 2018 physico-chemical and biometric sampling to compare the nutritional value of wild and cultured oyster meat. Sixty (60) oysters (4.0 cm SH and above) were sampled at the same time and each from the cleaned oysters (suspension culture) and the wild (close to the experimental set-up) for the analysis. Both samples were shucked and placed in labelled zip-lock bags and frozen. The method used for the estimation of the proximate composition was based on the procedure of the Association of Official Analytical Chemists (AOAC). Proximate analysis of the samples was done on dry weights. The oyster meat samples were oven-dried (100 - 110 °C) to a constant weight. Subsequently, the samples were homogenized by grinding with a mortar and pestle. The powdered samples were then analysed for moisture, ash, crude fat, crude protein, carbohydrate (soluble) and crude fibre (insoluble carbohydrate). Moisture was estimated by the loss in weight after oven drying. Ash was estimated by ignition at 550 °C; crude fat, by

Soxhlet extraction with petroleum ether; protein was determined by the semi-micro Kjeldahl method; carbohydrate was assumed to be the difference of the sum of ash, fat, fibre and protein estimates from 100 % as presented by Shafee (1989). A 2-sample independent t-test was used to compare the nutritional value of cultured and wild oysters.

3.3.11 Taste analysis

Two hundred and fifty (250) cultured oysters were sampled from the suspension culture and 250 from the wild into separate basins. To control stimulus error, the cultured and wild oysters were of comparable sizes. Moreover, the wild oysters were sourced near the culture set-up. The oysters used in this analysis ranged from 5 to 6 cm SH.

The oyster samples were washed thoroughly to get rid of debris and soil particles from the shells before boiling in separate cooking utensils under similar conditions. After boiling, the wild and cultured oyster meat were shucked using kitchen knife into separate labelled bowls. The meat were washed thoroughly to avoid soil particles and fried with frytol cooking oil.

Randomly selected 75 oyster consumers were the measuring instruments for the taste analysis. The consent of the participants was obtained before the exercise. Tasters were informed about the purpose of the exercise and the basic rules governing sensory evaluation a day before. The assessment was done in a small confined area away from the open space wher e the other assessors sat, to cut off any form of communication. This was done around 11 am after the tasters had taken their breakfast, the reason being that hunger might affect the sensitivity of the taste sensors of participants. Each taster was given three pieces of meat of each sample to assess. The cultured and wild oyster meat were coded

as 161 and 121, respectively to avoid expectation error (Fig. 6). The two samples were presented to the tasters at room temperature. Tasters rinsed their mouth before the first sample was tasted (by chewing) and in between samples to clean their taste buds, palate and inner walls of the mouth to avoid masking of sensations or reduce adaptation to taste buds (Figs. 6 & 7). Chewing of the samples was done in about 4 seconds to allow enough time for all the sensory buds of the tongue and the palate to be well stimulated. Individuals suffering from any form of ailment that might affect the sensitivity of the taste buds and palate (e.g., malaria and cold) were asked to exempt themselves from the taste evaluation.

Figure 6: Presentation of the three-digit-coded oyster samples for evaluation

Figure 7: Tasters under open shed waiting to have their turn to assess the wild and cultured oyster samples

Since most of the tasters could not read nor write, the scoresheet was attended to by a facilitator to record tasters' preferred sample. An Affective test, mainly Consumer Test, also known as Paired Preference Test was used to analyse preference between the two samples. Chi-square Goodness of Fit Test was used to ascertain the significance of the outcome.

3.3.12 Statistics and statistical packages

An alpha level of 0.05 was used for all inferential statistics. Statistics employed in the study were descriptive statistics, Chi-square test of independence, Chi-square test of best fit, independent 2-sample t-test, 1-sample t-test, 1-way ANOVA accompanied with Tukey post hoc test and repeated measure ANOVA complemented with Bonferroni post hoc test. For convenience purposes and better output, a number of statistical packages where used in the various analyses, these are Microsoft Excel 2013, Minitab (version

17), SPSS (version 20) and R software (version R-3.5.3) in conjunction with Rstudio (version 1.0.153).

CHAPTER FOUR

RESULTS

This chapter presents the results of the study. The data have been analysed and shown in tables and figures and arranged in a sequence that addresses the study objectives.

4.1 Socioeconomic Assessment of the Oyster Fishery

4.1.1 Demography of oyster fisherfolk

The gender distribution of 98 respondents sampled from Bortianor/Tsokomey and Tetegu is presented in Table 2. Figure 8 shows the age-sex distribution of the oyster fisherfolk. Table 2 and Figure 8 indicate female dominance (97 %) with a modal age group of 35 – 44 years.

Table 2: *Gender Distribution of Respondents (N = 98)*

Gender	No. of Respondents			
	Bortianor/Tsokomey	Tetegu	Total	%
Male	3	0	3	3 %
Female	77	18	95	97 %
Total	80	18	98	100 %

The marital status of the oyster fisherfolk is shown in Figure 9, indicating that majority of the respondents (71.4 %) were married. Figure 10 presents the level of dependants (including the young and old) on the oyster fisherfolk, which demonstrated a high level of dependency, i.e., about 37 % and 57 % of respondents had 5 - 9 and 1 - 4 dependants, respectively.

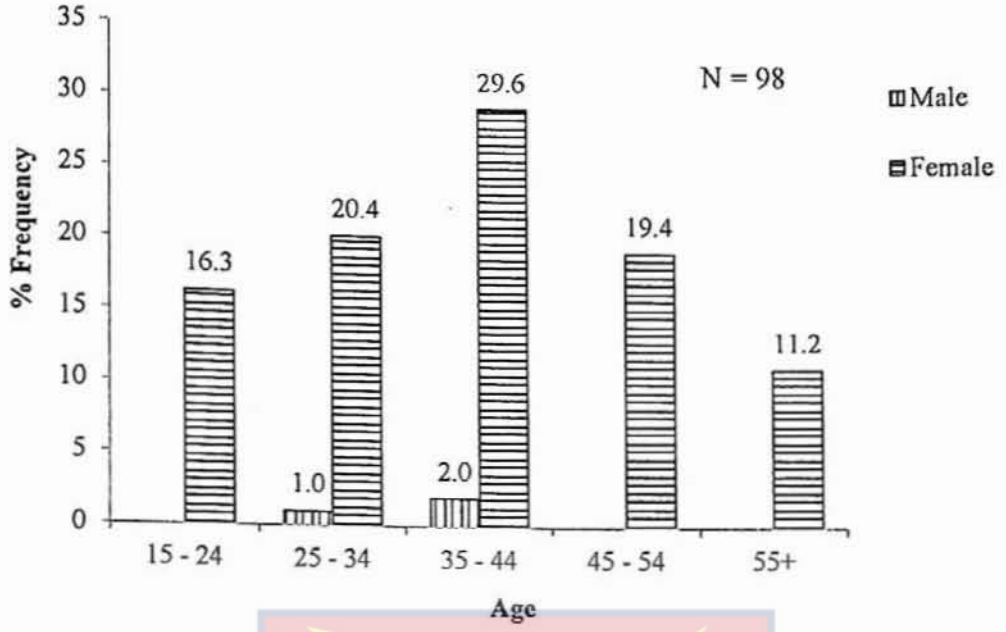

Figure 8: Age-sex distribution of respondents in the oyster fishery at Densu Delta (Numbers indicated above the bars are percentage frequencies)

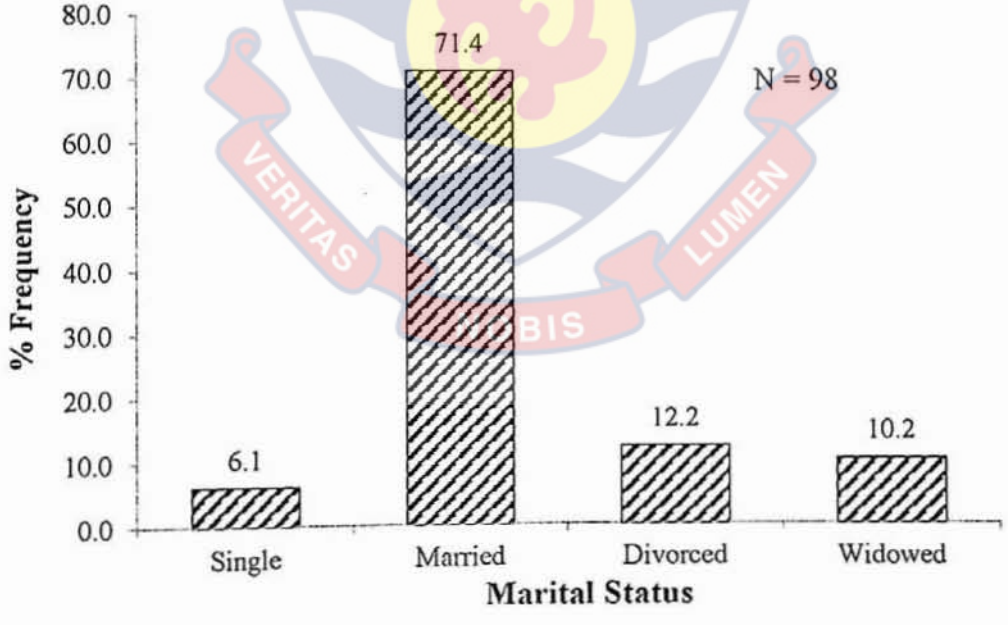

Figure 9: Marital status of respondents in the oyster fishery at Densu Delta (Percentage frequencies are indicated on top of the bars)

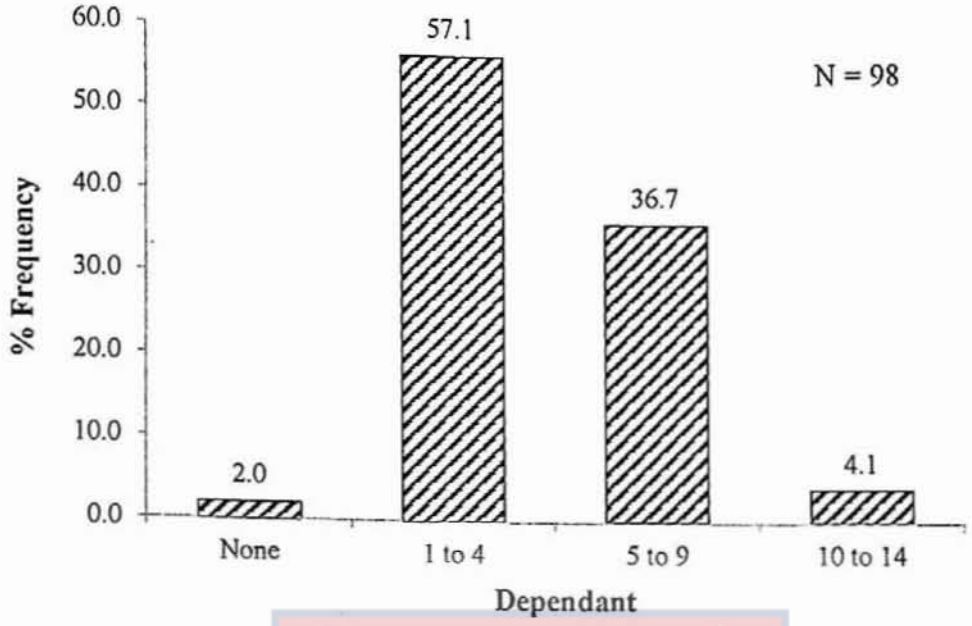

Figure 10: Level of dependants on respondents in the oyster fishery at Densu Delta (Percentage frequencies are indicated on top of the bars)

A cross-tabulation of ethnicity and origin of respondents in the oyster fishery is shown in Table 3. The natives were Gas while the migrants and settlers were Ewes. Ewes dominated the fishery (86 %), followed by 13 % of Gas and an Akan. A Chi-square test of independence showed that there was an association between ethnicity and origin ($\chi^2 = 73.43$, df = 4, $p < 0.001$). Figure 11 presents the level of formal education of oyster fisherfolk. About 76 % of the respondents did not attend school or ended their education at the Primary level, and close to half of this percentage did not get any formal education. Figure 12 shows the number of years respondents have been in the oyster fishery. It is seen that respondents with less than five years' experience in the fishery dominated the distribution (29 %). The percentages decreased steadily to 11.8 % for fishers with more than 20 years of experience in the fishery.

Table 3: *A Cross-tabulation of Ethnicity and Origin of Oyster Fisherfolk*

			Ethnicity			Total
			Ga	Ewe	Akan	
Origin	Native	Count	10	0	0	10
		% within Ethnicity	76.9%	0.0%	0.0%	10.2%
	Migrant	Count	1	30	0	31
		% within Ethnicity	7.7%	35.7%	0.0%	31.6%
	Settler	Count	2	54	1	57
		% within Ethnicity	15.4%	64.3%	100.0%	58.2%
Total		Count	13	84	1	98
			13.26%	85.71%	1.02%	100.0%

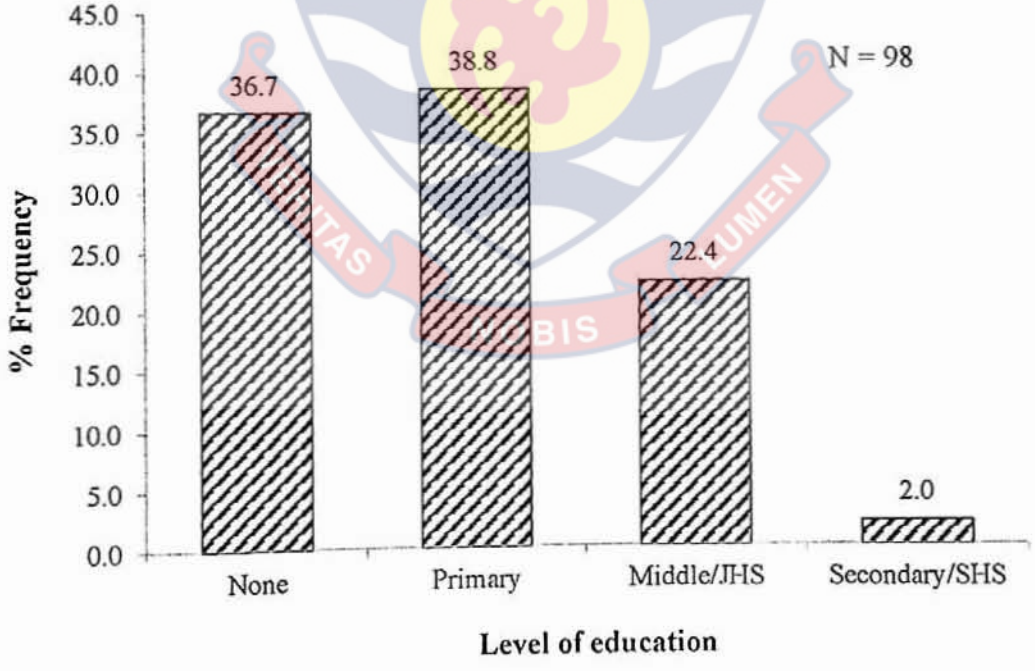

Figure 11: Level of formal education of respondents in the oyster fishery at Densu Delta (Percentage frequencies are indicated on top of the bars)

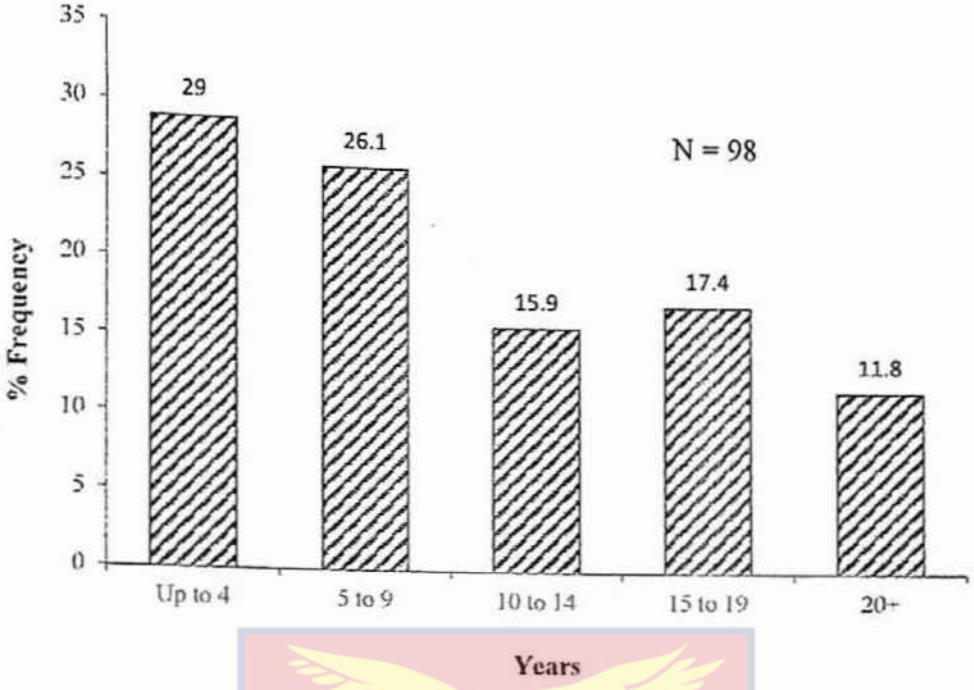

Figure 12: Number of years respondents have been in the oyster fishery at Densu Delta (Percentage frequencies are indicated on top of the bars)

On livelihoods, about 69 % of the respondents indicated that the oyster business was their primary source of income during the peak oyster season (April to September). Table 4 presents the forms of alternative livelihoods of the oyster fisherfolk. The oyster collectors have diversified livelihoods, but the majority (about 76 %) are fisheries-related.

4.1.2 Exploitation of the oyster fishery

The oyster fishery was an unregulated and open-access resource. Respondents indicated that oysters were not available year-round in the shallow waters (0.61 m depth), while in the deeper water (2.13 m depth), oysters were exploited year-round but at low densities during inundation of the Densu Delta by freshwater input. The resource was exploited by handpicking on oyster beds as fishers wade through the water body at the shallow portion (see Appendix B4) with improvised socks as well as diving in the deeper portion of the Delta.

Table 4: *Forms of other Livelihoods of Individuals Engaged in the Oyster Fishery*

Livelihoods	Number of Responses	Percentage (%)
Fishery-related activities		
Basket/ Handfishing	56	26.7
Fish processing	62	29.5
Head Porter	41	19.5
Unrelated fishery activities		
Food vending	16	7.6
Petty trading	14	6.7
Fuelwood retailing	4	1.9
Cleaning services	10	4.8
Handicraft/Artisan	7	3.3
Total	210	100

All the male respondents indicated that they sourced oysters at deeper depth by diving. About 95 % of females were restricted to the shallow portions of the water body due to their inability to dive in deep waters.

Respondents' engagement in the oyster fishery in terms of harvesting, processing and marketing is shown in Table 5. The results indicate that almost every individual was engaged in harvesting, processing and marketing. However, the three males encountered were all harvesters only. It takes about three to four hours to harvest four basins or baskets, depending on the availability of market-sized oysters. Oysters in the Delta were exploited in all the days of the week. Nonetheless, the average individual collector harvests twice in a week.

Table 5: *Roles in the Oyster Fishery*

		Responses N	Percent of Cases
Role in the oyster fishery[a]	Harvester	94	95.9%
	Processor	94	95.9%
	Marketer	92	93.9%
Total		280	285.7%

a. Dichotomy group tabulated at value 1.

4.1.3 Economics of the oyster fishery

Tables 6, 7 and 8 show the preliminary investment, running cost of the oyster fishery and total annual catch and value of oysters, respectively. The cost of replacement of items was factored in the preliminary investment, which was estimated between GHS 105 and 190 (USD 24.01 – 43.45), as seen in Table 6. These items were harvesting basins/baskets, cooking utensils, shucking knives and trays for marketing the oysters. The cost of the canoe was excluded in the preliminary investment because oyster fishers hire fishing vessels. Running costs (i.e., the expenses associated with the oyster business) for harvesting, processing and marketing were estimated to have ranged from GHS 3 to 13.5, GHS 0.5 to 12 and GHS 2 to 7, respectively (Table 7). The cost of engaging in the above three components of the oyster fishery was between GHS 5.5 and 32.5 (USD 1.26 – 7.43).

Table 6: *Preliminary Annual Investment of an Individual in the Oyster Fishery*

Item	Unit Cost (GHS)	Quantity	Total Cost/ Item (GHS)
Basin or basket	20 – 35	2	40 – 70
Cooking utensil	20 – 35	2	40 – 70
Shucking knife	5 – 10	3	15 – 30
Tray	5 – 10	2	10 – 20
Total			105 – 190

A canoe was shared by two or three fishers to cut down on cost. Usually, the fishers bought food and water for themselves and the canoe rower. On the processing, some respondents bought bundled fuelwood, while others cut or collected dried broken tree branches from the shrubs or mangroves fringing the water body. Water was bought for washing the mud and debris off the oysters before boiling with or without salt. In some cases, processors sought assistance at a fee (GHS 5) to expedite the work. Concerning marketing, oyster vendors displayed the wrapped meat in a transparent polyethene sheet on trays. The boiled meat were packaged in polyethene bags upon purchase. Marketers travelled to the next communities like Kokrobitey, Oshea, Aplaku and sometimes as far as Kaneshie market in Accra at the peak of the oyster season.

Table 7: *Running Cost of the Oyster Fishery by an Individual Fisher/Trip*

Harvesting/Trip		Processing		Marketing	
Item	Cost (GHS)	Item	Cost (GHS)	Item	Cost (GHS)
[a]Canoe Transportation	10 - 15 ([b]7.5)	Fuelwood	None - 5	Poly-bags	2 - 3
Canoe Owner	5 - 10	Water	0.5 -1	(Packaging)	
Canoe Rower	5	Salt	None - 1	Transportation	None - 4
Food and Water	3 - 6	Assistance	None - 5		
Range	3 - 13.5	Range	0.5 - 12	Range	2 - 7

[a] Cost is borne by fishers who use canoe [b] Cost incurred by one of the two occupants

Table 8: *Total Annual Catch and Value of Oysters*

Type of Receptacle	Mean Catch per ind./day (Kg)	Range (Kg)	Total Catch per day (Kg) (15 ind./day)	No. of Fishing Days in a Season (6 months) (7 days x 26 weeks)	Total Annual Catch (Kg)	Value of Catch (GHS)
Basin	87	81 - 93	1305	182	237,510	245,700
Basket	129	123 - 135	1935	182	352,170	327,600

The total annual catches and values by basin and basket are presented in Table 8. The mean weights of a basket and a basin full of shell-on oysters were estimated as 43 (41 - 45) Kg and 29 (27 - 31) Kg, respectively. The average fisher harvested three (3) basins or baskets of oysters a day. It was also estimated that an average of 15 oyster pickers went fishing in a day and a profit of GHS 10 to 20 was made on a basin or basket depending on the size. The catches for the season (6 months, i.e., 26 weeks) by basin and basket were estimated at 237,510 Kg and 352,170 Kg, respectively (Table 8). The mean catch for an individual per day was estimated by multiplying the mean weight of basin/basket (full of oysters) by the average number of basins/baskets fishers landed. The total annual catch was calculated by multiplying the total catch per day by the number of fishing days in a season. Each of these calculated weights was valued at GHS 245,700 and GHS 327,600, respectively (A basin of approximately 29 Kg of shell-on oysters was sold at GHS 30 whereas that of a basket, 43 Kg was sold at GHS 40). The annual catch ranged between 237,510 and 352,170, averaging 294,840 Kg. The corresponding values were appraised at, from GHS 245,700 to GHS 327,600, averaging GHS 286,650 (USD 65,558.96). The annual catch of oysters from the Densu Delta was estimated at 294.8 tonnes with an appraised value of GHS 286,650. The above was approximated by asking fishers the price they will sell a basket or basin full of shell-on oysters by taking into consideration harvests by the use of baskets and basins or the combination of the two.

Profitability of the oyster fishery at Densu Delta

1) Total Annual Cost of fishing = Fixed Cost + Annual Running Cost

   a) Preliminary investment and cost of replacement of items (Fixed Cost) (Table 6)

      i) The cost was given as **GHS 105 – 190**

   b) Annual running cost of the fishery

      i) Running cost of harvesting, processing & marketing was estimated at **GHS 5.5 – 32.5** (Table 7, summation of the three components)

      ii) Running cost of the average no. of fishers/day:15 x GHS (5.5 – 32.5) = **GHS 82.5 – 487.5**

      iii) Running cost for the fishing season (i.e. 182 days): 182 x GHS (82.5 – 487.5) = **GHS 15,015 – 88,725**

   c) Annual cost is therefore estimated as GHS {(105 – 190) + (15,015 – 88,725)} = **GHS 15,120 – 88,915 (Ave 52,018 = USD 11,896.90)**

2) Total Annual Profit

   a) A profit of **GHS 10 – 20** is realised per basin or basket; therefore profit per trip (day) for an individual will be 3 (average number of basin and/or basket/fisher/day) x (10 – 20) = **GHS 30 – 60 (Ave = 45)**

   b) Profit for the average no. of fishers per day: 15 x (30 – 60)

      = **GHS 450 – 900**

   c) Profit for the fishing season (i.e., 182 days): 182 x (450 – 900)

      = **GHS 81,900 – 163,800 (Ave 122,850 = USD 28,096.70)**

3) Gross Annual Income = Total Annual Profit + Total Annual Cost of fishing

   a) GHS 122,850 + GHS 52,017 = **GHS 174,867 (USD 39,993.37)**

By comparing the appraised value of the oyster fishery (GHS 283,500), see Table 8 and the gross annual income (GHS 172,948), a difference of **GHS 111,783 (USD 25,565.59)** was realised.

4.2 Physico-chemical Parameters

4.2.1 Temperature

Mean monthly variations in surface temperature of the Densu Delta have been illustrated in Figure 13a. A similar pattern of variations in surface temperature occurred at all stations in the Delta and fluctuated between 22.45 ± 0.06 and 31.47 ± 0.06 °C. Mean surface temperature ranges at Stations 1, 2, 3 and 4 were 25.87 – 31.47 °C, 26.37 – 31.34 °C, 26.73 – 31.57 °C and 26.43 – 31.47 °C, respectively. The temperature values at all stations decreased sharply from the highest in May to the lowest levels for all stations in August 2017 and increased sharply in November 2017 and thereafter fluctuated between 26 °C and 30 °C for the rest of the period. Highest temperature values in 2017 were recorded in May and lowest in August. In 2018, highest temperatures were recorded in October and the lowest in August.

Surface and bottom fluctuations of mean temperature at Station 4 are shown in Figure 13b. Generally, there were minimal monthly variations in the temperatures at the surface and bottom, except for the significant variations in July 2017 ($t = 4.11$, $df = 4$, $p < 0.05$), August 2017 ($t = 6.91$, $df = 4$, $p < 0.05$) and August 2018 ($t = 7.84$, $df = 4$, $p < 0.05$).

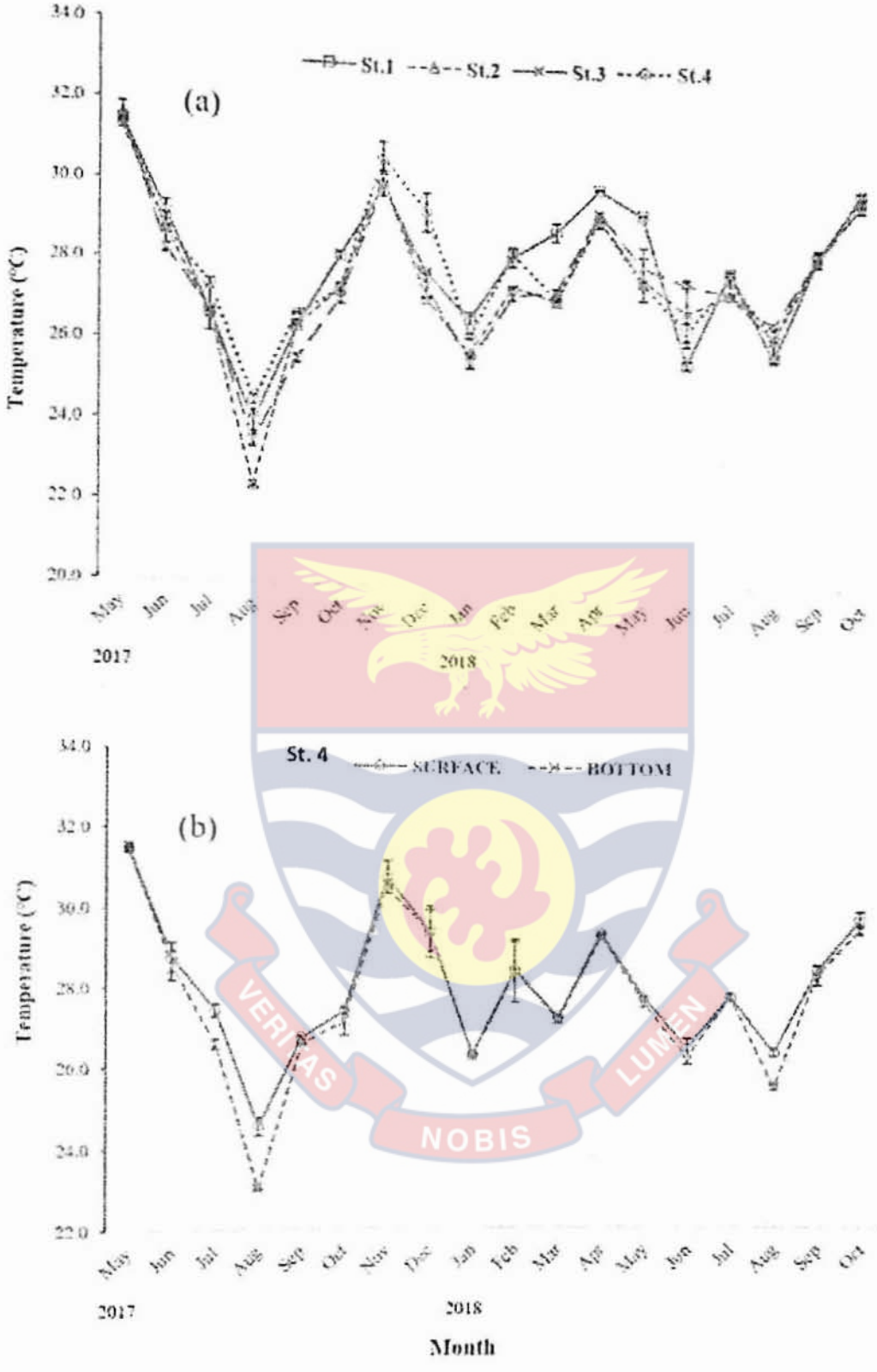

Figure 13: Mean monthly variations in temperature (a) at the surface among the various stations and (b) surface and bottom at Station 4 in the Densu Delta (the vertical bars indicate standard errors of means)

4.2.2 Dissolved oxygen (DO)

Figure 14a illustrates the fluctuations in surface mean DO for all stations in the Densu Delta, which were mostly similar and ranged from 0.38 ± 0.02 to 8.15 ± 1.11 mg/l. Mean DO ranges were 0.45 – 8.16 mg/l, 0.42 – 6.73 mg/l, 0.38 – 7.27 mg/l and 0.43 – 6.53 mg/l at Stations 1, 2, 3 and 4, respectively. Generally, in 2017 high DO values > 4 mg/l were recorded in June while low values < 2 mg/l were recorded in September and October. In 2018 high values were recorded in January/February and low values from March at Station 4 and from June at the other stations to October. Statistically significant lower DO values were recorded at St. 1 in October 2017 and from Dec 2017 to May 2018 (1-way ANOVA and Tukey's honestly significant difference, HSD test).

Figure 14b illustrates the surface and bottom variations of mean DO at Station 4. Fluctuations of DO in the surface and bottom were similar except in June 2018 ($t = 3.05$, $df = 4$, $p < 0.05$) and August 2018 ($t = 21.09$, $df = 3$, $p < 0.05$).

4.2.3 Salinity

Monthly fluctuations in surface mean salinity at the four stations are presented in Figure 15a. Mainly, the figure shows a similar pattern of fluctuations in surface salinity for all stations in the Densu Delta, which varied between 0 and 41.67 ± 0.06 ‰. Mean surface salinity ranges were 0 – 40.0 ‰, 0 – 40.33 ‰, 0 – 41.67 ‰ and 0 – 40.33 ‰ at Stations 1, 2, 3 and 4, respectively. Generally, in 2017 high values > 20 mg/l were recorded in August to October and in December while low salinity values < 5 ‰ were recorded in May, June, July and November. In 2018 high values were recorded in January to May and low values from June to October.

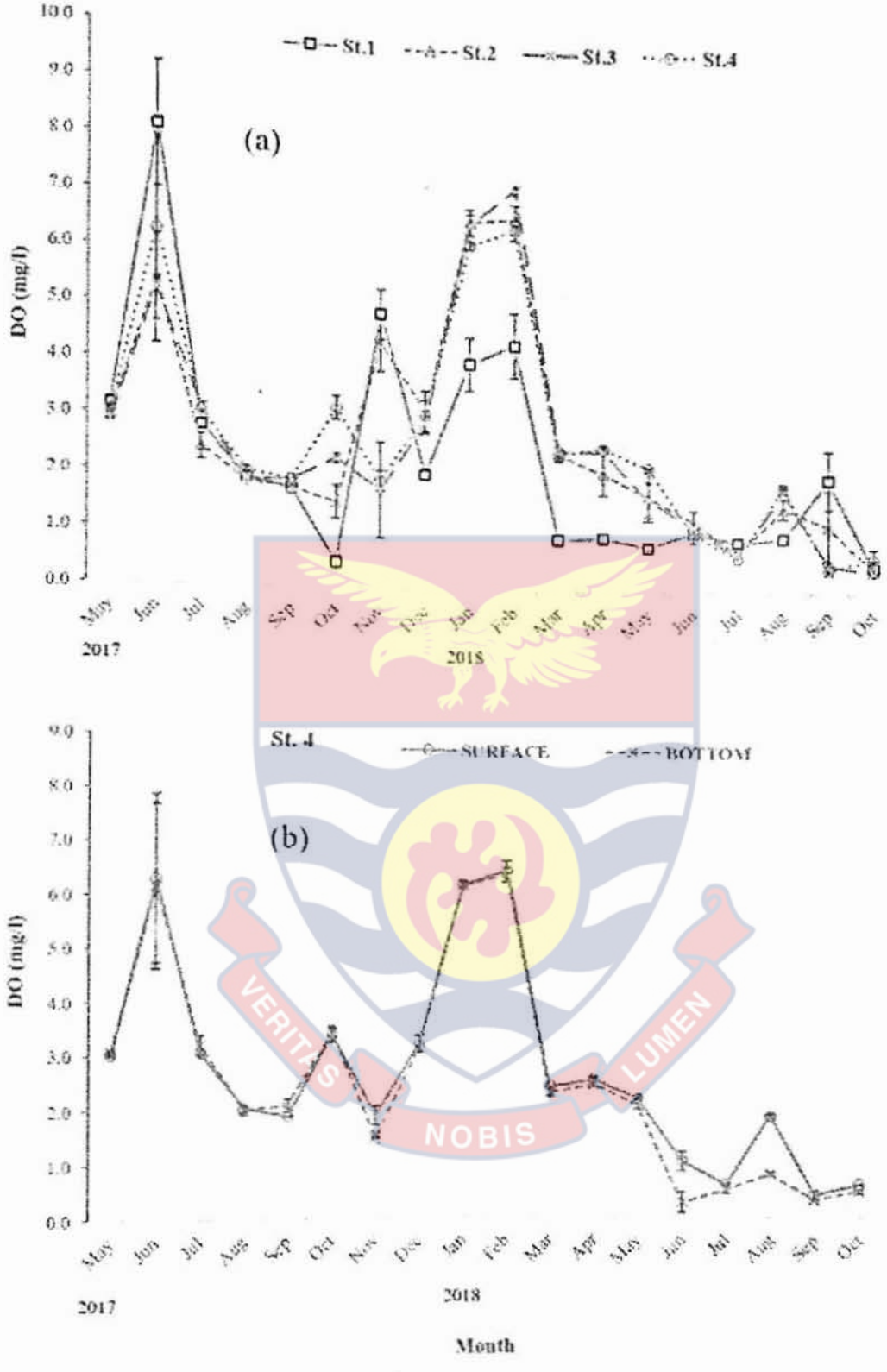

Figure 14: Mean monthly variations in DO (a) at the surface among the various stations and (b) surface and bottom at Station 4 in the Densu Delta (the vertical bars indicate standard errors of means)

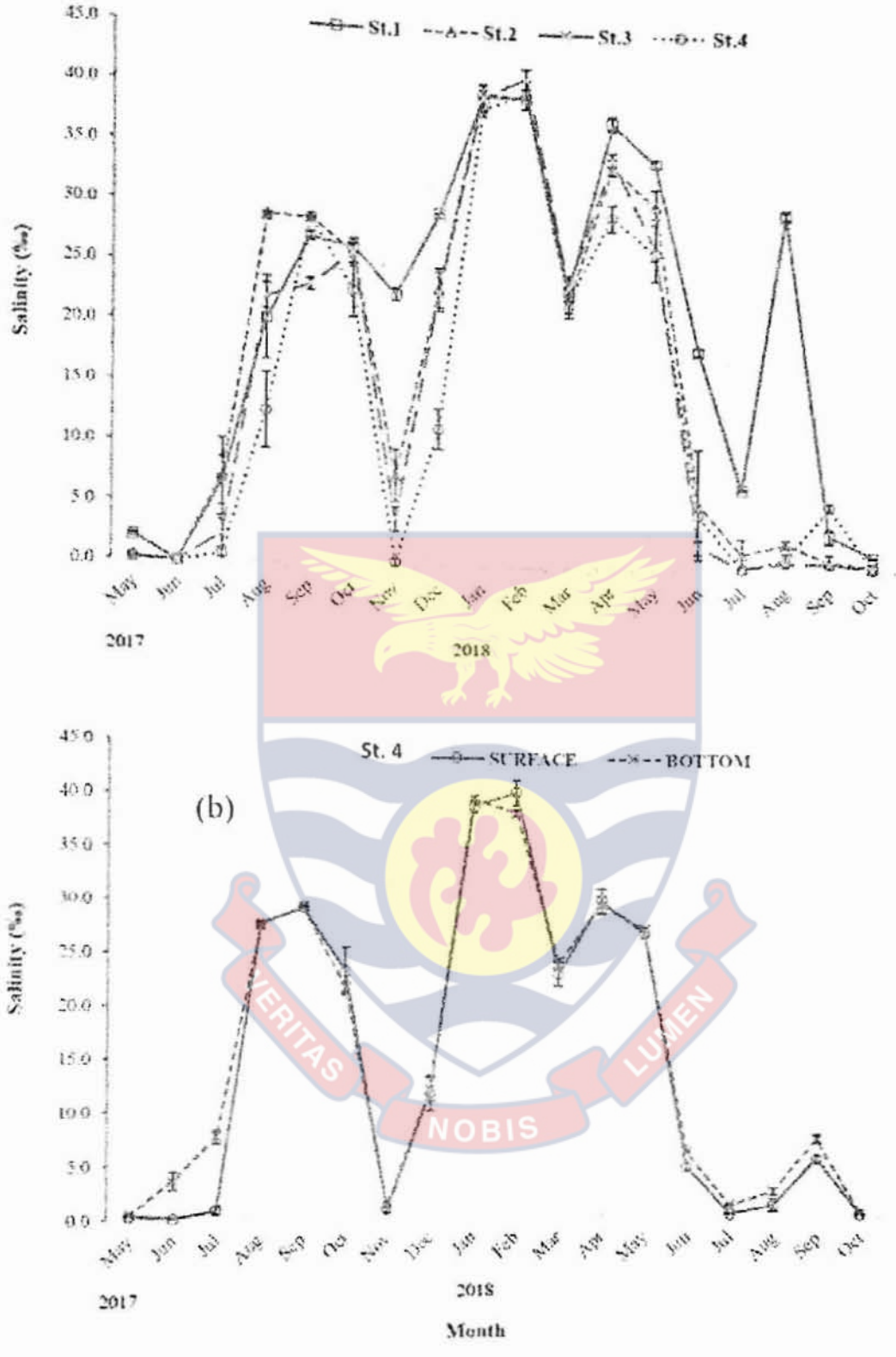

Figure 15: Mean monthly variations in Salinity (a) at the surface among the various stations and (b) surface and bottom at Station 4 in the Densu Delta (the vertical bars indicate standard errors of means)

Significantly highest salinity values were recorded at St. 1 in November 2017, June, July and August 2018 (1-way ANOVA and Tukey's HSD test).

The surface and bottom fluctuations of salinity at Station 4 is presented in Fig. 15b. Mean salinities at the surface and bottom were similar except in June 2017 ($t = 4.53$, $df = 2$, $p < 0.05$) and July 2017 ($t = 9.69$, $df = 3$, $p < 0.05$), which were statistically significant.

4.2.4 Hydrogen ion concentration (pH)

Figure 16a generally shows a similar pattern of the fluctuations in surface mean pH for all stations in the Densu Delta and ranged from 6.94 ± 0.19 to 10.82 ± 0.16. Mean surface pH ranges were 6.94 – 9.36, 7.00 – 9.00, 7.23 – 9.41 and 7.18 – 10.82 at Stations 1, 2, 3 and 4, respectively. In 2017, high values of pH > 8.50 were recorded from May to June and in November, while low values < 7.50 were documented in July and August. In 2018 high values were recorded in April and low values from June to October. Mean pH values were significantly highest at St.1 in May and June 2017 and Station 4 in November 2017 (1-way ANOVA and Tukey's HSD test).

Figure 16b illustrates the surface and bottom fluctuations of mean pH at Station 4. There were no significant variations in pH at the surface and bottom among all the months.

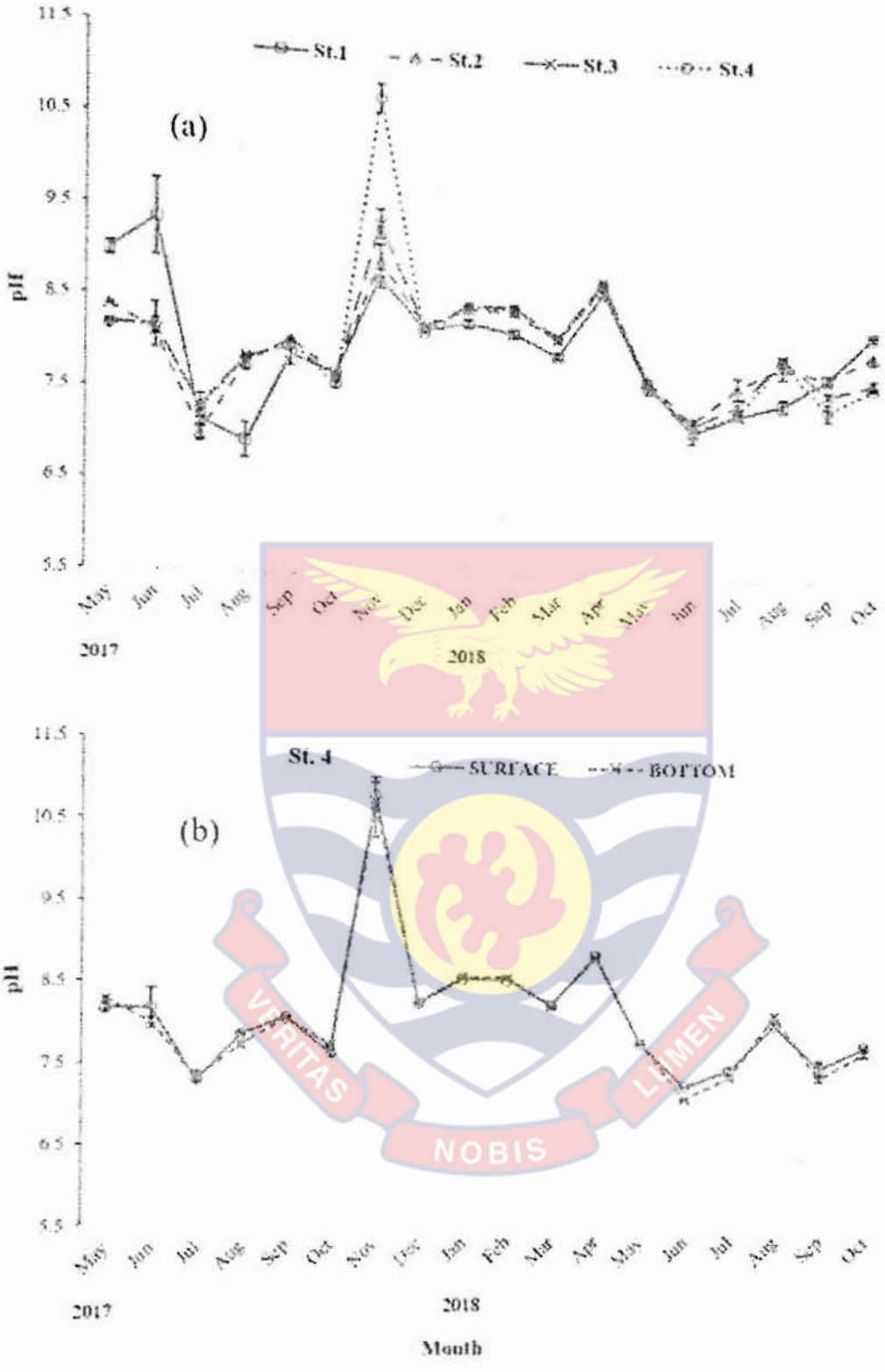

Figure 16: Mean monthly variations in pH (a) at the surface among the various stations and (b) surface and bottom at Station 4 in the Densu Delta (the vertical bars indicate standard errors of means)

4.2.5 Turbidity

Figure 17 shows the fluctuations in surface mean turbidity for all stations in the Densu Delta, which ranged from 2.00 ± 0.58 to 144.67 ± 7.75 NTU. High levels of turbidity > 20 NTU were documented in 2017 from June to July and November to December as well as in 2018 from June to August. Mean turbidity ranges were 4.67 – 29.43 NTU, 5.33 – 40.24 NTU, 2.33 – 24.17 NTU and 2 – 144.67 at Stations 1, 2, 3 and 4, respectively. Station 4 recorded the highest turbidity in November and December 2017 as well as in June 2018 (1-way ANOVA and Tukey's HSD test).

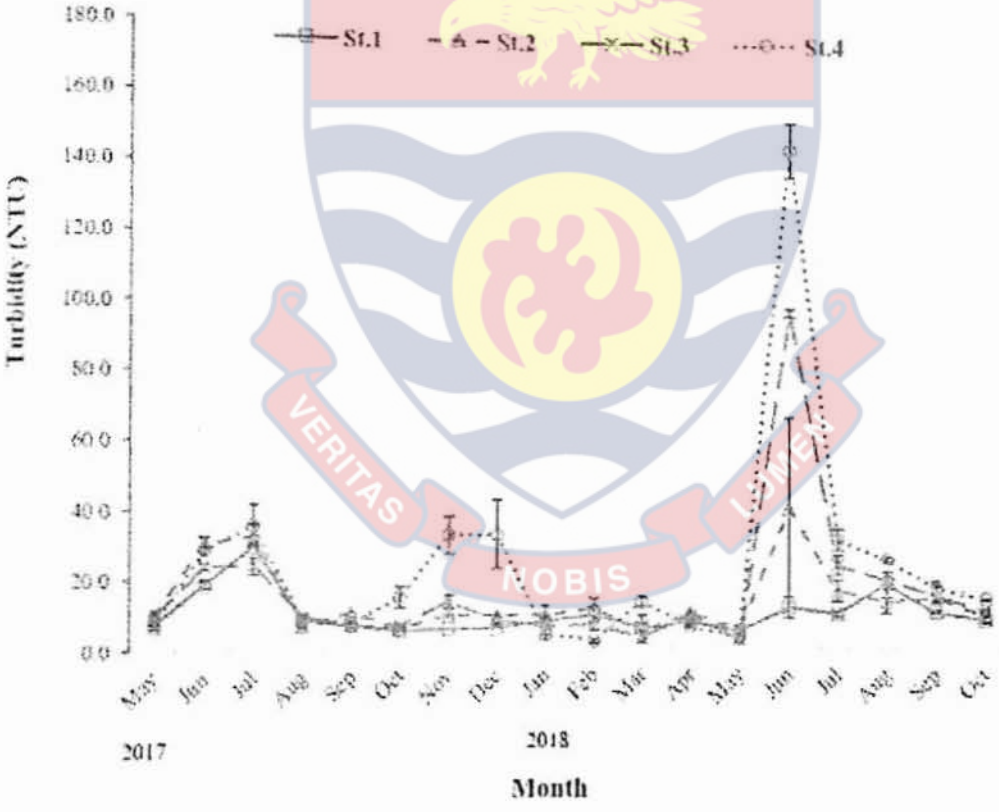

Figure 17: Mean monthly variations in surface turbidity among the various stations in the Densu Delta (the vertical bars indicate standard errors of means)

4.2.6 Nitrate concentration

Figure 18 illustrates the fluctuations in mean nitrate concentrations for all stations in the Densu Delta. These ranged from below detection point (BDL) to 26.73 ± 6.89 mg/l. The variations generally showed a similar pattern. Mean nitrate concentration ranges were 1.32 – 17.14 mg/l, BDL – 26.73 mg/l, BDL – 24.81 mg/l and BDL – 18.87 mg/l at Stations 1, 2, 3 and 4, respectively. Generally, in 2017 high values > 10 mg/l were recorded from September to December, while low salinity values < 5 mg/l were documented in May, June, July and November. In 2018 high values were recorded from January to July and low values from August to October.

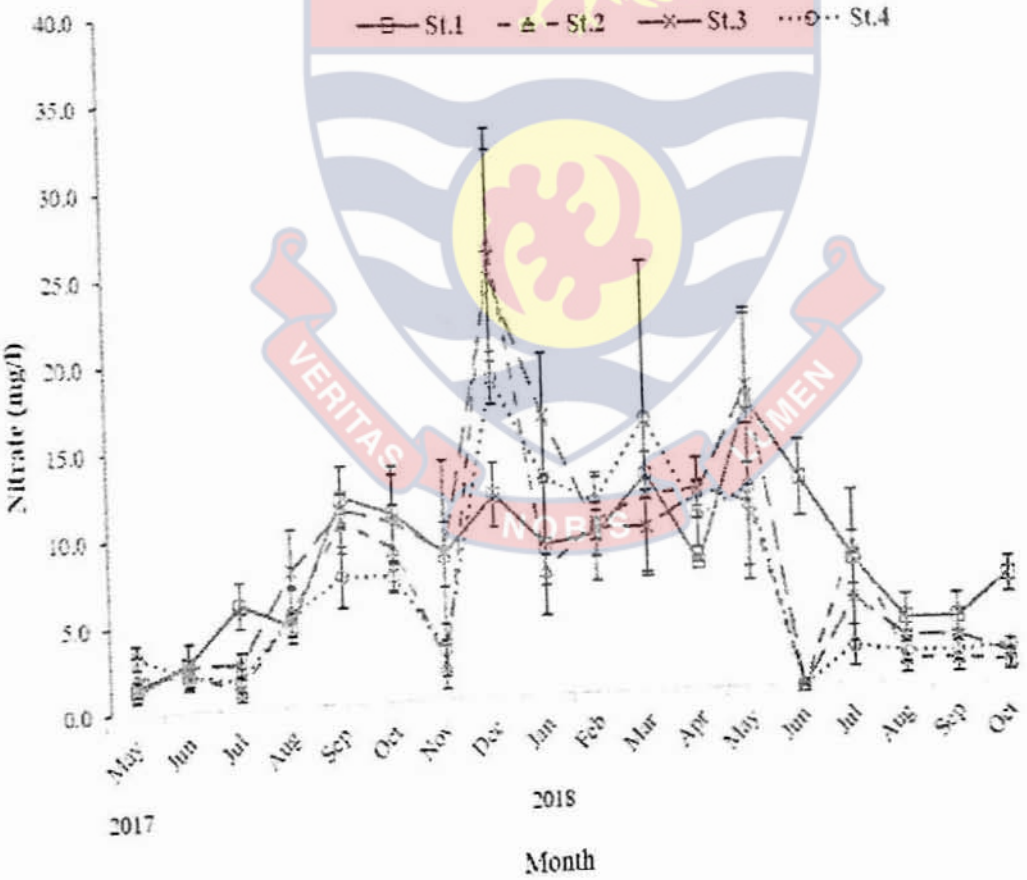

Figure 18: Mean monthly variations in nitrate concentration among the various stations in the Densu Delta (the vertical bars indicate standard errors of means)

4.2.7 Phosphate concentration

Generally, Figure 19 presents a similar pattern of fluctuations of mean phosphate concentrations at all stations in the Densu Delta and varied between 0.05 ± 0.06 and 11.13 ± 2.95 mg/l. Mean surface phosphate ranges were 0.11 – 9.16 mg/l, 0.09 – 11.07 mg/l, 0.11 – 5.16 mg/l and 0.08 – 11.13 mg/l at Stations 1, 2, 3 and 4, respectively. Mean phosphate concentrations at Station 1 was statistically higher than the other stations from July 2018 to September 2018 (1-way ANOVA and Tukey's HSD test). Generally, in 2017 high values > 4 mg/l were recorded in June and July while low values < 2 mg/l were documented in May and from August to December. Mainly low values of phosphate concentration were recorded throughout 2018.

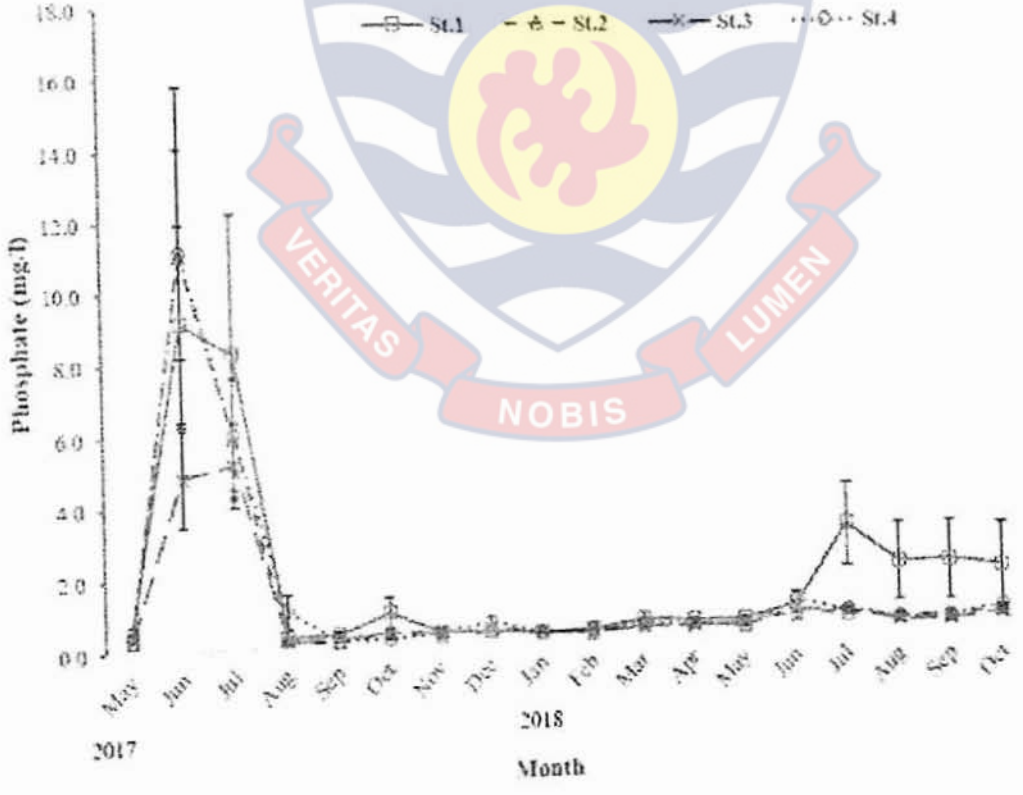

Figure 19: Mean monthly variations in phosphate concentration among the various stations in the Densu Delta (the vertical bars indicate standard errors of means)

4.2.8 Sediment bulk density

The mean sediment bulk densities of Stations 1 (0.14 ± 0.013 g/cm^3), 2 (0.12 ± 0.003 g/cm^3), 3 (0.12 ± 0.006 g/cm^3) and 4 (0.17 ± 0.003 g/cm^3) are presented in Figure 20. A 1-way ANOVA indicated a significant difference between the estimates of sediment bulk densities among the stations (F (3, 8) = 13.39, $p < 0.05$). Further analysis with Tukey's HSD test indicated that Station 4 sediment samples had significantly higher bulk density than the other three, which were comparable.

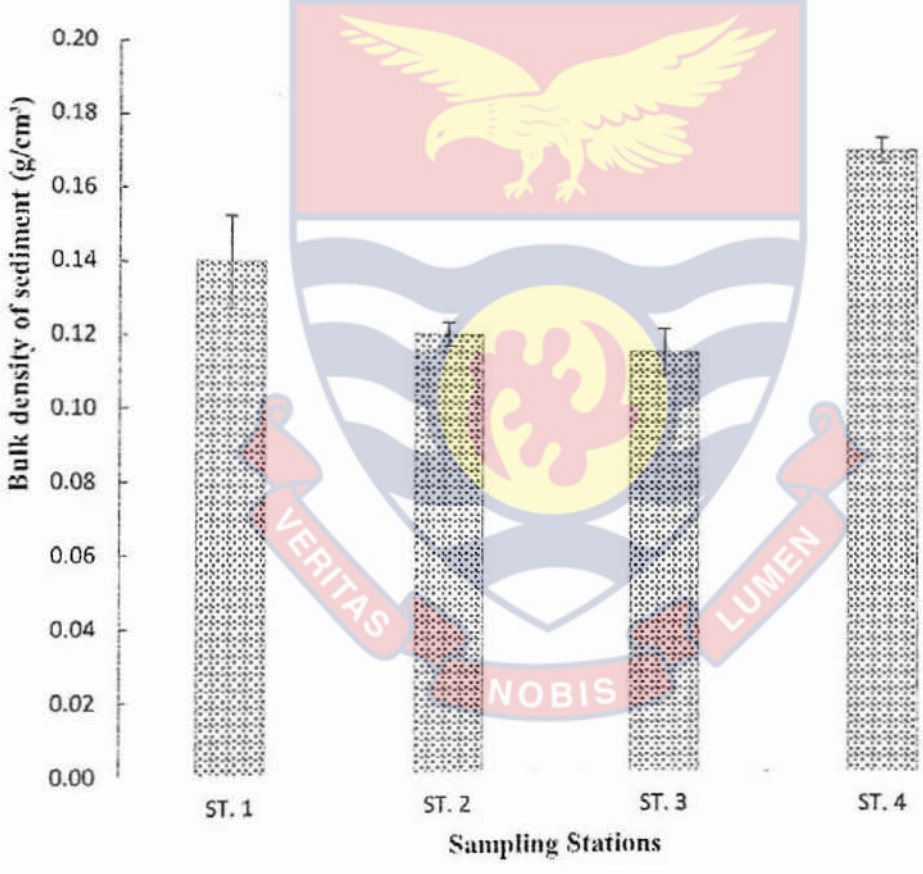

Figure 20: Mean bulk density of the sediments at the various stations in the Densu Delta (the vertical bars indicate standard errors of means)

4.3 Population Parameters

4.3.1 Population density

The monthly mean population densities of *C. tulipa* at Stations 3, 4a and 4b in the Densu Delta from May 2017 to October 2018 are shown in Figure 21. The means among the various sampling stations were found to be significantly different (Repeated measure ANOVA, F (969.16) = 27.65, df = 2, $p < 0.001$). Also, the month-station interaction indicated that there was a significant difference among stations in the various months ($F = 8.84$, $df = 34$, $p < 0.001$). A Bonferroni posthoc test showed that all the three population densities were different from one another ($p < 0.001$), with Station 4b having the highest density followed by Stations 4a and 3. Generally, relatively high mean population densities for the stations were recorded from February to May 2018. No oysters were sampled at Station 3 from May to November 2017 and from July to October 2018. In four out of the seven months in which live oysters were present at Station 3, the population densities were < 50 ind/m^2. Station 4b had the highest population density throughout the study period ranging from 245 ± 76.6 to 1648 ± 93.8 ind/m^2, followed by Station 4a with a range of 87 ± 19.2 to 763 ± 44.4 and then Station 3, ranging from 36 ± 8.3 to 176 ± 12.9 ind/m^2.

4.3.2 Size-frequency distribution

A total of 382, 840 and 802 specimens of *C. tulipa* were sampled from the Stations 3, 4a and 4b in the Densu Delta, respectively, as seen in Figure 22. All sampling stations exhibited unimodal size distribution with a modal shell height class of 4.0 - 4.9 cm. The oysters from Station 3, 4a and 4b ranged from 2.0 – 10.40, 2.0 – 13.0 and 2.0 – 14.6 cm SH, respectively. Therefore, the maximum observed sizes were 10.40, 13.0 and 14.6 cm SH, accordingly.

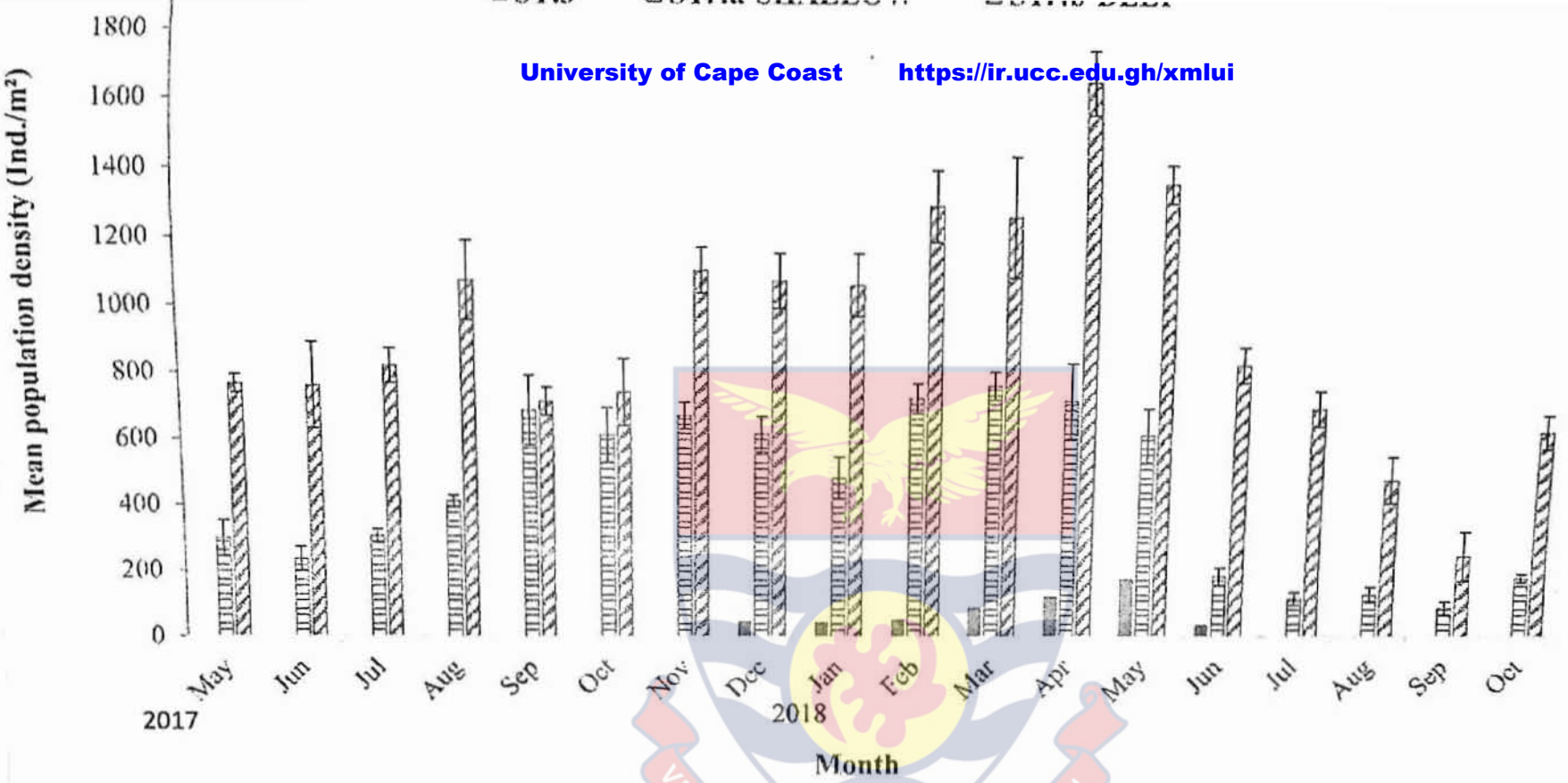

Figure 21: Monthly mean population densities of *Crassostrea tulipa* at Stations 3, 4a and 4b in the Densu Delta (the vertical bars indicate standard errors of means)

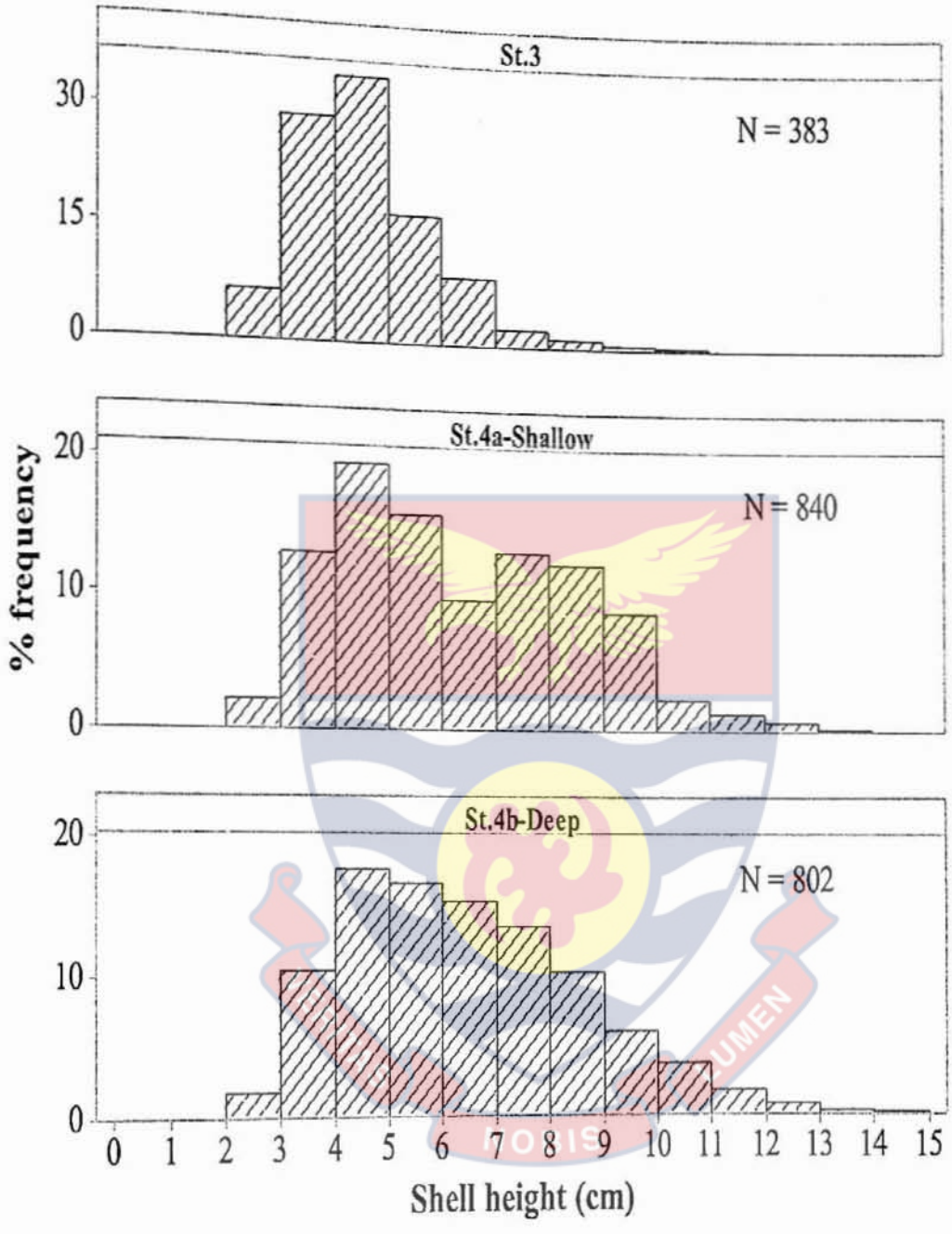

Figure 22: Pooled size-frequency distribution of *Crassostrea tulipa* population at Stations 3, 4a and 4b in the Densu Delta

4.3.3 Growth relationships

Shell height-length relationship

Shell height of oysters sampled from Stations 3, 4a and 4b, used for the analysis ranged from 2.10 to 10.40 cm (Mean ± SE, 5.03 ± 0.10 cm), 3.90 to 13.00 cm (8.00 ± 0.10 cm) and 3.10 to 13.00 cm (7.86 ± 0.10 cm), respectively. The shell lengths ranged from 1.80 to 7.30 cm (3.73 ± 0.07 cm), 3.20 to 7.60 cm (5.28 ± 0.05 cm) and 3.10 to 8.70 cm (5.25 ± 0.07 cm). From Figure 23, the slopes of the regressions of the oysters from the stations deviated from isometry. However, that of Station 3 was relatively closer to the hypothetical value (1).

The shell height-length regression of *C. tulipa* at Station 3 was described by the equation $\text{Log } L = 0.76 \text{ Log } H + 0.04$, where L = shell length and H = shell height (Figure 23a). The correlation coefficient ($r = 0.77$) and analysis of variance of the regression analysis ($F = 275.11$, $df = 1$, $p < 0.001$) suggested a positive and strong significant relationship between the shell height and shell length of oysters. The coefficient of determination ($R^2 = 0.60$) of the regression indicated that about 60 % of the increase in shell length could be explained by shell height. The slope of the equation ($b = 0.76$) was significantly different ($t = 3.28$, $p < 0.05$) from isometry ($b = 1$), thus negative allometry. This suggested that the variables were not growing in the same proportion, i.e., shell length grew relatively slower than shell height of the oysters at Station 3.

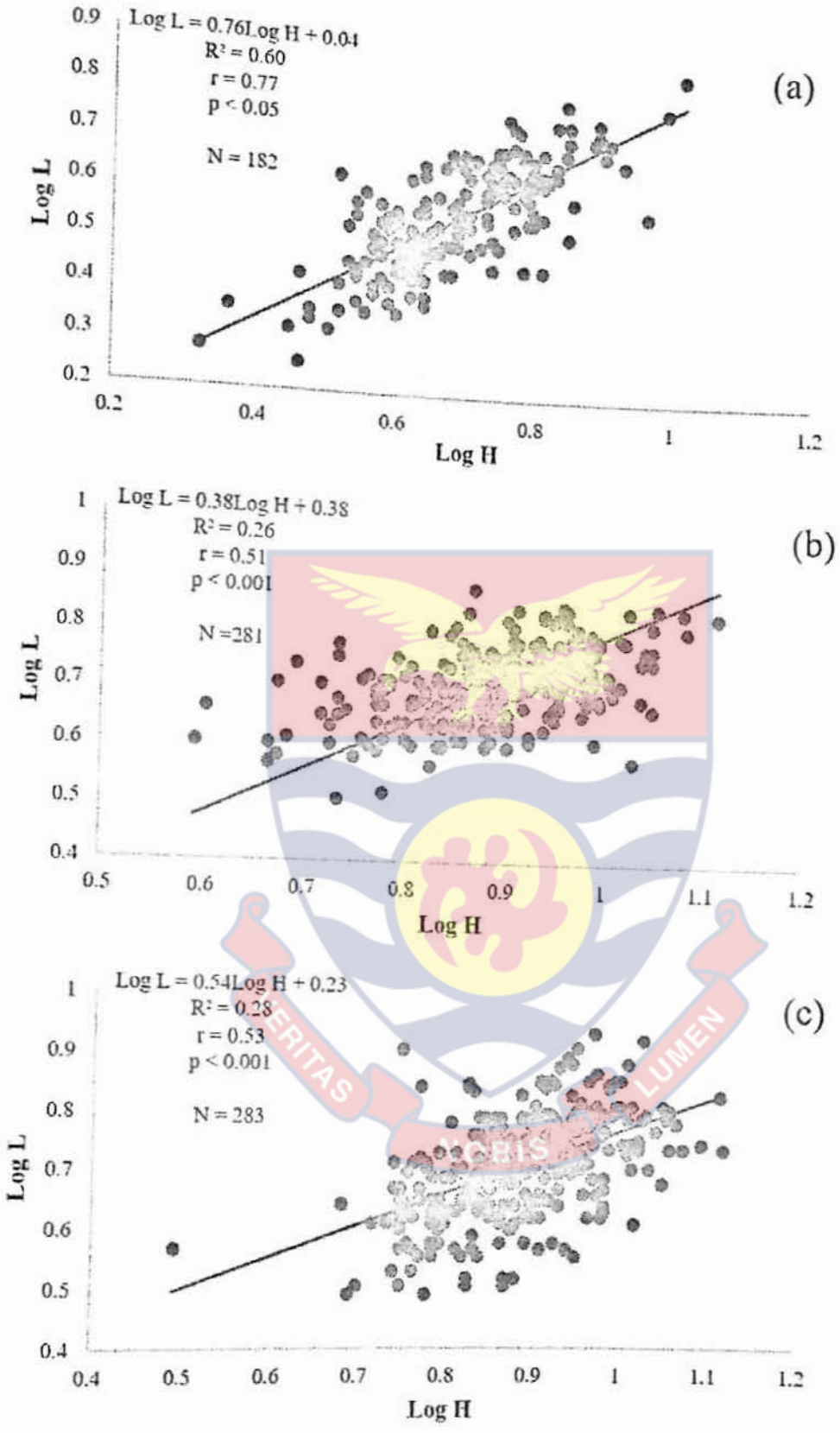

Figure 23: Shell height-shell length relationships of *Crassostrea tulipa* sampled from Stations 3, 4a and 4b in the Densu Delta as represented by graphs (a), (b) and (c), respectively

The height-length regression of *C. tulipa* at Station 4a was described by the equation Log L = 0.38 Log H + 0.38, where L = shell length and H = shell height (Figure 23b). The correlation coefficient (r = 0.51) and analysis of variance of the regression analysis (F = 100.16, df = 1, $p < 0.001$) suggested a positive and moderate significant relationship between the shell height and shell length of oysters at Station 4a. The coefficient of determination (R^2 = 0.26) of the regression indicated that about 26 % of the increase in shell length could be explained by shell height. The slope of the equation (b = 0.39) was significantly different (t = 6.58, $p < 0.001$) from isometry (b = 1), i.e. negative allometry. This indicated that the variables were not growing in the same proportion: shell length grew relatively slower than were shell height of the oysters at Station 4a.

The height-length regression of *C. tulipa* at Station 4b was described by the equation Log L = 0.54 Log H + 0.23, where L = shell length and H = shell height (Figure 23c). The correlation coefficient (r = 0.52) and analysis of variance of the regression analysis (F = 107.93, df = 1, $p < 0.001$) suggested a positive and moderate significant relationship between the shell height and shell length of oysters at Station 4b. The coefficient of determination (R^2 = 0.29) of the regression indicated that about 29 % of the increase in shell length could be explained by shell height. The slope of the equation (b = 0.54) was significantly different (t = 5.82, $p < 0.001$) from isometry (b = 1), i.e. negative allometry. This showed that the variables were not growing in the same proportion: shell length grew relatively slower than shell height of the oysters at Station 4b.

Shell height-width relationship

Shell width of the oysters from Stations 3, 4a and 4b used for the analysis ranged from 0.70 to 3.80 cm (Mean ± SE, 1.66 ± 0.04 cm), 1.10 to 5.60 cm (2.51 ± 0.04 cm) and 1.00 to 8.80 cm (2.56 ± 0.04 cm), respectively. The slopes of the regression of shell height and shell width of oysters from the stations deviated from isometry, except in Station 3 (Fig. 24).

The height-width regression of *C. tulipa* at Station 3 was described by the equation Log W = 0.82 Log H - 0.37, where W = shell width and H = shell height (Fig. 24a). The correlation coefficient (r = 0.71) and analysis of variance of the regression analysis (F = 185.56, df = 1, $p < 0.001$) suggested a positive and strong significant relationship between the shell height and shell width of oysters. The coefficient of determination (R^2 = 0.51) of the regression showed that about 51 % of the increase in shell width could be predicted by shell height. The slope of the equation (b = 0.82) did not deviate significantly (t = 1.91, $p >$ 0.05) from isometry (b = 1): shell height and shell width of the oysters at Station 3 grew proportionally.

The height-width regression of *C. tulipa* at Station 4a was described by the equation Log W = 0.57 Log H - 0.12, where W = shell width and H = shell height (Figure 24b).

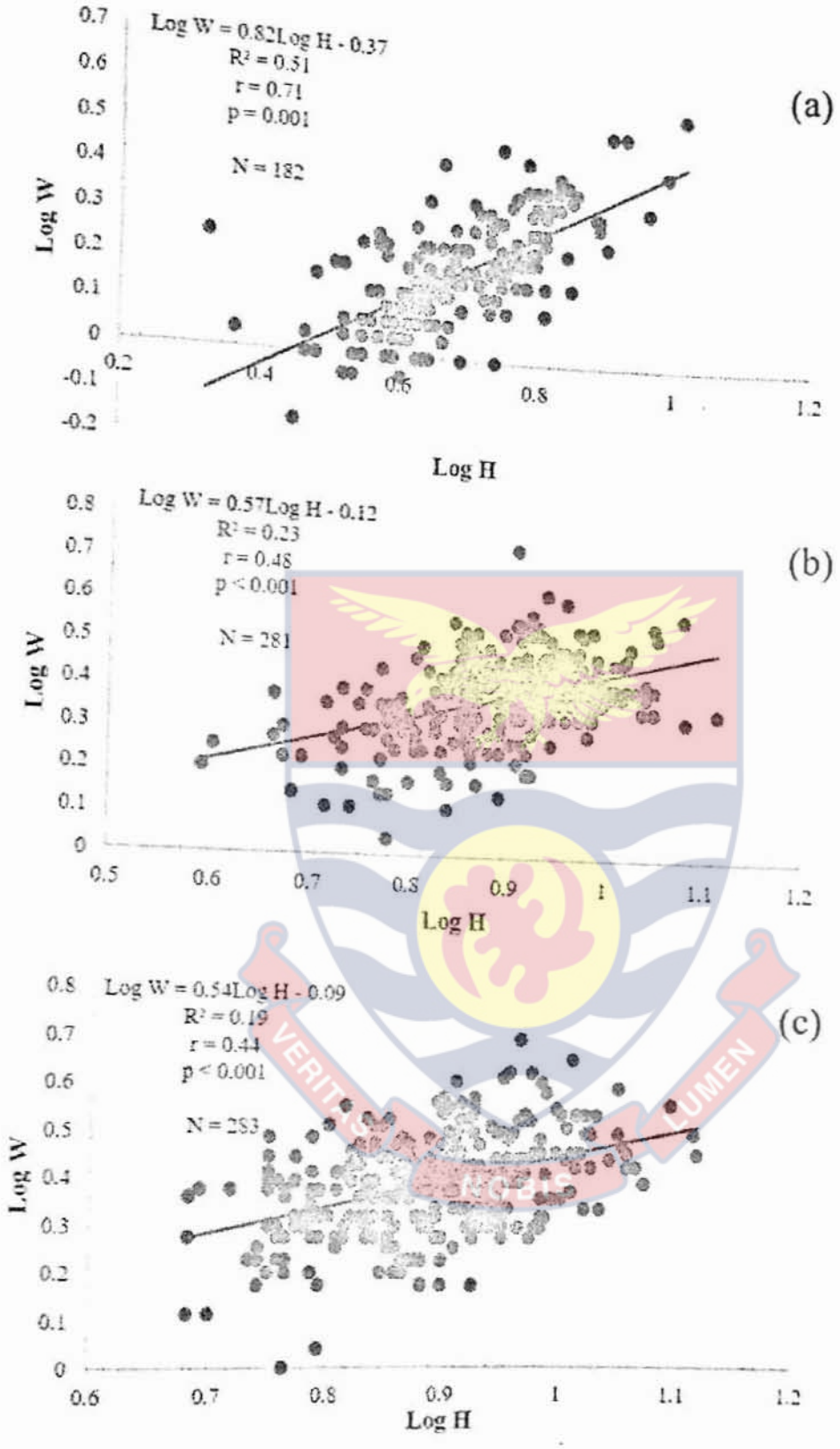

Figure 24: Shell height-shell width relationships of *Crassostrea tulipa* sampled from Stations 3, 4a and 4b in the Densu Delta as represented by graphs (a), (b) and (c), respectively

The correlation coefficient ($r = 0.48$) and analysis of variance of the regression analysis ($F = 84.09$, $df = 1$, $p < 0.001$) suggested a positive and moderate significant relationship between the shell height and shell width of oysters at Station 4a. The coefficient of determination ($R^2 = 0.23$) of the regression showed that about 23 % of the increase in shell width could be predicted by shell height. The slope of the equation ($b = 0.57$) deviated significantly ($t = 4.71$, $p < 0.001$) from isometry ($b = 1$), i.e. negative allometry: shell height grew at a relatively faster rate than shell width of the oysters at Station 4a.

The height-width regression of *C. tulipa* at Station 4b was described by the equation Log W = 0.54 Log H - 0.09, where W = shell width and H = shell height (Figure 24c). The correlation coefficient ($r = 0.44$) and analysis of variance of the regression analysis ($F = 62.74$, $df = 1$, $p < 0.001$) suggested a positive and moderate significant relationship between the shell height and shell width of oysters at Station 4b. The coefficient of determination ($R^2 = 0.19$) of the regression showed that about 19 % of the increase in shell width could be predicted by shell height. The slope of the equation ($b = 0.54$) deviated significantly ($t = 4.42$, $p < 0.001$) from isometry ($b = 1$), i.e. negative allometry: shell height grew at a relatively faster rate than shell width of the oysters at Station 4b.

Shell height-total weight relationship

The total weight of oysters from Stations 3, 4a and 4b used for the analysis ranged from 0.83 to 139.62 g (Mean ± SE, 17.85 ± 1.19 g), 13.68 to 164.04 g (52.35 ± 1.33 g) and 12.87 to 146.95 g (47.92 ± 1.55 g), respectively. From Figure 25, the gradients of the regression of the oysters from the various

stations deviated from isometry, with that of Station 3 relatively closer to the hypothetical value (3).

The shell height-total weight regression of *C. tulipa* at Station 3 was described by the equation Log $Tw = 2.45\text{Log } H - 0.55$, where Tw = total weight and H = shell height (Figure 25a). The correlation coefficient ($r = 0.88$) and analysis of variance of the regression analysis ($F = 655.95$, $df = 1$, $p < 0.001$) suggested a positive and strong significant relationship between the shell height and total weight of oysters at Station 3. The coefficient of determination ($R^2 = 0.78$) of the regression showed that about 78 % of the increase in total weight could be explained by shell height. The slope of the equation ($b = 2.45$) deviated significantly ($t = 3.81$, $p < 0.001$) from isometry ($b = 3$), i.e. negative allometry: shell height grew at a faster rate than total weight of the oysters at Station 3.

The shell height-total weight regression of *C. tulipa* at Station 4a was described by the equation Log $Tw = 1.77\text{Log } H + 0.09$, where Tw = total weight and H = shell height (Figure 25b). The correlation coefficient ($r = 0.79$) and analysis of variance of the regression analysis ($F = 457.41$, $df = 1$, $p < 0.001$) suggested a positive and strong significant relationship between the shell height and total weight of oysters at Station 4a. The coefficient of determination ($R^2 = 0.62$) of the regression showed that about 62 % of the increase in total weight could be explained by shell height. The slope of the equation ($b = 1.77$) deviated significantly ($t = 10.06$, $p < 0.001$) from isometry ($b = 3$), i.e. negative allometry: shell height grew at a faster rate than total weight of the oysters at Station 4a.

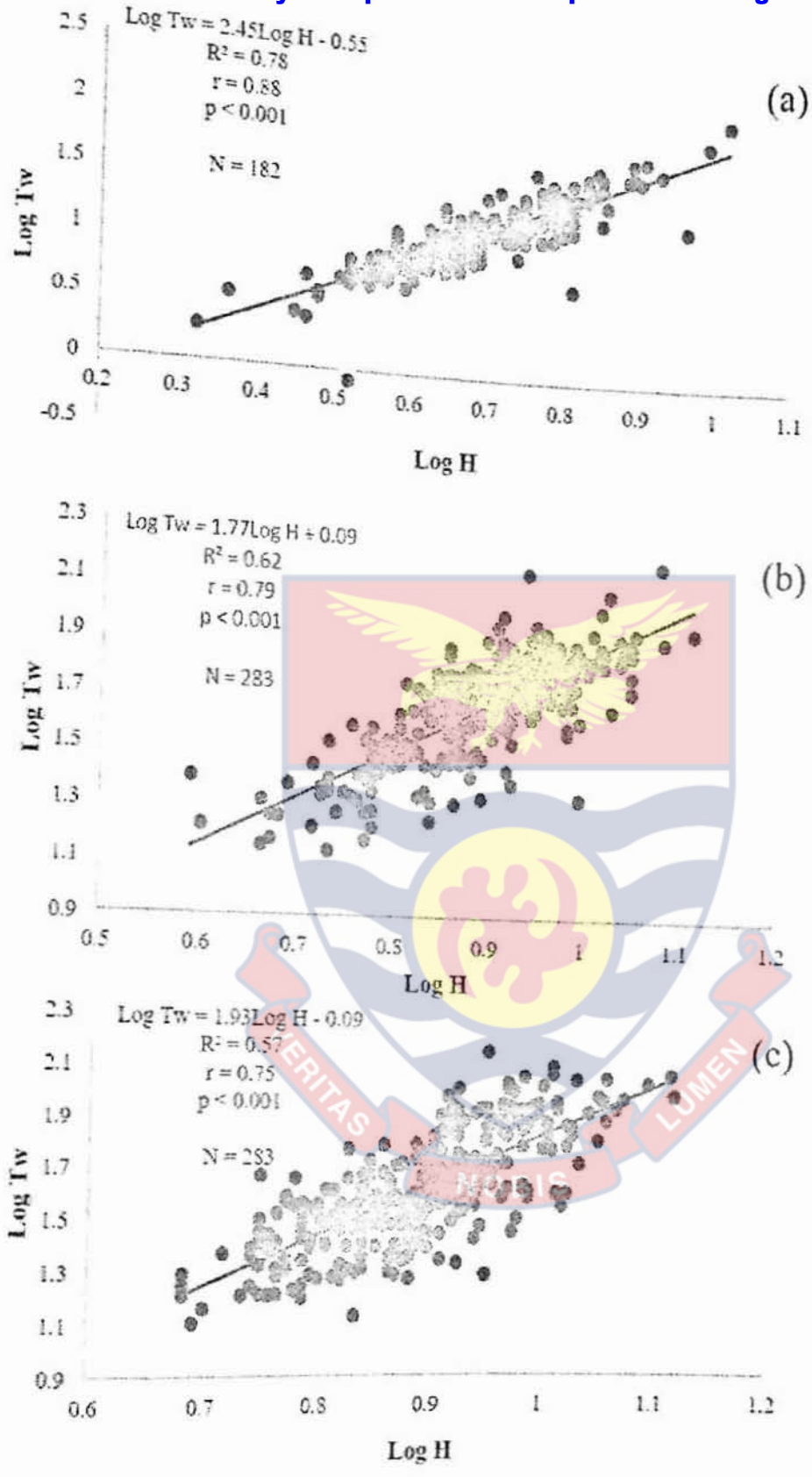

Figure 25: Shell height-total weight relationships of *Crassostrea tulipa* sampled from Stations 3, 4a and 4b in the Densu Delta as represented by graphs (a), (b) and (c), respectively

The shell height-total weight regression of *C. tulipa* at Station 4b was described by the equation Log Tw = 1.93Log H - 0.09, where Tw = total weight and H = shell height (Figure 25c). The correlation coefficient (r = 0.79) and analysis of variance of the regression analysis (F = 378.57, df = 1, $p < 0.001$) suggested a positive and strong significant relationship between the shell height and total weight of oysters at Station 4b. The coefficient of determination (R^2 = 0.57) of the regression showed that about 57 % of the increase in total weight could be explained by shell height. The slope of the equation (b = 1.93) deviated significantly (t = 7.14, $p < 0.001$) from isometry (b = 3), i.e. negative allometry: shell height grew at a faster rate than the total weight of the oysters at Station 4b.

Shell height-wet meat weight relationship

The wet meat weight of oysters from Stations 3, 4a and 4b used for the analysis ranged from 0.24 to 10.70 g (Mean ± SE, 1.96 ± 0.12 g), 1.33 to 18.67 g (5.79 ± 0.20 g) and 1.26 to 13.55 g (5.39 ± 0.15 g), respectively. The gradients of the regression of the oysters from the various stations deviated from isometry, however, that of Station 3 was closer to the hypothetical value, 3 (Fig. 26).

The shell height-wet meat weight regression of *C. tulipa* at Station 3 was described by the equation Log Mw = 2.30Log H – 1.41, where Mw = wet meat weight and H = shell height (Figure 26a).

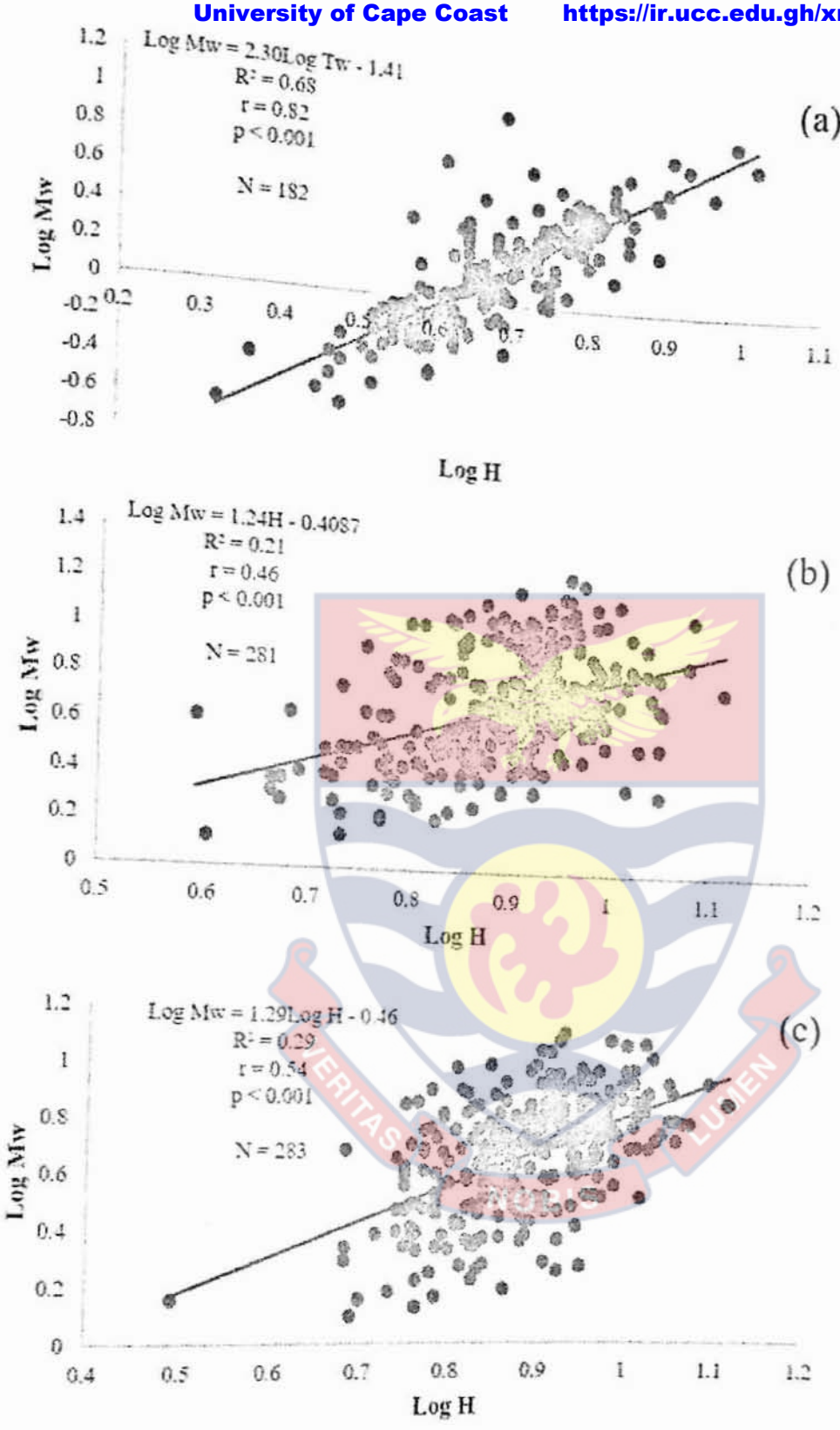

Figure 26: Shell height-wet meat weight relationships of *Crassostrea tulipa* sampled from Stations 3, 4a and 4b in the Densu Delta as represented by graphs (a), (b) and (c), respectively.

The correlation coefficient ($r = 0.82$) and analysis of variance of the regression analysis ($F = 378.34$, $df = 1$, $p < 0.001$) suggested a positive and strong significant relationship between the shell height and wet meat weight of oysters at Station 3. The coefficient of determination ($R^2 = 0.68$) of the regression indicated that about 68 % of the increase in wet meat weight could be explained by shell height. The slope of the equation ($b = 2.30$) deviated significantly ($t = 3.69$, $p < 0.001$) from isometry ($b = 3$), i.e. negative allometry: sh ell height grew at a faster rate than wet meat weight of the oysters at Station 3.

The shell height-wet meat weight regression of *C. tulipa* at Station 4a was described by the equation Log $Mw = 1.24\text{Log } H - 0.41$, where Mw = wet meat weight and H = shell height (Figure 26b). The correlation coefficient ($r = 0.46$) and analysis of variance of the regression analysis ($F = 74.75$, $df = 1$, $p < 0.001$) suggested a positive and moderately significant relationship between the shell height and wet meat weight of the oysters. The coefficient of determination ($R^2 = 0.21$) of the regression shows that about 21 % of the increase in wet meat weight could be explained by shell height. The slope of the equation ($b = 2.30$) deviated significantly ($t = 8.38$, $p < 0.001$) from isometry ($b = 3$), i.e. negative allometry: shell height grew at a faster rate than total weight of the oysters Station 4a.

The shell height-wet meat weight regression of *C. tulipa* at Station 4b was described by the equation Log $Mw = 1.29\text{Log } H - 0.46$, where Mw = wet meat weight and H = shell height (Figure 26c). The correlation coefficient ($r = 0.54$) and analysis of variance of the regression analysis ($F = 114.74$, $df = 1$, $p < 0.001$) suggested a positive and moderate significant relationship between the shell height and wet meat weight of oysters. The coefficient of determination

($R^2 = 0.29$) of the regression shows that about 29 % of the increase in wet meat weight could be explained by shell height. The slope of the equation ($b = 2.30$) deviated significantly ($t = 9.49$, $p < 0.001$) from isometry ($b = 3$), i.e. negative allometry: shell height grew at a faster rate than total weight of the oysters at Station 4b.

4.3.4 Morphological index

The morphological indices (MI), which quantify the shell shapes of the oysters at Stations 3, 4a and 4b were estimated as mean = 185.30, $SE \pm 3.39$, n = 300 (74.98 – 468.75) ; mean = 179.76, $SE \pm 4.65$ (55.64 - 527.27), $n = 300$ and mean = 190.92, $SE \pm 5.79$, $n = 300$ (51.68 – 900.00), respectively. A statistical comparison of the estimates from the various stations indicate that there was no statistical difference between the shell shape of the oysters from the various stations ($F = 1.40$, $df = 2$, $p > 0.05$).

4.3.5 Growth parameters

Figure 27 illustrates the restructured monthly shell height-frequency distributions of *C. tulipa* population at Stations 3, 4a and 4b in the Densu Delta fitted with the seasonalised VBGF. From Station 3 panel, generally, the distribution could be described as unimodal with a modal progression of 0.5 cm SH/month of the population. This is evident in the 1 cm SH shift from December 2017 to the February 2018 samples. Again, the same population growth rate is seen in the samples from February to April. In both Stations 4a and 4b, the distributions appeared to be bimodal with inconsistent modal progression. However, there seemed to be 1 cm SH/month population growth rate in Station 4b samples, as seen in November 2017 to January 2018.

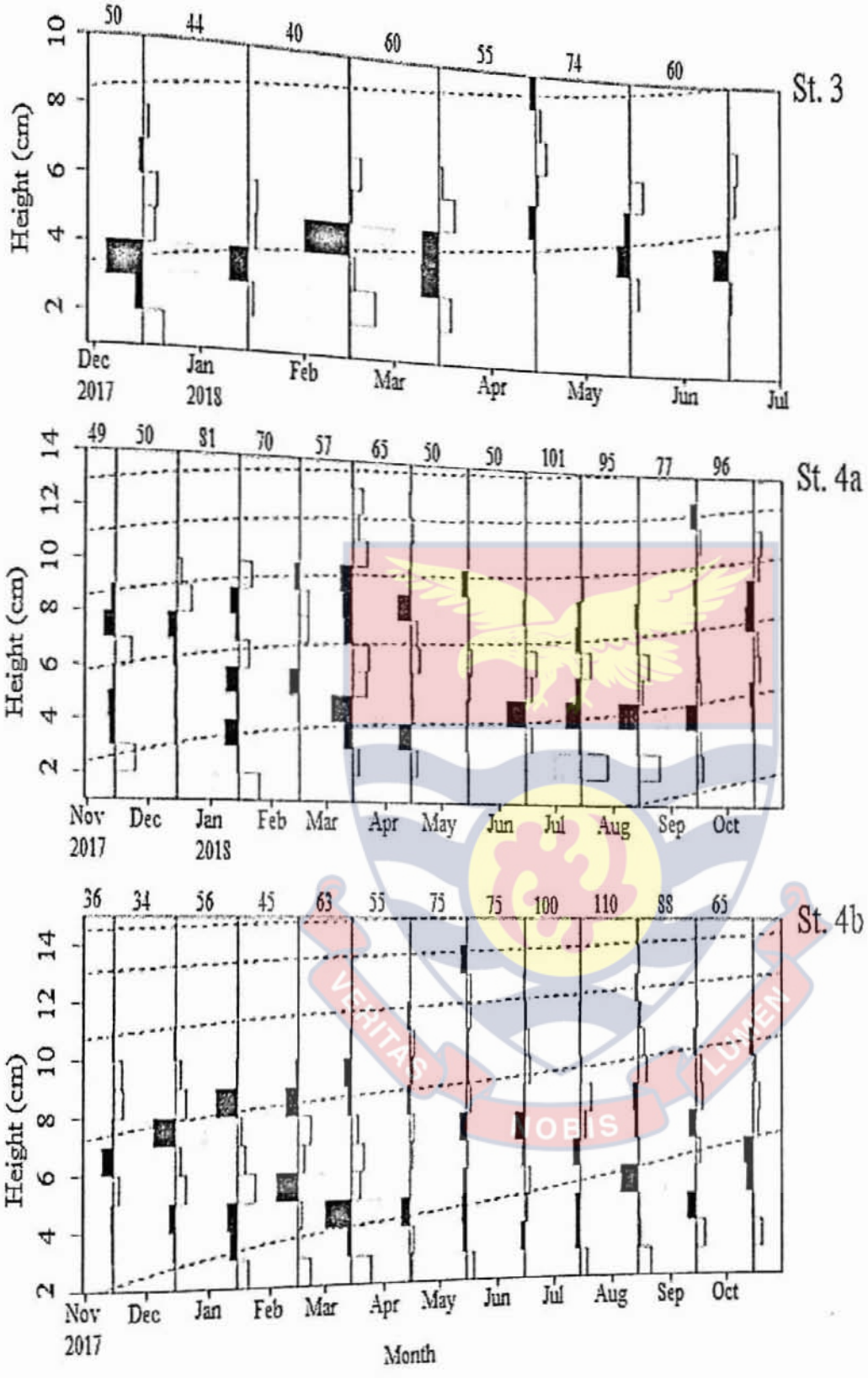

Figure 27: Restructured monthly shell height-frequency distributions of *Crassostrea tulipa* population at Stations 3, 4a and 4b in the Densu Delta fitted with the seasonalised Von Bertalanffy Growth Function (VBGF) (Numbers above various panels are sample sizes)

Population growth curves for the various sampling stations are presented in Figure 28, which shows the maximum density peak of the kernel density distribution with its 95% confidence contours and curve swarms fitted with ELEFAN_GA_boot. Mainly, the three graphs indicate a widespread confidence interval with samples from Station 3 being the smallest. The asymptotic shell height was lowest in Station 3 samples but comparable in samples from Stations 4a and 4b. Growth coefficient (K) was relatively higher in Station 3 samples (0.43 yr^{-1}) than Station 4a (0.30 yr^{-1}) but comparable to Station 4b samples (0.47 yr^{-1}). The t_{anchor}, which is the portion of the year where annually repeating growth curve crosses shell height equal to zero was estimated at 0.50 (July), 0.47 (June) and 0.45 (May) for Stations 3, 4a and 4b, respectively.

The intensity of the sinusoidal oscillation, C, was comparatively higher in Station 3 samples at 0.56 than Stations 4a (0.50) and 4b (0.51). The above showed that samples from the various stations underwent seasonal growth. The 'summer' point, t_s (the fraction of a year, relative to the age of recruitment where the sine wave oscillation begins) was estimated at 0.73 (September), 0.18 (February) and 0.39 (April) for Stations 3, 4a and 4b, respectively.

Figure 29 presents the length-converted catch curve of *C. tulipa* samples at Stations 3, 4a and 4b from the Densu Delta. The total mortality (Z) at Stations 3, 4a and 4b were estimated at 3.92 ± 0.59 yr^{-1}, 1.90 ± 0.27 yr^{-1} and 1.92 ± 0.08 yr^{-1}

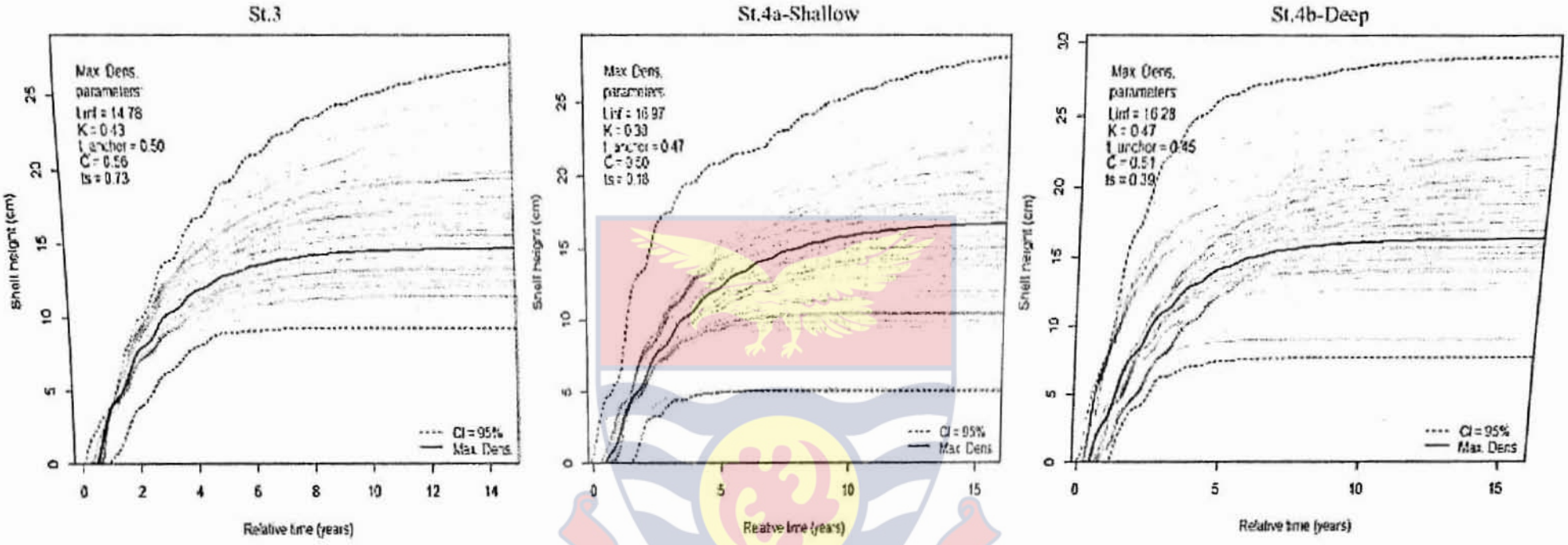

Figure 28: Growth curves representing the maximum density peak (thick black line) of the kernel density distribution with its 95% confidence contours (black dashed lines) and curve swarms (grey lines) of *Crassostrea tulipa* samples from Stations 3, 4a and 4b fitted with ELEFAN_GA_boot

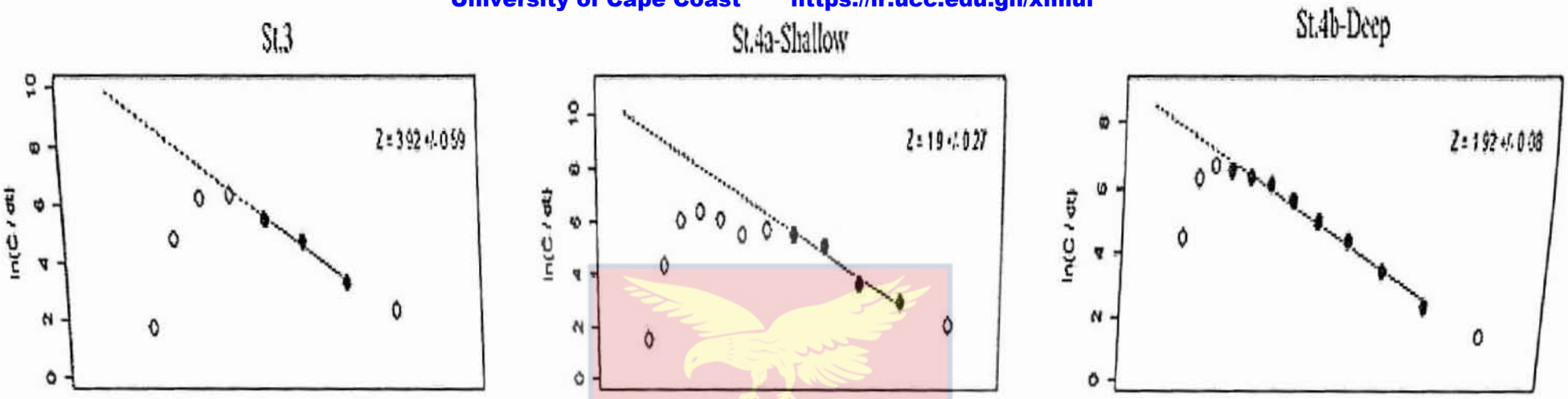

Figure 29: Length-converted catch curves of *Crassostrea tulipa* samples at Stations 3, 4a and 4b from the Densu Delta indicating the value of *Z* with its corresponding standard error (filled circles are data used for the estimates)

4.3.6 Mortality parameters and exploitation estimates

The natural and fishing mortality, exploitation rate, growth performance index (Φ'), longevity (t_{max}) and M/K ratio were presented in Table 9. Figure 30 illustrates the yield per recruit (YPR) and biomass per recruit (BPR) of *C. tulipa* at Station 4b in the Densu Delta using Thompson and Bell model with its attendant Isopleth diagram, indicating the shell height at first capture ($L_c = 3.73$ cm). The current fishing mortality (F_{cur}), fishing mortality that exploits 50 % of the virgin biomass ($F_{0.5}$) and fishing mortality that gives the maximum sustainable yield (F_{msy}) were estimated as 0.56 yr^{-1}, 1.70 yr^{-1} and 0.80 yr^{-1}, respectively. The current exploitation (E_{cur}) that exploits 50 % of the virgin biomass ($E_{0.5}$) and exploitation rate that harvests the maximum sustainable yield (E_{msy}) were estimated as 0.31, 0.36 and 0.59, respectively as seen in Table 10. The current yield and biomass were estimated at 17.84 and 40.40 tonnes, respectively.

4.3.7 Recruitment

The recruitment patterns of *C. tulipa* at Stations 3, 4a and 4b in the Densu Delta are shown in Figure 31. All panels of the graph indicate that recruitment into the fishery occurred throughout the year. Samples from Stations 3 and 4a (both shallow portions) showed a higher proportion of recruits were observed during the middle of the year (May to July), contrary to Station 4b (deep portion) samples (which showed peaks in January and February as well as in September).

Table 9: *Mortality and Exploitation Parameters of Crassostrea tulipa in the Densu Delta*

Parameters	Sampling Stations		
	St. 3	St. 4a	St. 4b
M (yr^{-1})	1.23	1.26	1.27
F (yr^{-1})	2.69	0.65	0.56
E	0.69	0.34	0.31
M/K ratio	2.86	4.20	2.70
Φ'	1.97	1.94	2.09
t_{max} (yrs)	6.98	10.00	6.38

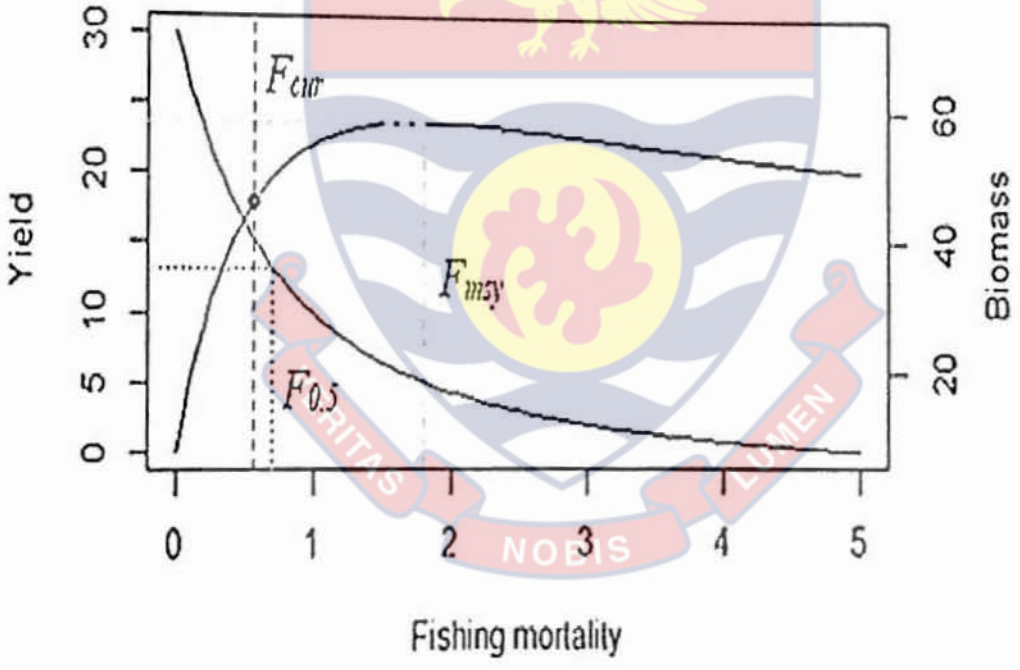

Figure 30: YPR and BPR of *Crassostrea tulipa* at Station 4b in the Densu Delta using Thompson-Bell model ($F_{cur} = 0.56\ yr^{-1}$, $F_{0.5} = 0.70\ yr^{-1}$, $F_{msy} = 1.80\ yr^{-1}$)

Table 10: *Exploitation, YPR and BPR Reference Point Estimates from the ELEFAN_GA_boot Fit Method for Station 4b Crassostrea tulipa samples*

Parameters	E_{cur}	E_{msy}	$E_{0.5}$	Y_{cur} (tonnes)	B_{cur} (tonnes)
Estimates	0.31	0.59	0.36	17.84	40.40

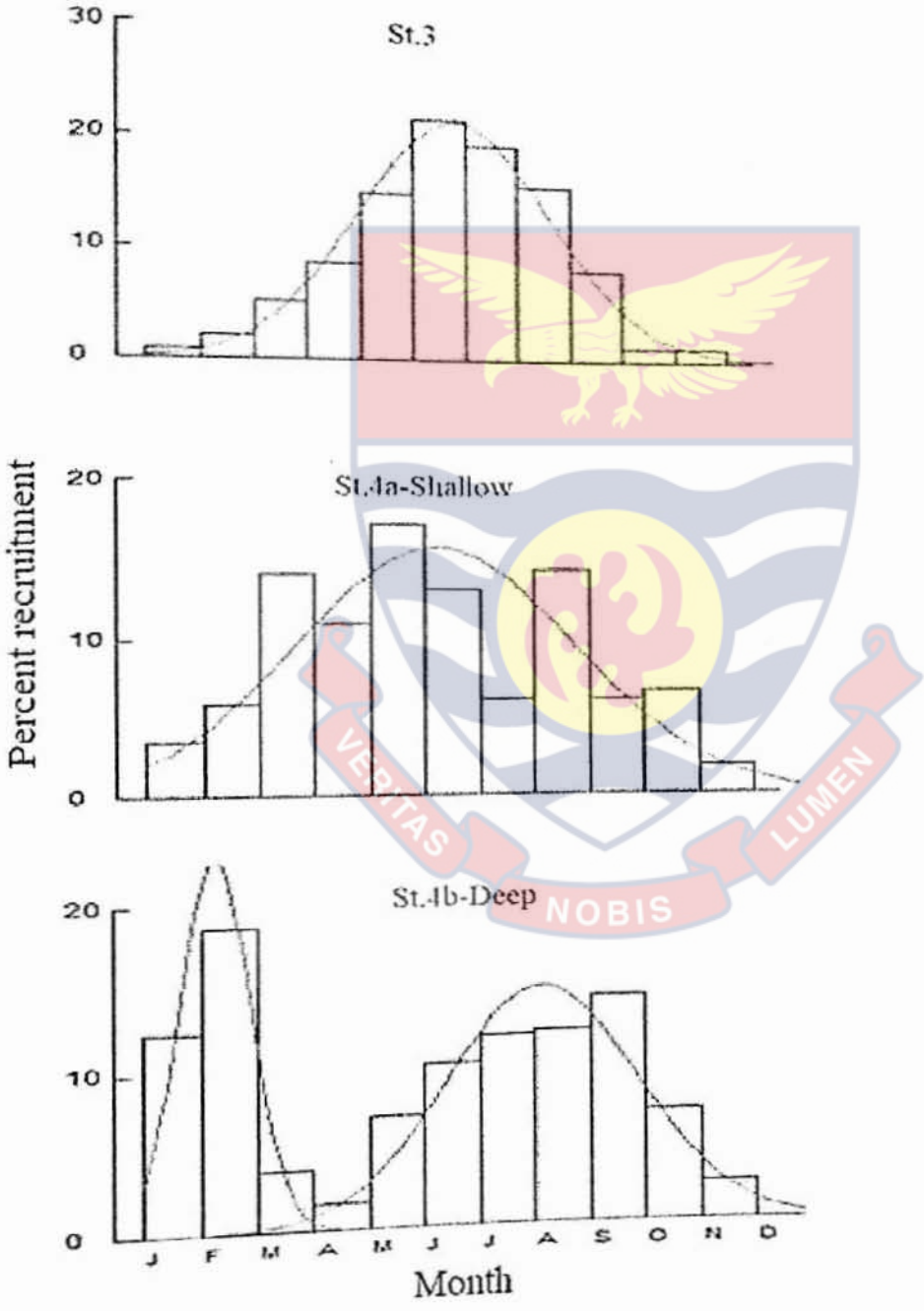

Figure 31: Recruitment patterns of *Crassostrea tulipa* at Stations 3, 4a and 4b in the Densu Delta

4.4 Reproduction and Condition Index

4.4.1 Sex ratio

The monthly sex ratio of *C. tulipa* at Station 3 is shown in Table 11. Of the, 98 oysters sexed, there was no significant departure from 1:1 sex ratio ($\chi^2 = 3.31$, $df = 1$, $p > 0.05$). Generally, there was no significant deviation from the hypothetical sex ratio of 1:1 among the months except in the June 2018 sample, which showed female dominance ($\chi^2 = 9.95$, $df = 1$, $p < 0.05$).

Table 12 presents the monthly sex ratio of *C. tulipa* at Station 4a (shallow). The 191 oysters sexed, showed significant deviation in the overall sex ratio ($\chi^2 = 4.40$, $df = 1$, $p < 0.05$) in favour of females. There was no significant deviation from the hypothetical sex ratio of 1:1 among the months.

Table 11: *Monthly Sex Ratio of Crassostrea tulipa at Station 3 in the Densu Delta*

Month	*N*	Male	Female	Sex ratio	χ^2	$P_{(0.05)}$
Dec-17	16	9	7	1.3 : 1.0	0.25	NS
Jan-18	12	6	6	1.0 : 1.0	0.00	NS
Feb-18	11	4	7	1.0 : 1.7	0.81	NS
Mar-18	17	10	7	1.4 : 1.0	0.53	NS
Apr-18	8	2	6	1.0 : 3.0	2.00	NS
May-18	17	7	10	1.0 : 1.4	0.53	NS
Jun-18	17	2	15	1.0 : 7.5	9.95	S
TOTAL	98	40	58	1.0 : 1.5	3.31	NS

NS = not significant; S = significant; $df = 1$

Table 12: *Monthly Sex Ratio of Crassostrea tulipa at Station 4a in the Densu Delta*

Month	*N*	Male	Female	Sex ratio	χ^2	$P_{(0.05)}$
Nov-17	19	7	12	1.0 : 1.7	1.32	NS
Dec-17	16	11	5	2.2 : 1.0	2.25	NS
Jan-18	17	6	11	1.0 : 1.8	1.47	NS
Feb-18	17	11	6	1.8 : 1.0	1.47	NS
Mar-18	5	3	2	1.5 : 1.0	0.20	NS
Apr-18	12	6	6	1.0 : 1.0	0.00	NS
May-18	17	7	10	1.0 : 1.4	0.53	NS
Jun-18	17	5	12	1.0 : 2.4	2.88	NS
Jul-18	16	8	8	1.0 : 1.0	0.00	NS
Aug-18	18	5	13	1.0 : 2.6	3.56	NS
Sep-18	20	6	14	1.0 : 2.3	3.20	NS
Oct-18	17	6	11	1.0 : 1.8	1.47	NS
TOTAL	191	81	110	1.0 : 1.4	4.40	S

NS = not significant; S = significant; $df = 1$

The 192 individual oysters at Station 4b (deep) that were sexed showed no significant departure from the 1:1 sex ratio ($\chi^2 = 0.75$, $df = 1$, $p > 0.05$) as seen in Table 13. Generally, there was no significant deviation of sex ratio from unity among the months except in May 2018, which showed a significant preponderance of male oysters ($\chi^2 = 9.95$, $df = 1$, $p < 0.05$).

Table 13: *Monthly Sex Ratio of Crassostrea tulipa at Station 4b in the Densu Delta*

Month	*N*	Male	Female	Sex ratio	χ^2	$P_{(0.05)}$
Nov-17	20	11	9	1.2 : 1.0	0.20	NS
Dec-17	17	10	7	1.4 : 1.0	0.53	NS
Jan-18	19	7	12	1.0 : 1.7	1.32	NS
Feb-18	16	10	6	1.7 : 1.0	1.00	NS
Mar-18	15	8	7	1.1 : 1.0	0.07	NS
Apr-18	10	7	3	2.3 : 1.0	1.60	NS
May-18	15	13	2	6.5 : 1.0	8.07	S
Jun-18	7	3	4	1.0 : 1.3	0.14	NS
Jul-18	18	5	13	1.0 : 2.6	3.56	NS
Aug-18	16	10	6	1.7 : 1.0	1.00	NS
Sep-18	20	9	11	1.0 : 1.2	0.20	NS
Oct-18	19	9	10	1.0 : 1.1	0.05	NS
TOTAL	192	102	90	1.1 : 1.0	0.75	NS

NS = not significant; S = significant; *df* = 1

Gonad development

Figure 32 illustrates the photomicrographs of five gametogenic stages of male and female *C. tulipa* in the Densu Delta, namely developing, ripening, ripe, spawning and resorption/redevelopment. The letters *a* and *b* represent female and male developmental stages, respectively.

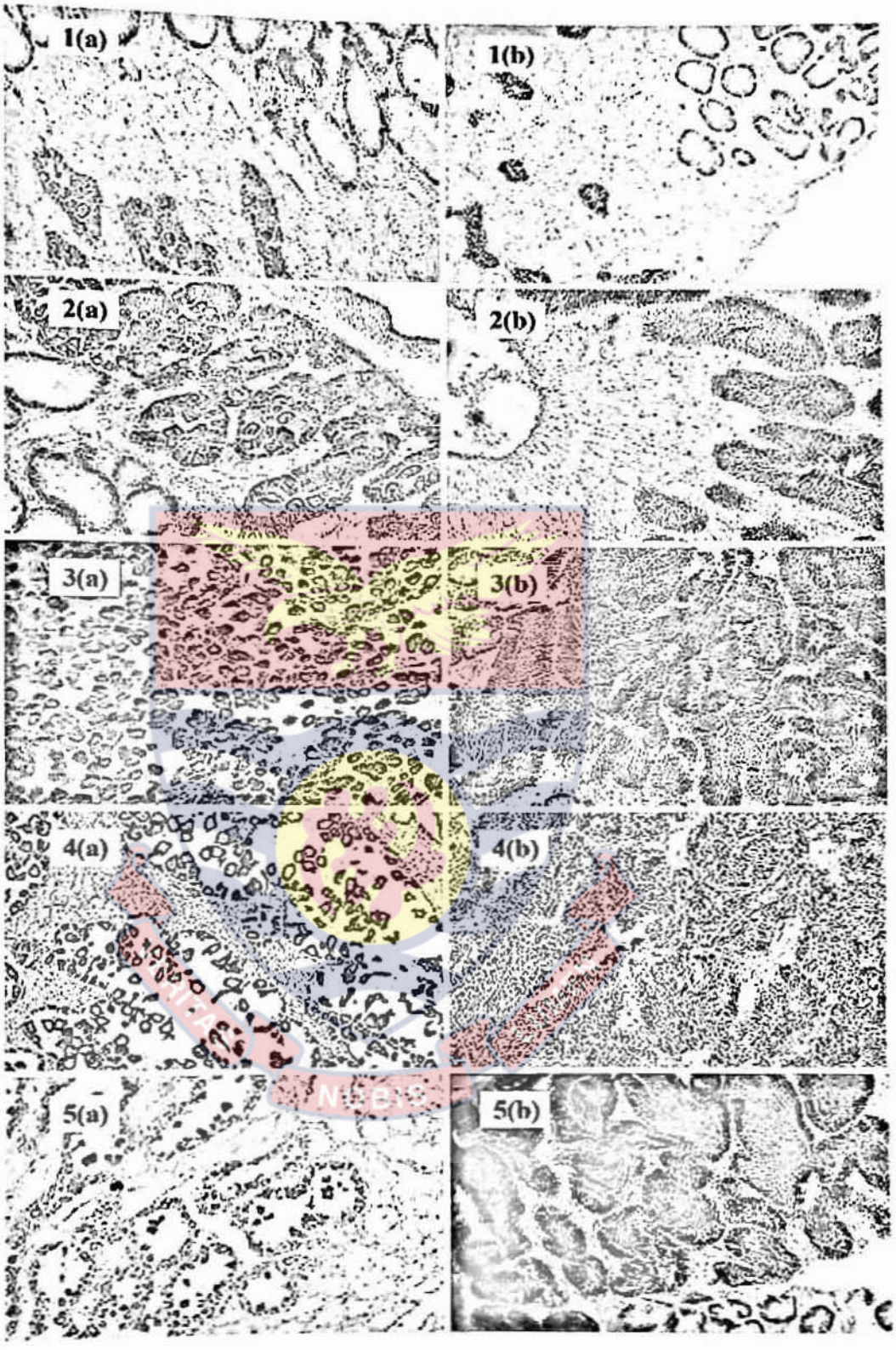

Figure 32: Photomicrographs of gametogenic stages of *Crassostrea tulipa*: developing – (1a) female, (1b) male; ripening – (2a) female, (2b) male; ripe – (3a) female, (3b) male; spawning – (4a) female, (4b) male; resorption/redevelopment – (5a) female, (5b) male, (×400)

Sex cells within follicles are typically primary oocytes in females (Figure 32: 1a) and primary spermatocytes in males (Figure 32: 1b).

Stage 2: ripening

Stage 2 female and male oysters show relatively bigger follicles, which have displaced a greater gonadal connective tissue as compared to Stage 1 specimens. Sex cells within follicles were typically oocytes in females (Figure 32: 2a) and for the males, spermatocytes and spermatozoa (Figure 32: 2b). Oocytes in the follicles are tightly packed and separated from the follicular walls, while the spermatozoa are relatively few and confined to the lumen of the follicles.

Stage 3: ripe

Oysters in this stage of development have gonads fully occupied with expanded follicles. The gonadal connective tissues in both sexes are completely displaced. Female and male follicles contain mainly loose matured ova (Figure 32: 3a) and well-packed spermatozoa with tails toward the lumen of the follicle (Figure 32: 3b), respectively. Follicular walls are intact in both sexes

Stage 4: spawning

Stage 4 female and male oysters discharging or have released gametes and hence have partially empty follicles as seen in Figure 32: 4a and 4b). Follicular walls are thin and broken.

Stage 5: resorption/redevelopment

This stage shows almost empty shrunken follicles as a result of spawning with a few dispersed remnant gametes. These follicles are seen to be undergoing resorption of relic gametes or redevelopment of oocytes (Figure 32: 5a) and spermatocytes (Figure 32: 5b).

4.4.2 Monthly gonadal stages

The monthly gonadal stages of *C. tulipa* represented as the percentage distribution of the different reproductive stages at Stations 3, 4a (shallow) and 4b (deep) are presented in Figures 33 to 35. Generally, at all the stations, there was active gametogenic activity throughout the sampling period, with Station 3 oysters showing relatively higher proportions of ripe gonads and continuous spawning activity. Oysters from the shallow stations (St. 3 and St. 4a) exhibited continuous spawning while no spawning occurred at the deep water (St. 4b) during March, April and June of 2018.

At Station 3, two major spawning activities occurred from December to February and in April (Fig. 33).

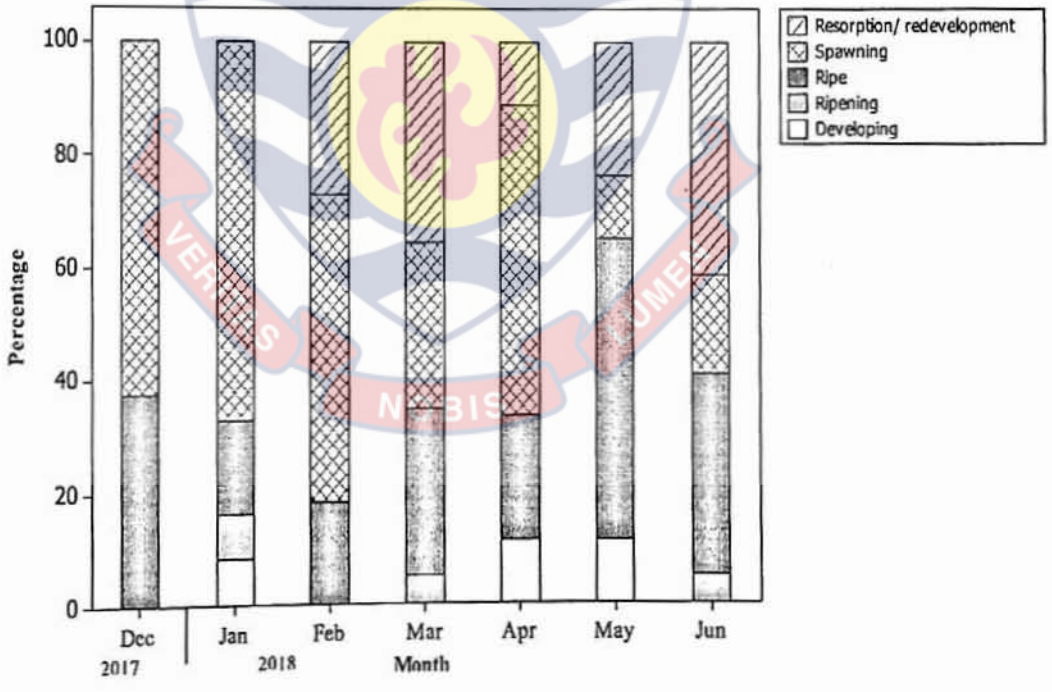

Figure 33: Gonadal development of *Crassostrea tulipa* at Station 3 in the Densu Delta

Figure 34 indicates that gonadal development of Station 4a oysters had multiple spawning peaks (> 20 %) from November 2017 to March 2018, June

to August 2018 and October 2018. Minor proportions of spawning activity (< 10 %) were recorded in April, May and September 2018.

Gonad development in Station 4b oysters showed two extended spawning events from November 2017 to February 2018 and then from July to October 2018 (Figure 35). The intervening period of March to June was characterised by a preponderance of resorption and developing stages.

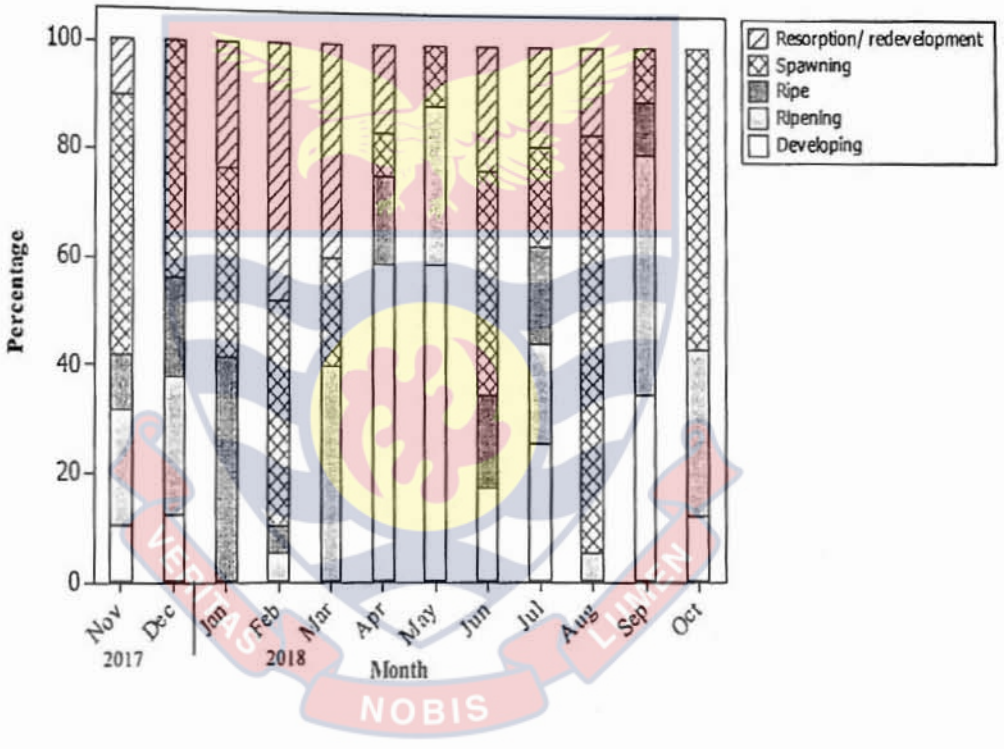

Figure 34: Gonadal development of *Crassostrea tulipa* at Station 4a (shallow) in the Densu Delta

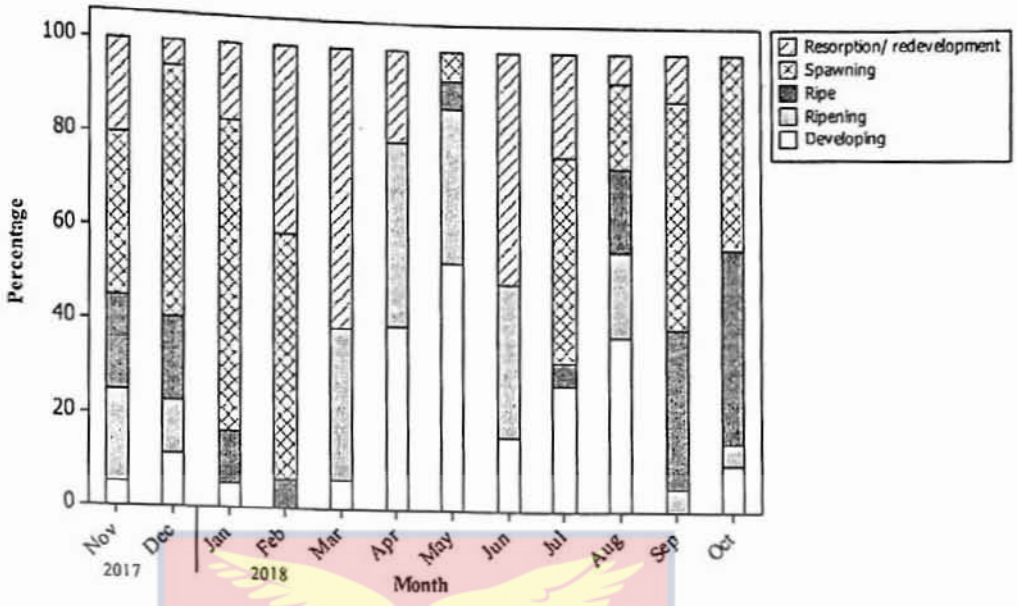

Figure 35: Gonadal development of *Crassostrea tulipa* at Station 4b (deep) in the Densu Delta

4.4.3 Gonad index (GI)

The annual variations in the mean gonad indices of *C. tulipa* at Stations 3, 4a and 4b in the Densu Delta are shown in Figure 36. Generally, the gonadal indices of oysters sampled from Stations 4a and 4b followed a similar pattern as both fluctuated alternatively from a peak in December – January and declined to low values in March to June, and thereafter increased to peaks in October. At Station 3, the gonad index decreased from a major peak in December (2.38) to low values in February-March (averaging 1.93) and subsequently increased to a minor peak in May (2.18) and declined in January (1.94) sample. Station 3 oysters maintained higher gonad index (> 1.90) than their counterparts at Stations 4a and 4b.

4.4.4 Condition index (CI)

Figure 37 presents the annual variations in the mean CI of *C. tulipa* at Stations 3, 4a and 4b in the Densu Delta. Generally, the Stations 4a and 4b indices followed a similar pattern with low values (< 30 %) in January to April 2018 and high values (> 35%) in November and December 2017 and July to October 2018. Station 3 oysters maintained higher CI (> 35 %) than those at Stations 4a and 4b.

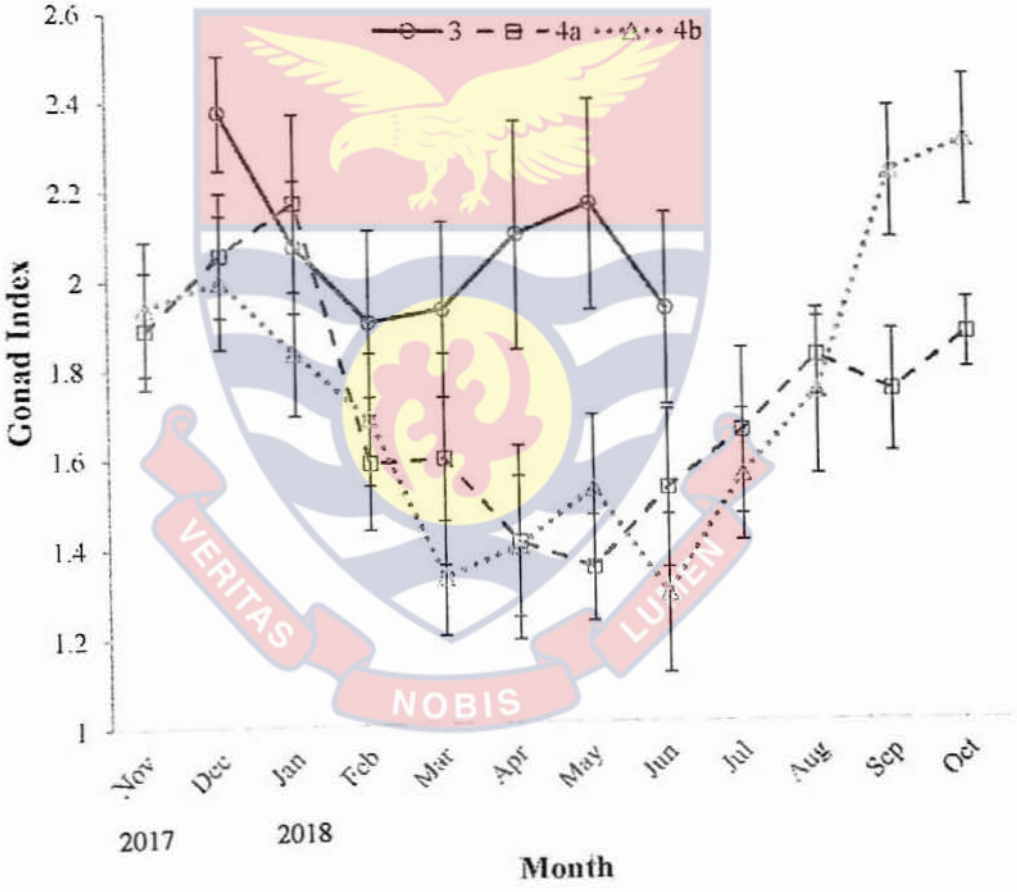

Figure 36: Mean monthly variations of gonad indices of *Crassostrea tulipa* sampled from Stations 3, 4a and 4b in the Densu Delta (vertical bars indicate standard errors of means)

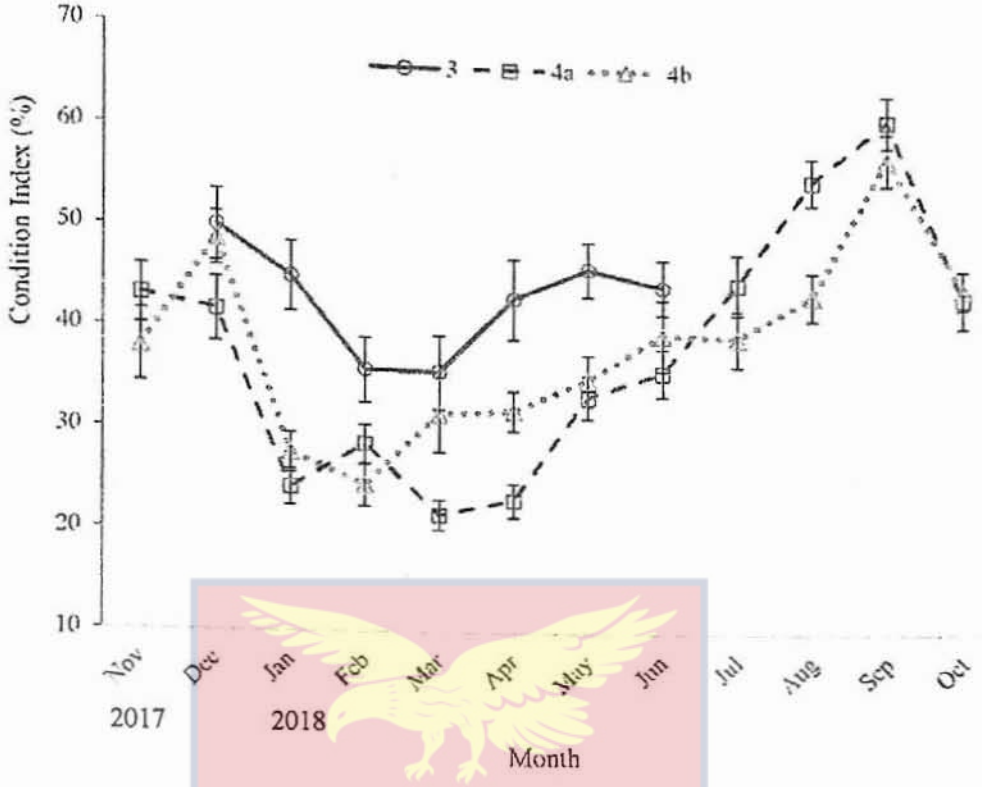

Figure 37: Mean monthly variations of condition indices of *Crassostrea tulipa* sampled from Stations 3, 4a and 4b in the Densu Delta (vertical bars indicate standard errors of means)

4.4.5 Effect of physico-chemical parameters on GI and CI

Multiple linear regression of gonad indices of *C. tulipa* on temperature, DO, salinity, pH, turbidity, nitrate and phosphate were established as indicated in Table 14. Generally, there was no significant relationship between gonad indices and the physico-chemical parameters. According to the variance inflation factor (VIF), which detects multicollinearity that is the correlation among the predictors (physico-chemical parameters), it is seen that phosphate (12.61) and salinity (8.62) showed the most multicollinearity. The R^2 of the regression suggests that the physico-chemical parameters explained 43.54 % of the variations in oyster gonad indices, although the value was insignificant ($p > 0.05$).

Table 15 shows a multiple linear regression of condition indices of *C. tulipa* on temperature, dissolved oxygen, salinity, pH, turbidity, nitrate and phosphate. Salinity, pH and phosphate were the only physico-chemical parameters that showed a statistically significant relationship with CI. The VIF indicated that phosphate (12.10) and salinity (7.67) showed the most multicollinearity. The R^2 of the regression suggested that the physico-chemical parameters explained 50.63 % of the variations in condition indices of *C. tulipa*, which was statistically significant ($F = 3.37$, $df = 7$, $p < 0.05$).

Table 14: *Multiple Linear Regression of Gonad Indices on some Physico-chemical Parameters of Crassostrea tulipa in the Densu Delta*

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	0.68	2.36	(-5.40, 6.75)	0.29	0.79	
Temp	0.07	0.14	(-0.29, 0.42)	0.47	0.66	3.26
DO	0.16	0.13	(-0.18, 0.49)	1.22	0.28	5.42
Salinity	-0.02	0.02	(-0.07, 0.03)	-1.03	0.35	8.62
pH	-0.10	0.27	(-0.80, 0.61)	-0.36	0.74	5.65
Turbidity	-0.01	0.01	(-0.02, 0.01)	-0.8	0.46	5.01
Nitrate	-0.002	0.03	(-0.07, 0.06)	-0.11	0.92	2.3
Phosphate	0.51	1.86	(-4.29, 5.30)	0.27	0.80	12.61

$R^2 = 43.54$ %, $F = 0.55$, $df = 7$, $p = 0.77$

Based on the significant physico-chemical parameters, that is salinity, pH and phosphate, a significant condition index was modelled, as shown in

Table 16. The R^2 showed that salinity, pH, phosphate explained 46.91 % of the changes in condition index of *C. tulipa* in the Densu Delta. The model is described by the equation $CI = 97.5 - 0.625\ Salinity - 4.62\ pH - 31.0\ Phosphate$ ($F = 7.95$, $df = 3$, $p < 0.001$).

Table 15: *Multiple Linear Regression of Condition Indices on some Physico-chemical Parameters of Crassostrea tulipa in the Densu Delta*

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	69.70	37.00	(-6.80, 146.10)	1.89	0.07	
Temp	2.16	1.91	(-1.78, 6.11)	1.13	0.27	2.86
DO	1.45	1.61	(-1.88, 4.77)	0.90	0.38	5.18
Salinity	-0.85	0.26	(-1.39, -0.31)	-3.27	**0.003***	7.67
pH	-8.27	3.68	(-15.88, -0.66)	-2.25	**0.034***	4.7
Turbidity	0.06	0.08	(-0.11, 0.23)	0.76	0.46	4.24
Nitrate	0.13	0.27	(-0.42, 0.68)	0.48	0.64	1.52
Phosphate	-52.1	25.00	(-103.80, -0.30)	-2.08	**0.049***	12.10

*Denotes significant estimates; $R^2 = 50.63$ %, $F = 3.37$, $df = 7$, $p = 0.05$

Table 16: *Modelling of Condition Indices on Salinity, pH and Phosphate of Crassostrea tulipa in the Densu Delta*

Term	Coef	SE Coef	95% CI	T -Value	P-Value	VIF
Constant	97.50	20.3	(55.80, 139.10)	4.80	0.001	
Salinity	-0.63	0.15	(-0.93, -0.32)	-4.26	0.001	2.66
pH	-4.62	2.03	(-8.77, -0.46)	-2.28	0.031	1.56
Phosphate	-31.00	12.90	(-57.4, -4.50)	-2.40	0.023	3.50

$R^2 = 50.63\ \%$, $F = 3.37$, $df = 7$, $p < 0.001$

4.5 Oyster Culture Experiments

Two oyster culture experiments were carried out, namely suspension and bottom culture and biofouling at Stations 3 and 4a. The results from the two culture stations were comparable. However, some culture subjects at Station 4a survived a month longer than that of Station 3, hence data from the former station were used for the ensuing analyses.

4.5.1 Suspension and bottom culture experiment

Growth of oysters on the convex and concave surfaces of coconut-shell and oyster-shell cultches

The growth of oysters cultured on the convex and concave surfaces of the two cultches using suspension and bottom culture methods are presented in Figure 38. Generally, the oysters showed a similar growth pattern.

Oysters cultured by the suspension method on oyster -shell cultches grew significantly better than their bottom counterparts. However, there was no statistical difference in the growth of oysters in suspension and at the bottom on coconut-shell cultches, though oysters cultivated on suspension seemed better

than their counterparts. Measurements were not taken for oysters cultured on bottom cultches in July due to the heavy mortality suffered by experimental subjects (Appendix E4).

Panel (a) of Figure 38 shows the growth of oysters cultured by suspension and bottom culture methods on the convex surface of coconut-shell cultches. The suspension and bottom cultured oysters grew up to 5.15 ± 0.10 cm SH and 4.41 ± 0.13 cm SH with mean growth rates of 0.89 ± 0.20 cm/month and 0.79 ± 0.22 cm/month, respectively (see Appendix F1 for growth rates). However, there was no statistical significance difference between the treatments ($F = 0.27$, $df = 1$, $p = 0.61$).

Panel (b) of Figure 38 indicates a similar growth of oysters cultivated by both culture methods on the concave surface of coconut-shell cultches. The suspension and bottom cultured oysters grew up to 5.04 ± 0.12 cm SH and 4.74 ± 0.12 cm SH with mean growth rates of 0.90 ± 0.25 cm/month and 0.86 ± 0.30 cm/month, respectively (see Appendix F2). However, there was no statistical significance difference between the treatments ($F = 1.47$, $df = 1$, $p = 0.23$).

The third panel (c) of Figure 38 shows the growth of oysters cultivated by suspension and bottom culture methods on the convex surface of oyster-shell cultches. The suspension and bottom cultured oysters grew up to 5.56 ± 0.10 cm SH and 4.60 ± 0.14 cm SH with mean growth rates of 1.02 ± 0.24 cm/month and 0.80 ± 0.23 cm/month, respectively (see Appendix F3). There was a statistical significance difference between the treatments ($F = 36.26$, $df = 1$, $p = 0.001$).

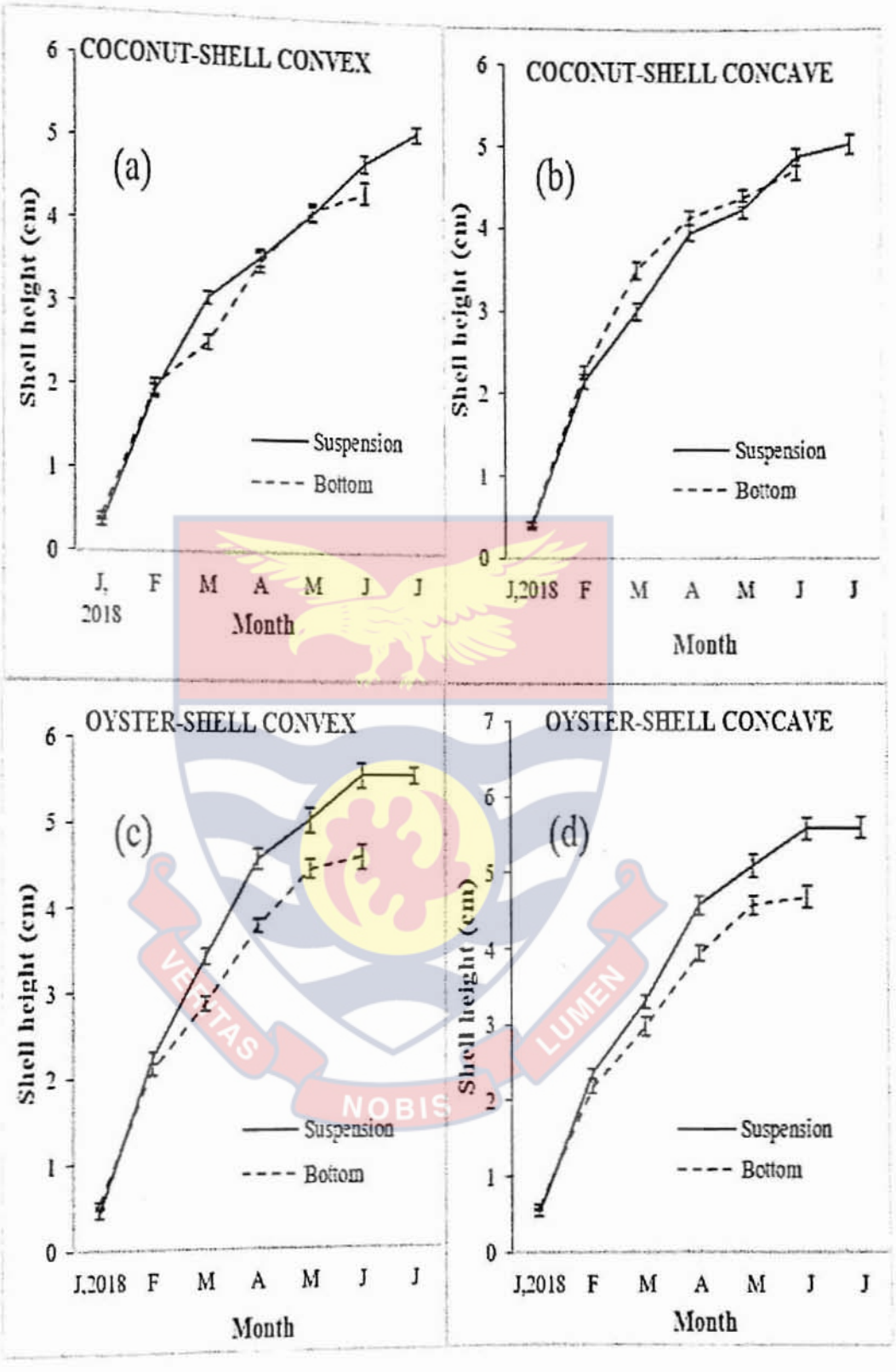

Figure 38: Growth of *Crassostrea tulipa* cultured on the convex and concave surfaces of coconut-shell and oyster-shell cultches in the Densu Delta (vertical bars indicate standard errors of means)

Panel (d) of Figure 38 indicates the growth of oysters cultivated by suspension and bottom culture methods on the concave surface of oyster-shell cultches. The suspension and bottom cultured oysters grew up to 5.59 ± 0.14 cm SH and 4.68 ± 0.14 cm SH with mean growth rates of 1.00 ± 0.24 cm/month and 0.81 ± 0.23 cm/month, respectively (see Appendix F4). There was a statistical significance difference between the treatments ($F = 22.32$, $df = 1$, $p < 0.001$).

Survival of oysters on the convex and concave surfaces of coconut-shell and oyster-shell cultches using suspension and bottom culture methods

Figure 39 shows the survival of oysters cultured on the convex and concave surfaces of coconut-shell and oyster-shell cultches. Generally, the survival of oysters cultured by both methods on the coconut-shell and oyster-shell cultches showed a similar pattern.

From the first panel (a) of Figure 39, 46.11 % of oysters cultured by suspension method survived in July 2018. The difference in survival of the treatments up to June was not statistically significant ($\chi^2 = 0.08$, $df = 4$, $p = 0.99$). Panel (b) of Figure 39 shows the survival of oysters cultivated on the concave surface of coconut-shell cultches by suspension and bottom culture methods. A percentage of 50.77 of oysters cultured by suspension method survived in July 2018. The difference in survival of the treatments up to June was not statistically significant ($\chi^2 = 0.48$, $df = 4$, $p = 0.97$).

The third panel (c) of Figure 39 shows the survival of oysters cultivated on the convex surface of oyster-shell cultches by suspension and bottom culture methods. Oysters cultured the suspension method had a survival of 47.45 % in July 2018.

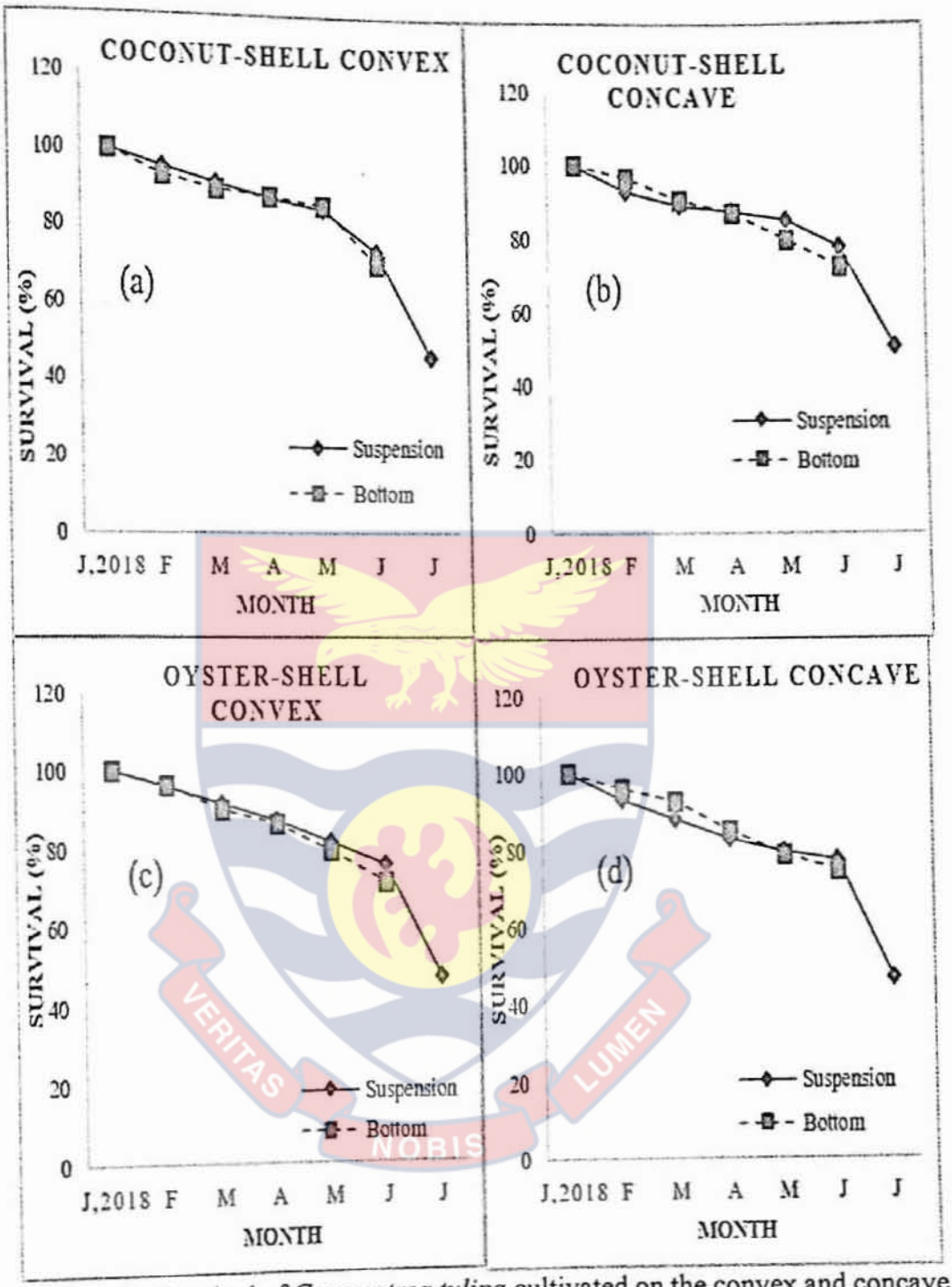

Figure 39: Survival of *Crassostrea tulipa* cultivated on the convex and concave surfaces of coconut-shell and oyster-shell cultches using the suspension and bottom culture methods in the Densu Delta

The difference in survival of the treatments over the study period was not statistically significant ($\chi2 = 0.06$, df = 4, p = 0.99). Panel (d) of Figure 39 displays survival of oysters cultivated on the concave surface of oyster-shell cultches by suspension and bottom culture methods. A percentage of 46.73 of oysters survived by the suspension culture method in July 2018. The difference in survival of the treatments over the study period was not statistically significant ($\chi2 = 0.19$, df = 4, p = 0.99).

4.5.2 Biofouling experiment

Observed biofoulers

The observed sedentary fouling organisms were identified as *Fistubalanus pallidus* (barnacle), *Brachidontes* sp. (mussel), *Ficopomatus* sp. (tube worm), sea anemone and algae, as shown in Figure 40.

Growth of oysters on the convex and concave surfaces of biofouled and cleaned coconut-shell and oyster-shell cultches

The growth performance of oysters on the surfaces of biofouled and cleaned cultches are presented in Figure 41. Generally, the oysters on biofouled and cleaned cultches showed a similar growth pattern.

Panel (a) of Figure 41 illustrates the growth of oysters cultivated on the convex surface of biofouled and cleaned of coconut-shell cultches. Oysters on the biofouled and cleaned cultches grew up to 5.38 ± 0.15 cm SH and 5.10 ± 0.13 cm SH with mean growth rates of 0.82 ± 0.19 cm/month and 0.78 ± 0.20 cm/month, respectively (see Appendix G1 for growth rates). However, there was no statistical significance difference between the treatments ($F = 2.60$, $df = 1$, $p = 0.12$).

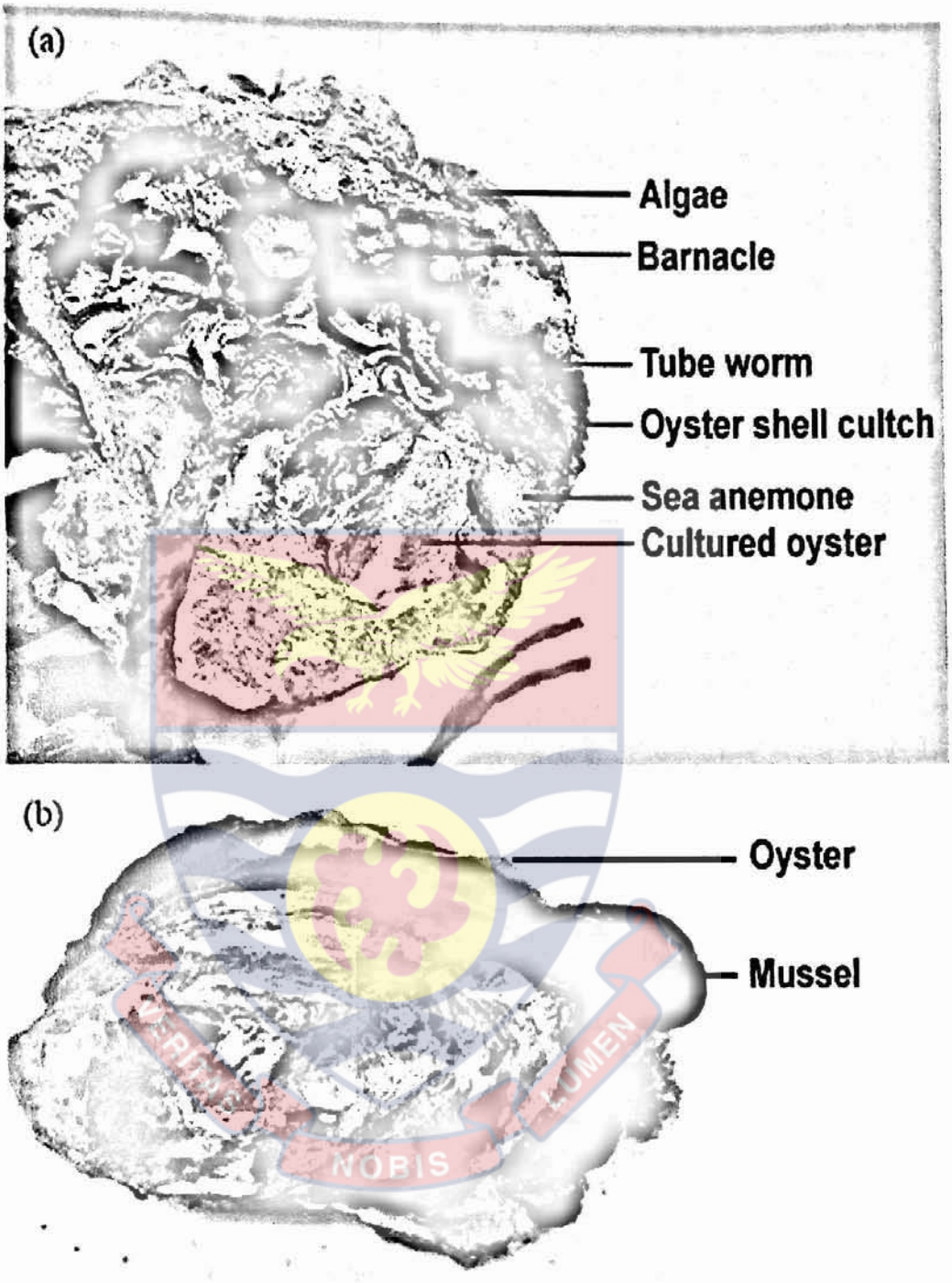

Figure 40: A photograph of biofoulers on (a) an oyster shell cultch: alga, barnacle, tubeworm, sea anemone and (b) cultured oyster: mussel

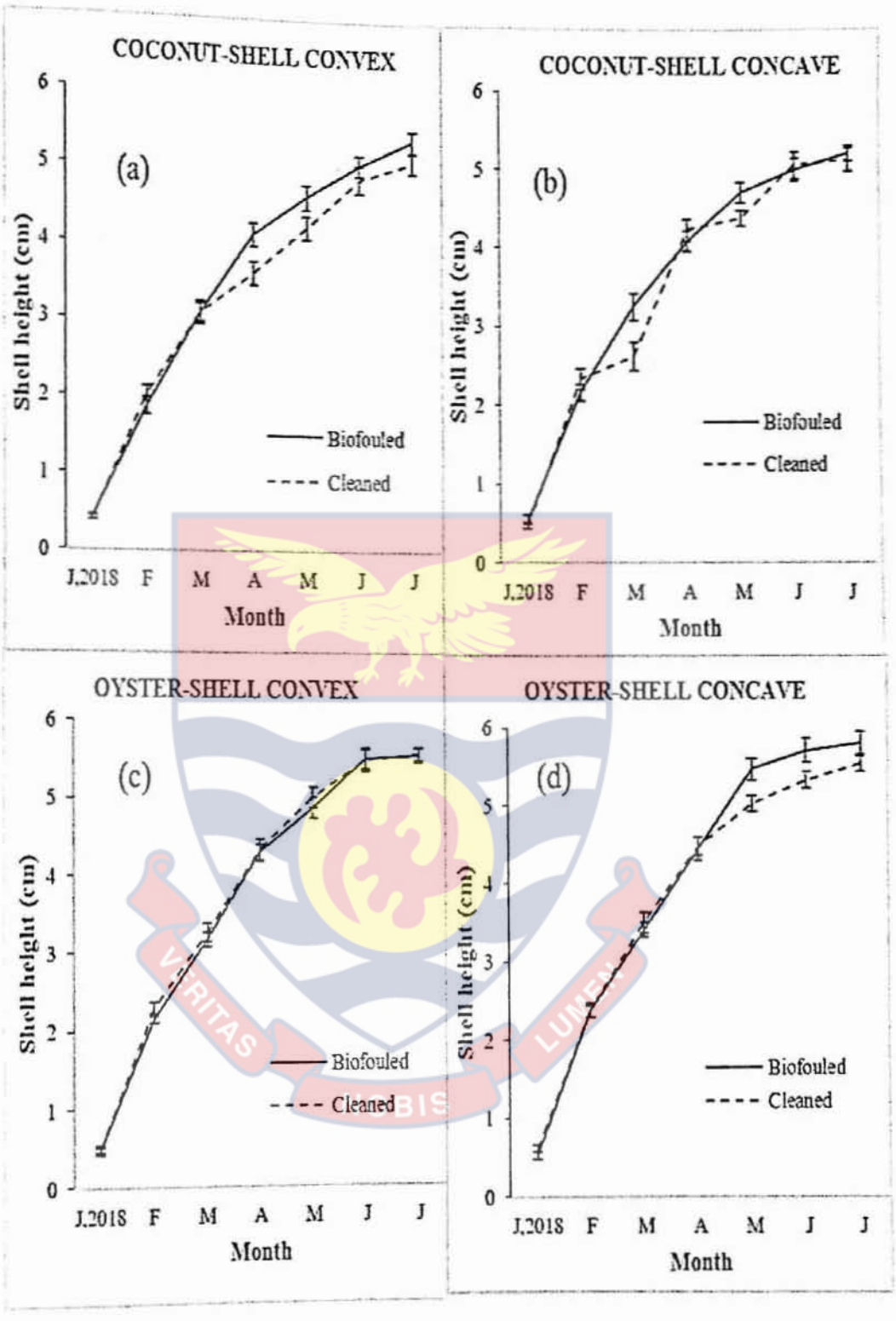

Figure 41: Growth of *Crassostrea tulipa* cultured on the convex and concave surfaces of biofouled and cleaned coconut-shell and oyster-shell cultches using the suspension culture method in the Densu Delta (vertical bars indicate standard errors of means)

Panel (b) of Figure 41 indicates the growth of oysters cultured on the concave surface of biofouled and cleaned coconut-shell cultches. Oysters on the biofouled and cleaned cultches grew up to 5.22 ± 0.10 cm SH and 5.14 ± 0.15 cm SH with mean growth rates of 1.03 ± 0.22 cm/month and 0.95 ± 0.43 cm/month, respectively (see Appendix G2). However, there was no statistical significance difference between the treatments ($F = 1.02$, $df = 1$, $p = 0.32$).

The third panel (c) of Figure 41 illustrates the growth of oysters cultivated on the convex surface of biofouled and cleaned of oyster-shell cultches. Oysters on the biofouled and cleaned cultches grew up to 5.55 ± 0.09 cm SH and 5.56 ± 0.09 cm SH with mean growth rates of 0.85 ± 0.22 cm/month and 0.84 ± 0.24 cm/month, respectively (see Appendix G3). There was no statistical significance difference between the treatments ($F = 0.20$, $df = 1$, $p = 0.66$).

Panel (d) of Figure 41 indicates the growth of oysters cultivated on the concave surface of biofouled and cleaned of oyster-shell cultches. Oysters on the biofouled and cleaned cultches grew up to 5.80 ± 0.15 cm SH and 5.54 ± 0.10 cm SH with mean growth rates of 0.87 ± 0.26 cm/month and 0.81 ± 0.24 cm/month, respectively (see Appendix G4). The treatments were significantly different ($F = 5.07$, $df = 1$, $p = 0.03$).

Survival of oysters on the convex and concave surfaces of biofouled and cleaned coconut-shell and oyster-shell cultches

The survival of oysters cultured on the surfaces of biofouled and cleaned cultches are shown in Figure 42. Generally, oyster survival for both treatments showed a similar pattern. Both declined slightly from January to June and subsequently decreased sharply from June to July.

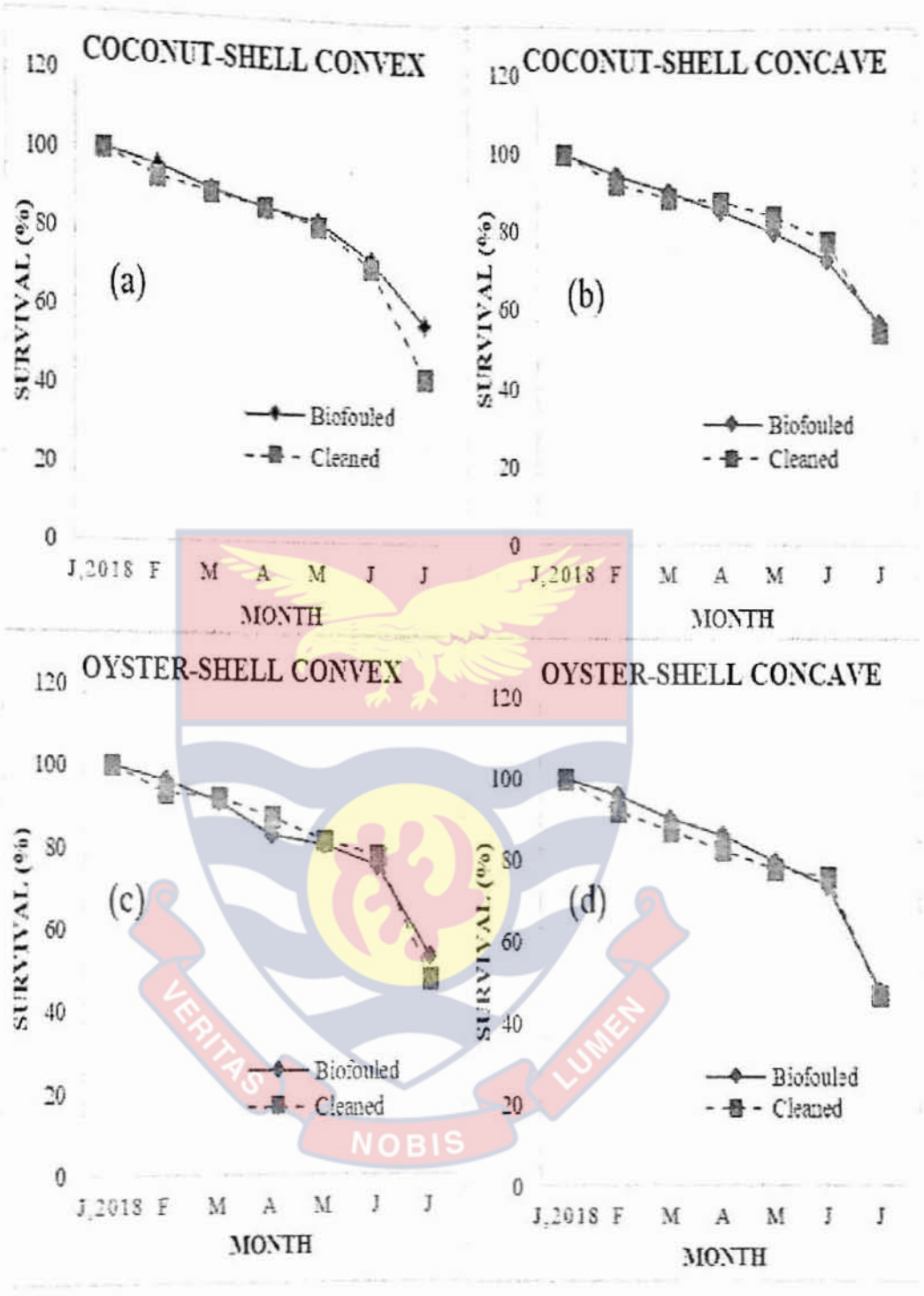

Figure 42: Survival of *Crassostrea tulipa* cultivated on the convex and concave surfaces of biofouled and cleaned coconut-shell and oyster-shell cultches using the suspension culture method in the Densu Delta

The experiment was terminated in August because of the low number of survivors.

The first panel (a) of Figure 42 shows the survival of oysters cultivated on the convex surface of biofouled and cleaned of coconut-shell cultches. Survival of oysters cultured on the biofouled and cleaned cultches were 56.77 % and 43.00 %, respectively in July 2018. The difference in survival of the treatments was not statistically significant ($\chi^2 = 0.07$, $df = 4$, $p = 0.99$). Panel (b) of Figure 42 shows the survival of oysters cultivated on the concave surface of biofouled and cleaned of coconut-shell cultches. Survival of oysters cultivated on the biofouled and cleaned cultches were 56.06 % and 54.82 %, respectively in July 2018. The difference in survival of the treatments was not statistically significant ($\chi^2 = 0.33$, $df = 4$, $p = 0.98$).

From the third panel (c) of Figure 42, displays the survival of oysters cultivated on the convex surface of biofouled and cleaned of oyster-shell cultches. Survival of oysters cultured on the biofouled and cleaned cultches were 53.85 % and 48.21 %, respectively in July 2018. There was no statistical difference between the treatments ($\chi^2 = 0.34$, $df = 4$, $p = 0.98$). Panel (d) of Figure 42 shows the survival of oysters cultivated on the concave surface of biofouled and cleaned of oyster-shell cultches. Survival of oysters cultivated on the biofouled and cleaned cultches were estimated as 46.73 % and 48.21 %, respectively in July 2018. There was no statistical significance in the survival of the treatments ($\chi^2 = 0.13$, $df = 4$, $p = 0.99$).

Growth of oysters cultured on the top- and bottom-2-collectors of biofouled and cleaned coconut-shell and oyster shell-cultches

Figure 43 shows the growth performance of oysters cultivated on the top- and bottom-2-collectors of biofouled and cleaned cultches. Generally, both treatments showed a similar growth pattern.

Panel (a) of Figure 43, illustrates the growth of oysters cultured on the top-2-collectors of biofouled and cleaned coconut-shell cultches. Oysters at this position of biofouled and cleaned cultches grew up to 4.93 ± 0.11 cm SH and 4.79 ± 0.13 cm SH with mean growth rates of 0.77 ± 0.10 cm/month and 0.74 ± 0.21 cm/month, respectively (see Appendix H1 for growth rates). Nonetheless, the treatments were statistically significant ($F = 1.74$, $df = 4$, $p = 0.15$).

Panel (b) of Figure 43 shows the growth of oysters on the bottom-2-collectors of biofouled and cleaned coconut-shell cultches. Oysters at this position on the biofouled and cleaned cultches grew up to 5.24 ± 0.08 cm SH and 5.32 ± 0.21 cm SH with mean growth rates of 0.76 ± 0.27 cm/month and 0.79 ± 0.30 cm/month, respectively (see Appendix H2). However, there was no statistical significant difference between the treatments ($F = 0.62$, $df = 1$, $p = 0.44$).

The third panel (c) of Figure 43 illustrates the growth of oysters cultured on the top-2-collectors of biofouled and cleaned oyster-shell cultches. Oysters at this position on the biofouled and cleaned cultches grew up to 5.36 ± 0.16 cm SH and 5.48 ± 0.13 cm SH with mean growth rates of 0.83 ± 0.21 cm/month and 0.85 ± 0.19 cm/month, respectively (see Appendix H3).

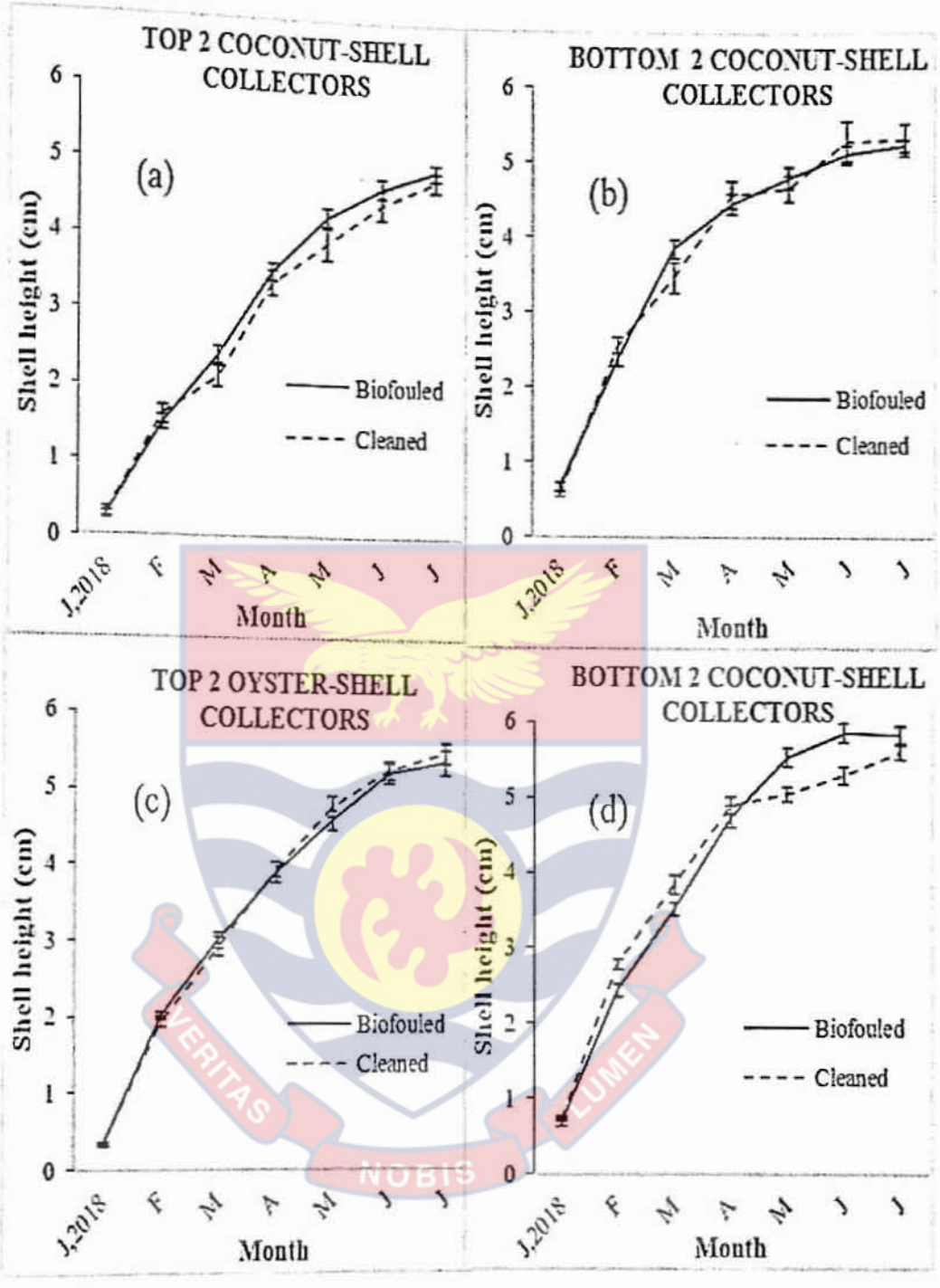

Figure 43: Growth of *Crassostrea tulipa* cultured on the top- and bottom-2-collectors of biofouled and cleaned coconut-shell and oyster-shell cultches using the suspension culture method in the Densu Delta (vertical bars indicate standard errors of means)

Nonetheless, there was no statistical significance difference between the treatments ($F = 0.01$, $df = 1$, $p = 0.99$).

Panel (d) of Figure 43 shows the growth of oysters cultured on the bottom-2-collectors of biofouled and cleaned oyster-shell cultches. Oysters at this position on the biofouled and cleaned cultches grew up to 5.83 ± 0.12 cm SH and 5.60 ± 0.10 cm SH with mean growth rates of 0.85 ± 0.26 cm/month and 0.81 ± 0.29 cm/month, respectively (see Appendix H4). The treatments were statistically insignificant ($F = 0.90$, $df = 1$, $p = 0.35$).

Survival of oysters cultured on the top- and bottom-2-collectors of biofouled and cleaned coconut-shell and oyster shell-cultches

The survival of biofouled and cleaned oysters cultured at the top- and bottom-2-collectors of coconut-shell and oyster-shell cultches is presented in Figure 44. Generally, the survival of biofouled and cleaned oysters followed a similar pattern, where it declined relatively gentle from January to June and thereafter decreased sharply from June to July.

The first panel (a) of Figure 44 illustrates the survival of oysters cultured on the top-2-collectors of biofouled and cleaned coconut-shell cultches. Survival of oysters on the biofouled and cleaned were 59.49 % and 50.90 %, respectively in July 2018. The difference in survival of the treatments was not statistically significant ($\chi^2 = 0.22$, $df = 4$, $p = 0.99$). Panel (b) of Figure 44 shows the survival of oysters cultured on the bottom-2-collectors of biofouled and cleaned coconut-shell cultches. Survival of oysters on the biofouled and cleaned cultches were 54.79 % and 43.32 %, respectively in July 2018. The difference in survival of the treatments was not statistically significant ($\chi^2 = 0.46$, $df = 4$, $p = 0.97$).

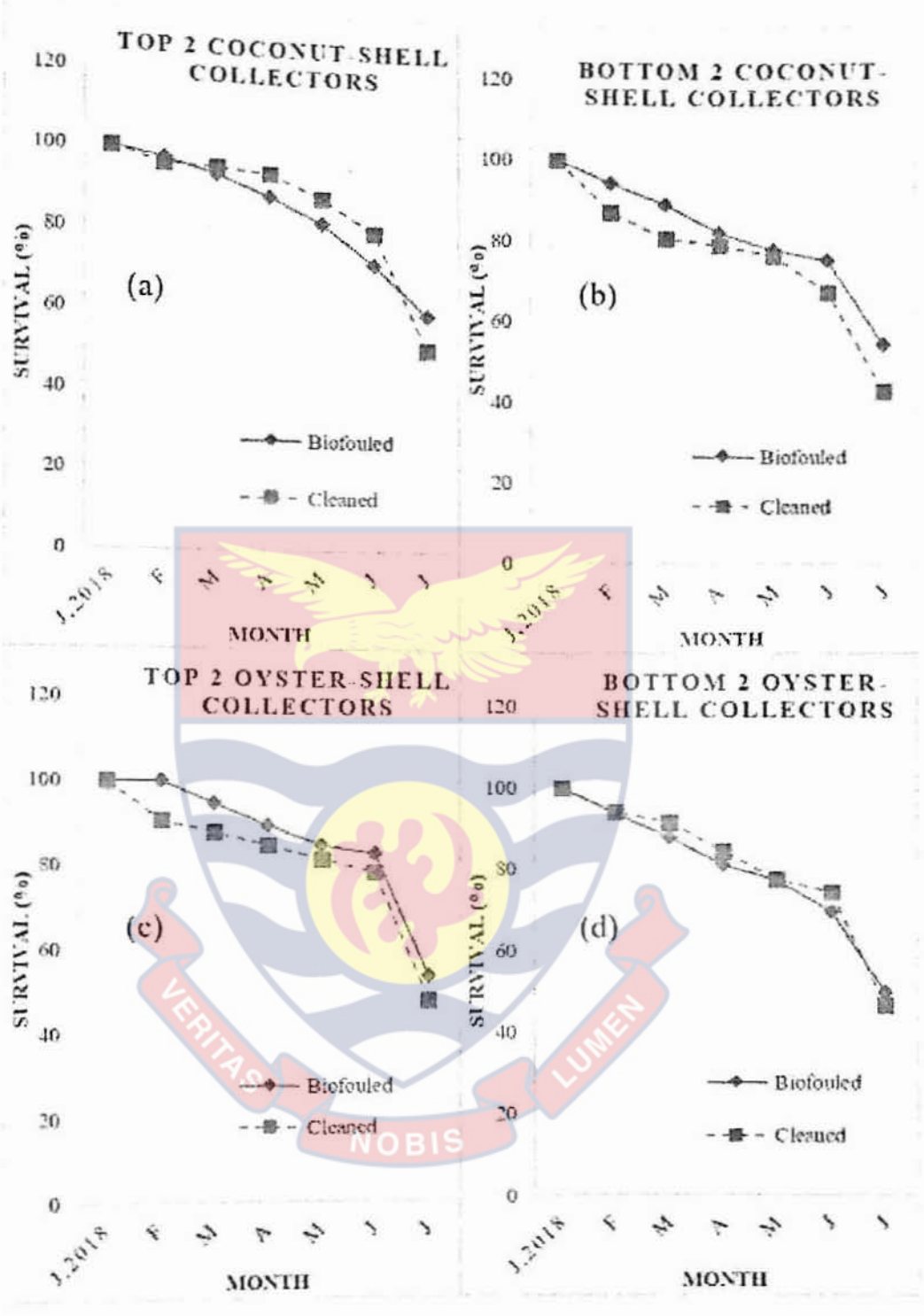

Figure 44: Survival of *Crassostrea tulipa* cultured on the top- and bottom-2-collectors of biofouled and cleaned coconut-shell and oyster-shell cultches using the suspension culture method in the Densu Delta

From the third panel (c) of Figure 44, illustrates the survival of oysters cultured on the top-2-collectors of biofouled and cleaned oyster-shell cultches. Survival of oysters on the biofouled and cleaned cultches were 53.95 % and 48.10 %, respectively in July 2018. There was no statistical difference between the treatments ($\chi^2 = 0.18$, $df = 4$, $p = 0.99$). Panel (d) of Figure 44 shows the survival of oysters cultured on the bottom-2-collectors of biofouled and cleaned oyster-shell cultches. Survival of oysters on the biofouled and cleaned cultches were 49.68 % and 46.81 %, respectively in July 2018. There was no statistical significance in the survival of the treatments ($\chi^2 = 0.06$, $df = 4$, $p = 0.99$).

4.6 Proximate Analysis

The proximate components of wild and cultured oyster meat in the Densu Delta are presented in Table 17. Of the various constituents of the samples, moisture ($t = 5.59$, $df = 3$, $p < 0.001$) and carbohydrate ($t = 25.24$, $df = 3$, $p < 0.001$) were significantly higher in the cultured oyster meat samples. Protein, carbohydrate (soluble), lipid, ash and fibre (insoluble carbohydrates) were obtained from the dry matter of the two groups of oyster meat samples (see Appendix I).

4.7 Taste Analysis

The tally of tasters' response with respect to samples 161 (wild oyster meat) and 121 (cultured oyster meat) are presented in Table 18. Chi-square Goodness-of-fit test was conducted and it showed that tasters who preferred the cultured oyster meat were significantly higher than those who preferred wild oysters ($\chi^2 = 16.33$, $df = 1$, $p < 0.001$).

Table 17: *Proximate Composition of Wild and Cultured Crassostrea tulipa Samples from the Densu Delta, expressed as percentages of Dry Weight, except Moisture*

Composition (%)	Wild Oyster Meat	Cultured Oyster Meat	*t*	$P_{(0.05)}$
Moisture	80.54 ± 0.30	82.61 ± 0.21	5.59	S
Protein	51.55 ± 0.57	51.60 ± 0.21	0.07	NS
Carbohydrate	32.77 ± 0.09	36.83 ± 0.14	25.24	S
lipids	10.42 ± 0.12	10.48 ± 0.13	0.29	NS
Ash	3.04 ± 0.13	3.13 ± 0.21	0.35	NS
Fibre	1.98 ± 0.19	1.59 ± 0.06	1.96	NS

S = Significant; NS = Not significant

Table 18: *Taste Preference of Wild and Cultured Crassostrea tulipa, N = 75*

Record Sheet – Paired Preference Test			
Sample	Tasters' Preference	χ^2	$P_{(0.05)}$
161 (wild oyster meat)	21	16.33	S
121 (cultured oyster meat)	54		

S = Significant; df = 1

CHAPTER FIVE

DISCUSSION

This chapter presents the interpretation of the current findings with reference to pertinent previous literature. It covers the oyster fishery, biology and culture of *C. tulipa* as well as the nutritional and taste analyses of wild and cultured oysters in the Densu Delta.

5.1 Socioeconomic Assessment of the Oyster Fishery

The Ghanaian fishery is categorised by gender roles, according to Odotei (1995). The current study indicates that the oyster fishery, which comprised harvesting, processing and marketing is carried out by 97 % of females (Table 2). The high percentage of females in the fishery agrees with the earlier qualitative assertion by Janha et al. (2017). They carried out a participatory rural appraisal study on the same oyster fishery. The three males encountered in the present study indicated that they were engaged in harvesting only. Their catches were given to family members mainly for subsistence purposes or sold after processing. The above findings suggest that the fishery is gender-specific, with female dominance. Female preponderance was also reported for oyster fisheries in other parts of Ghana (Asare et al., 2019; Obodai, 1997; Yankson, 2004), Nigeria (Ansa & Bashir, 2007) and The Gambia (Njie & Drammeh, 2011). Furthermore, the clam fishery in the Lower Volta Basin of Ghana has been reported to have supported the livelihood of mostly women (Abarike, Alhassan & Alipi, 2015; Adjei-Boateng et al., 2012) just as the periwinkle fishery of Rivers State, Nigeria (Akinrotimi, Abu, Ibemere & Opara, 2009). Nonetheless, the exploitation of bivalve shellfish is not always

dominated by females, as reported by Ansa and Ansa (2004) in the clam fishery in Nigeria, where males dominated the harvesting sector.

Based on the Ghana Statistical Service [GSS] (2016) report, it is clear that the age range of respondents (i.e.15 to 62 years) recorded in the present study (Fig. 8) agrees with the working population (15 – 64 years) in Ghana. This suggests that the oyster fishery supports all ages within the working population of Ghana. However, it must be mentioned that children support their parents, especially in processing and marketing of the oyster meat. Orewa and Iteke (2013) consider the active labour force in Nigeria to range from 18 to 40 years.

The dominance of married women in this study (Fig. 9) implies that the oyster fishery is gender-based. A similar observation was made in a study of the clam fishery in the Volta Basin by Abarike et al. (2015), which the authors attributed to low capital of the trade. Mainly, fishers had to support a large family size, both young and old. The high dependency level (Fig. 10) comes with some merit and demerit. Some respondents engaged their dependants (mainly children) in the processing and marketing of oysters to maximise income. The disadvantage is that the children may drop out of school or perform poorly due to the extended time spent in processing and marketing. Oysters are usually sold in a boiled shucked form. On days of low patronage, marketers utilise the leftover by later frying the meat for stew or soup.

As indicated by Janha et al. (2017), the oyster workers were the poorest in the fishing communities around the Densu Delta. In the present study, females in the oyster fishery who were mainly settlers and migrants probably were attracted to the business because it requires little capital (GHS 5.5 to 32.5, running cost) and the oysters are easily accessed by handpicking in the shallow

waters without any skill in swimming. The men concentrated mainly on the exploitation of finfish in the Densu Delta using pole seining, cast netting, bottle fishing and Brush parks (Acadja).

The indigenes or natives in Bortianor/Tsokomey and Tetegu communities are Gas (Table 3). In Ghana, Ga-Adangmes, Ewes and Fantis are noted for their participation in fishing and fish-related activities along the coastal area of the country. Apart from the 64 % of Ewe settlers in the stakeholder communities and a about half of this percentage had joined as migrants (35.7 %) to make ends meet by mainly engaging in fisheries-related activities (Table 4). According to Odotei (1995), the motive of female fisherfolk migration is to assist their husbands (fishers), and upon settling successfully, their children and relatives are invited to support the business (particularly, processing and marketing the fish). Only about 13 % of the oyster fisherfolk were Gas with the majority being Ewes (86 %), possibly due to the unpopularity of the oyster business among the Gas. This is obvious in a popular statement like, "if one wants to enjoy fish then that should not be a shellfish" at the backdrop of availability of high valued finfish. However, this narrative is changing due to the dwindling fish stocks of Ghana.

It is evident in the results that a greater proportion (76 %) of the respondents did not attend school or ended their education at the Primary level, and about half of this percentage did not get any formal education (Fig. 11). It is common knowledge that less-educated individuals in Ghana dominate the fish trade. This situation stalls their prospects of taking innovative measures to make their trade more profitable. Despite the low level of education, respondents have shown great interest in upgrading their knowledge about the fishery and ways

of adding value to the oysters. Oyster workers who have attained Senior and Junior Secondary School could be trained on value addition practices, which could be passed on to the relatively less educated. High illiteracy rates in developing countries have been attributed to insufficient funds to train members in large household sizes (Orema & Iteke, 2013).

The commercialisation of the oyster fishery started some ten (10) years ago. This implies that about 45 % of the respondents (experience from 10 to 20 years or more, Fig. 12) were probably exploiting the fishery initially on a subsistence level. In the current study, about 5 % of the respondents indicated that they harvested oysters for personal consumption only, suggesting that the fishery has gained higher economic value compared to a decade ago. The commercial fishers also sustain their families with oyster meat. The highest proportion of oyster fishers with experience up to 4 years (Fig. 12) is indicative of recent recruitment of individuals into the oyster business. This substantiates the report that the number of fishers had increased from 150 to 400 in the past five (5) years (Janha et al., 2017). It could be inferred that by their standards, the fishery was a profitable venture. By extension, one could expect increased recruitment into the fishery, hence the need for a management strategy. Like the clam fishery in the Volta Lake, respondents have built strong relationships through many years of working, which has led to the formation of an association spearheaded by the Sustainable Fisheries Management Project (SFMP) through the Development Action Association (DAA). These institutions have been working with the oyster fisherfolk to develop management plans for the sustainability of the resource and profit enhancement.

With respect to the majority of fishers (76 %) having fishery-related livelihoods, individuals in the oyster fishery could be trained or supported to take up non-fishery-related activities like dressmaking, baking, hairdressing, etc. as an alternative livelihood. Such enterprises will be of great benefit to fishers during the off-season (six months, from October to March).

Generally, an individual oyster fisher engages in all three components, i.e., harvesting, processing and marketing (Table 5). The three male respondents indicated that they sourced oysters at the deeper part of the Densu Delta by diving. The fishing down of oysters at the shallow portions as compared to the deep area could be ascribed to the harvesting pressure exerted by the high proportion of females (95 %) confined to shallow areas due to their inability to source oysters at the deeper areas by diving. Although there was no regulation on the oyster fishery, the respondents pointed out that activities were halted on the water body during the Ga Homowo customary rites for a couple of days. However, Koranteng (1995) made an observation that taboos are not entirely obeyed on the Densu Delta; this he attributed to the breakdown of traditional norms due to urbanisation.

The GHS 111,783 (USD 25,565.59) difference between the appraised value, GHS 286,650 (USD 65,558.96, Table 8) and the gross annual income, GHS 174,867 (USD 39,993.37) could be attributed to the consumption of oyster catches by the fishers as oysters serve as a cheaper source of protein. In other words, the oyster fishers saved an amount of GHS 111,783, which could have been used in purchasing other forms of protein like finfish, mutton or beef. The fishery was found to be lucrative, with an annual profit of GHS 122,850. By comparing the income made in a week by the average fisher (thus, twice fishing

per week which equals GHS 90) to Ghana's 2018 weekly minimum wage which is about GHS 68 (daily wage = GHS 9.68) indicates that individuals in the oyster fishery were doing better financially (Minimum Wages in Ghana, 2018). Nonetheless, considering the number of fishing trips per week by an average fisher, the seasonality of the fishery (at the shallow portions, which last for six months) and the high dependency level of the oyster collectors, the profit accrued could be insufficient for their daily expenditure. This condition necessitates alternative sources of income to make ends meet. Alternatively, as marketing is not a problem, the fishers could be taught to culture the oysters to maximise their returns. Hence the ensuing aspects of the present study address the biology and culture of the species in the Densu Delta to provide a basis for its rational management and culture.

5.2 Physico-chemical Parameters

Temperature has been reported widely as a critical factor in determining the habitat, geographical distribution and survival of living aquatic organisms. Dame (1996), Gosling (2015) and Ward et al. (2000) have indicated that temperature influences growth, physiology and reproduction of bivalves. It has been reported that most marine bivalves thrive within a temperature range of -3 °C to 44 °C (Vernberg & Vernberg (1972) as cited by Gosling, 2004). In the current study, the mean surface temperature ranges of the various sampling stations (22.45 ± 0.06 to 31.47 ± 0.06 °C), as shown in Figure 13a, lie within the tolerance range indicated by Galtsoff (1964) and Gosling (2015). The temperature ranges recorded in the present study also compare with records from other Ghanaian lagoons by Obodai (1997) (27 - 34 °C, 24 - 32 °C and 27 - 36 °C in Jange, Benya and Nakwa lagoons, respectively) and estuaries by

Dzakpasu (2012) (23.36 °C – 32.01 °C, and 23.36 °C – 32.01 °C Kakum and Nyan estuaries, respectively). The monthly temperature values measured in the Densu Delta did not fluctuate much, particularly in 2018 (Fig. 13), which agrees with Obodai et al. (1994) and is typical of tropical coastal water systems (Afinowi, 1985; NERR, 1997). The highest temperature values recorded in May 2017 and lowest in August 2017 coincided with periods of dry and rainy months, respectively, similar to the findings of Akpan, Offem and Nya (2006) and Dzakpasu (2012).

Dissolved oxygen is among the key physico-chemical factors that support the growth and survival of living aquatic organisms. According to Molner et al. (2008) and Quayle (1980), the oxygen concentration of oyster growing waters is most important. Galtsoff (1964) reported that larval and juvenile oysters could survive anoxic conditions for hours or days, while adults may tolerate up to a couple of weeks (i.e., facultative anaerobes). However, Baker and Mann (1992) indicated that hypoxic and anoxic waters might have detrimental effects on oyster setting and recruitment. In the present study, surface DO ranged from 0.38 ± 0.02 to 8.15 ± 1.11 mg/l (Fig. 14a), which was lower than the reported range by Obodai (1997) in Jange, Benya and Nakwa lagoons (8.44 – 10.03 mg/l, 2.19 – 9.94 mg/l and 5.62 – 13.17 mg/l, respectively in Ghana). However, Dzakpasu (2012) reported generally lower estimates of DO in Nyan (5.0 – 6.79 mg/l) and Kakum estuaries (1.60 – 6.92 mg/l) compared to the current study. The differences in DO concentrations in the above water bodies could be ascribed to the possibility of having different levels of primary production, decomposition rates and freshwater inputs.

The lowest DO values which coincided with the rainy months (August, September 2017, and July 2018, etc. as seen in Fig. 14a) and the significantly lower concentration of DO values at the bottom of the Delta (Fig. 14b) could be explained by the consumption of DO by decomposers in degrading organic matter, washed into the Delta by land runoff and effluents (i.e., Weija Dam).

Bivalves have adapted to different salinity regimes, from freshwater to hypersaline pools or water bodies. Oysters being osmoconformers are confined to areas of coastal water bodies where the salinity range is favourable to their metabolic activities. In this study, the salinity ranges for all the sampling stations were comparable, with a mean surface value between 0 and 41.67 ± 0.06 ‰ (Fig. 15a). Similar ranges of salinity were reported by Obodai (1997) (0 – 35 ‰, 5.0 – 38.0 ‰ and 0 - 35 ‰ in Jange, Benya and Nakwa lagoons, respectively) and Dzakpazu (2012) (0 – 38.67 ‰ and 0 – 35.67 ‰ in Nyan and Kakum estuaries, respectively). The wide range of salinity observed in the current study could be ascribed to the high freshwater inputs (from spillage of the Weija dam) and tidal influence.

The significant vertical distribution of salinity in June and July 2017 (Fig. 15b) could be attributed to the high freshwater intrusion from the spilling of the dam resulting in saline water at the bottom and an overlying freshwater.

Hydrogen ion concentration (pH) is known to be relatively stable in estuarine systems due to the buffering effect of the seawater (NERR, 1997, Obodai et al., 1994). However, according to Quayle and Newkirk (1989), there are instances when the pH can change significantly, which could be deleterious to bivalves. For example, a drop in salinity could cause a hike in pH (Quayle,

1980). It has been reported by Bhatnagar et al. (2004), that pH values < 4 or > 10.5 may be lethal to fish. The observed range of pH in the current study (6.94 ± 0.19 to 10.82 ± 0.16, Fig. 16) was relatively higher compared to Arakawa's (1990) range (7.0 – 8.5), which was described as suitable for oyster culture and fattening. The highest pH of 10.82 ± 0.16 measured at Station 4 in November 2017, may have a detrimental effect on the oysters. The concurrence of high pH with low surface salinity (< 2 ‰, Fig. 16b) agrees with Quayle (1990). The lower pH values in July and August 2017 and from June to October 2018 could be ascribed to the decomposition of organic matter by decomposers during the rainy months. The low DO concentrations (Fig. 14) during the months mentioned above corroborates this assertion. Besides, there is a possibility of reduced photosynthetic activity during periods of high turbidity, which could lead to increased carbon dioxide concentration in the water and in turn, lower the pH values. At the deep portion (Station 4b), there was no significant variation in the vertical distribution of pH, although the bottom concentrations were generally lower during the rainy months.

It is a general knowledge that high turbidity impedes light penetration into water systems, which in turn reduces or prevents primary production. Also, high turbidity may cause the gills to clog during filtration. Quayle (1980) noted that high turbidity might result in high sedimentation (deposition of silt), which, if sufficient enough may smother oysters. An adaptation to this effect is the ability of oysters to close their shells for hours to days (Bayne, 2017; Blay, 1990; Obodai et al., 1994).

The high levels of turbidity > 20 NTU in the Densu Delta recorded from June to July and November to December 2017 as well as in 2018 from June to

August (Fig. 17) could be due to silt or soil particles from the high influx of freshwater due to the rains. Turbidity was below 20 NTU during non-rainy months, which relatively presents a healthy state of the Delta. A comparison of mean turbidity range of the current study (2.0 – 144.67 NTU) with that of Kakum and Nyan estuaries (2.33 – 49.78 NTU and 2.0 – 100 NTU, respectively) recorded by Dzakpasu (2012), indicates that the Densu Delta was relatively more turbid, which could be attributed to the periodic massive spillage from the Weija Dam.

Primary productivity in estuarine and coastal marine systems has been reported to have a strong correlation with the concentrations of nitrogen and phosphorus in the water column (Howarth et al., 1996; Nixon, 1992; Smith, Joye & Howarth, 2006). Nitrate and phosphate concentrations could independently cause the proliferation of algae (food for oysters) and other aquatic macrophytes (Howarth, 1998; Howarth et al., 1996; NRC, 2000).

In the current study, concentrations of phosphate were generally lower than nitrate (see Figs. 18 & 19). This could be due to the naturally low concentrations of phosphorus in water (NRC, 2000). Generally, nitrate concentrations were relatively lower during the rainy months from May to July and November in 2017 as well as June to October 2018 and vice versa. This corroborates the finding by Okyere (2019) in his assessment of the environmental conditions of the Pra estuary. It is expected that with the intensification of land runoff and freshwater input into the Densu Delta, there would be an increase in the nitrate concentration. On the contrary, there was a decrease which could be due to denitrification (i.e., anaerobic microbial reduction of nitrates to nitrogen gas or nitrous oxide). Firestone (1982) reported

that the bacteria responsible for denitrification use nitrate for respiration during low oxygen levels. This elucidates the low nitrate observed in the current study, particularly from June to October 2019 (Fig. 18) when DO concentrations were low (Fig. 14). For phosphate, relatively, very high concentrations were observed in June and July 2017 (rainy months) at all stations (Fig. 19), which is similar to an observation made by Okyere (2019). This could be ascribed to land runoffs or effluents from the Weija Dam conveying decomposed organic matter, sewage, agricultural waste and fertilizers.

According to NOAA/EPA (1988), suitable levels of nitrate and phosphate in coastal ecosystems that prevent algal blooms should be less than 1.0 mg/l and 0.1 mg/l, respectively. This indicates that the estimated nitrate concentrations in the current study were above the recommended threshold throughout the sampling period. Also, the phosphate concentrations were above the threshold, mainly during the rainy months. Therefore there is a potential for algal bloom should the turbidity reduce in the presence of sunlight.

Galtsoff (1964) and Quayle (1980) indicated that sediments could influence the distribution and abundance of oysters. A comparison of the mean bulk density of sediments of the current study (0.14 ± 0.01 g/cm^3, Fig. 20) with three other lagoons with oyster populations Jange (1.32 g/cm^3), Benya (0.41 g/cm^3) and Nakwa (1.09 g/cm^3) in Ghana as reported by Obodai (1997), shows that the estimates of the current study were lower. This suggests that the current study sites had the lowest soil compactness as compared to the above three lagoons. Obodai attributed the absence of oysters on the bottom substrates in the Benya lagoon to the low bulk density of the sediment. From the current study the bulk density of sediments at Stations 1 (0.14 ± 0.02 g/cm^3), 2 ($0.12 \pm$

0.01 g/cm^3) and 3 (0.11 ± 0.01 g/cm^3) were similar. However, Station 3 supported oysters but not Stations 1 and 2. The presence of oysters at Station 3 compared to Stations 1 and 2 cannot be explained with the current data since the observed physico-chemical factors and sediment bulk densities were comparable among Stations 1, 2 and 3.

Some potential threats such as water spillage from the Weija Dam with its attendant high turbidity and low salinity, low bulk density of sediments as well as high nutrients levels with its concomitant algal bloom were observed at the Densu Delta. However, the oyster fishery produced an annual yield between 278 and 352 tonnes (ave. 295 tonnes), which is suggestive of a thriving resource.

5.3 Biology

Stations 3 and 4a are the most intensely exploited oyster beds in the Densu Delta due to their shallowness and ease of accessibility. During the sampling period, Station 3 population was recovering from high fishing mortality and natural mortality, possibly from the high influx of freshwater spilled from the Weija Dam during the rainy months. These accounted for the low population density at this station (36 ± 8.3 to 176 ± 12.9 ind/m^2) compared to 87 ± 19.2 to 763 ± 44.4 ind/m^2 and 245 ± 76.6 to 1648 ± 93.8 ind/m^2 at Stations 4a and 4b, respectively (Fig. 21). This possibly explains the relatively small oyster sizes at Station 3, as shown in Figure 22.

Similarly, Station 4a oysters were exploited more than Station 4b because of its relatively shallow depth (0.61 m). This explains the lower population density of oysters at Station 4a compared to Station 4b. Also, the oyster populations at the three stations showed significant monthly variations. The relatively lower mean population densities, particularly at Station 4b during

the rainy months could be attributed to the low DO (Fig. 14b), low salinity (Fig. 15b), and high turbidity (Fig. 17).

In the Wadden Sea (Germany), *C. gigas* was reported to have a population density ranging from 2 to 1460 ind/m^2 (Schmidt, Wehrmann & Dittmann, 2010) while on the French Atlantic Coast it ranged between 4 and 4550 ind/m^2 (Dutertre, Beninger, Barille, Papin & Haure, 2010). In Ghana, *Perna perna* (a mussel) population was found to have a density between 56 and 466 ind/m^2, where low values were attributed to intense overexploitation (Krampah, 2016) just as in the Germany and France populations.

The pooled data for the three oyster sampling stations showed unimodal size distributions with the same modal class (4.0 - 4.9 cm SH). However, Station 4b had the widest range (2.0 – 14.6 cm SH) followed by Station 4a (2.0 – 13.0 cm SH) and then Station 3 (2.0 – 10.40 cm SH) as seen in Figure 22. The unimodal size distributions at the stations suggest that the oyster cohorts that were recruited into the population at different periods were lumped together, which is typical of tropical fish populations (Bagenal & Tesch, 1978; King, 2007; Osei, 2015). Bagenal and Tesch (1978) ascribed the above observation to the continuous recruitment, faster growth rate of juveniles and a longer life-span (which gives room for younger fast-growing cohorts to catch up with the relatively slow-growing older cohorts). The smaller size distribution range and lack of bigger individuals at Station 3 are indicative of mortality dominated population as indicated earlier and also suggests growth overfishing as asserted by Pauly, Christensen, Dalsgaard, Froese and Torres (1998). Though the size distribution ranges of oysters at Stations 4a and 4b were comparable, the fewer proportion of bigger individuals (> 4 cm SH) at Station 4a (Fig. 22) suggests

that the population was more heavily exploited compared to the deeper Station 4b oysters.

The mean shell height of oysters from Station 3 (5.03 ± 0.10 cm) was lower than Stations 4a (8.00 ± 0.10 cm) and 4b (7.86 ± 0.10 cm). As pointed out earlier, the population at Station 3 was recovering from massive mortality. The coefficient of determination of shell height-shell length relationship was highest at Station 3 ($R^2 = 0.60$) compared to Stations 4b ($R^2 = 0.28$) and 4a ($R^2 = 0.26$) (Fig. 23). This suggests that shell height explained the increase in shell length best at Station 3. The slopes of the regressions (b) of log L on Log H for the various stations deviated from isometry (i.e., negative allometry). In Ghana, a similar finding was made by Asare (2017) on cultured and wild *C. tulipa* samples from the Nakwa lagoon. However, Gongora-Gomez, Leal-Sepulveda, Garcia-Ulloa, Aragon-Noriega and Valenzuela-Quinonez (2018) reported positive allometry for shell height and shell length relationship for *C. corteziensis* in the Gulf of California (Mexico).

The coefficient of determination of the regression of shell height and shell width was highest at Station 3 ($R^2 = 0.51$) compared to Stations 4a ($R^2 = 0.23$) and 4b ($R^2 = 0.19$) (Fig. 24). This suggests that, comparatively, the shell height of Station 3 oysters could best predict its corresponding shell width. The slope of the regression (b) of log W on log H for Station 3 was isometric, while those of Stations 4a and 4b deviated from unity (i.e., negative allometry). The isometric relationship between shell height and shell width at Station 3 indicates that the two dimensions increased proportionally. In other words, the oysters grew deeper with an increase in shell height, consistently. Asare (2017) reported negative allometry for a regression analysis between shell height and shell width

in cultured and wild *C. tulipa* samples in the Nakwa lagoon. Similarly, Gongora-Gomez et al. (2018) reported negative allometry for this dimensional regression analysis for *C. corteziensis*.

The coefficient of determination of the regression between shell height and total weight of oysters was highest at Station 3 ($R^2 = 0.78$) compared to Stations 4a ($R^2 = 0.62$) and 4b ($R^2 = 0.57$) as seen in Figure 25. This means that, comparatively, shell height of Station 3 oysters could best predict its corresponding total weight. The gradients of the regression of oysters from the various stations deviated from isometry (i.e., negative allometry). In other words, shell height grew at a faster rate than total weight of the oysters. A similar observation was made at Nakwa (Ghana) on cultured and wild *C. tulipa* by Asare (2017). Similar findings were recorded, elsewhere in St. Martin (Bangladesh) on *C. virginica* population as well as in Goa (India) on *C. madrasensis* and *C. gryphoides* by Amin et al. (2006) and Nagi et al. (2011), respectively. However, positive allometry has been reported on *Ostrea edulis* by Acarli, Lok, Kucukdermenci, Yildiz and Serdar (2011) in Mersin Bay (Turkey). Besides, Gongora-Gomez et al. (2018) reported positive allometry for shell height and total weight relationship for *C. corteziensis*.

The coefficient of determination of the regression between shell height and wet meat weight was highest at Station 3 ($R^2 = 0.68$) compared to Stations 4a ($R^2 = 0.29$) and 4b ($R^2 = 0.21$) (Fig. 26). This is an indication of relatively reliable prediction of wet meat production with shell height at Station 3. The gradients of the regression of log *Mw* on log *H* from the various stations deviated from isometry (i.e., negative allometry). This implies that shell height grew at a faster rate than its corresponding wet meat weight. Nagi et al. (2011)

presented negative allometry for shell height and wet meat weight relationship for *C. madrasensis* and *C. gryphoides.*

In literature, the value of *b* of the regression between a fish's length (size) and weight has been used to quantify its condition (Bagenal & Tesh, 1978; Le Cren, 1951), where fish of isometric or positive allometry (i.e., a bigger fish with a relatively smaller size) is said to be better conditioned than the one with a negative allometry growth. In the present study, comparatively, the *b* value of the regressions between shell height and total weight/wet meat weight of Station 3 were consistently closest to the hypothetical value (3), i.e., isometric growth; this implies that Station 3 oysters were of a better condition than those at Stations 4a and 4b. However, the regression between shell height and wet meat weight is more meaningful to the species being studied, since condition in bivalves as defined by Quayle and Newkirk (1989), is the plumpness or the extent to which the oyster's body (meat) fills the shell cavity.

Moreover, the significant isometric growth between shell height and shell width as well as the closeness of the *b* value of the regression between shell height and shell length to unity, both at Station 3 stand to reason that oysters at this station were relatively growing deeper and broader with an increase in shell height. This observation could be an adaptation for Station 3 oysters to create bigger inner shell space for gonadal development and maturation even at their relatively smaller shell size (height, length and width) and weights to maximise spawning in order to revamp the population. Though the sediments at Stations 4a and b (0.17 ± 0.003) were firmer than at Station 3 (0.12 ± 0.01), the effect of the sediment type was not evident in this study, as shell shape was generally similar among the stations (similar Morphological

indices, MI). Probably the sediment types were not different enough to influence the shape of the oyster shells at the various stations. Also, the gregarious settlement of oyster spat on hard substrates could take out the effect of the sediments as the shells get distorted during growth.

Generally, the better coefficient of determination (R^2) of the regression between shell height and shell length/shell width/total weight at Station 3 compared to Stations 4a and 4b indicate that the shell dimensions at Station 3 are more predictable than their counterparts. This is in line with the relatively smaller variation in the morphological index at Station 3 (74.98 – 468.75) compared to Stations 4a (55.64 - 527.27) and 4b (51.68 – 900.00). However, the differences among the means at the stations were not statistically significant. Krampah (2016) reported an MI range of 52.38 to 88.89 in studying a *Perna perna* population at a rocky beach near Cape Coast, Ghana. It could be inferred that the current findings have wider ranges than Krampah's. This resonates with the popular assertion that oysters have a highly variable shape as compared to mussels (Galtsoff, 1964; Gosling, 2015; Quayle & Newkirk, 1989).

Comparing the coefficients of determination (R^2) of shell height (H) - shell length (L)/shell width (W)/total weight (Tw), wet meat weight (Mw) for the various stations, it could be deduced that the most predictable relationships in order of importance were *H-Tw*, *H-Mw*, *H-L* and *H-W* despite the reported extreme variability in the shell shapes.

The bimodal monthly distributions in Stations 4a and 4b, as opposed to Station 3 (Fig. 27), could be explained by the recruitment of young individuals into the oyster fishery in addition to the older lumped cohorts. Generally, the monthly shell height frequency distributions did not show clear consistent shifts

in their modes. Possibly, due to younger individuals catching up with older cohorts due to the decline in growth rate with age (Gosling, 2015; King, 1995). However, Stations 3 and 4b showed a population growth rate of 0.5 cm SH/month and 1.0 cm SH/month, respectively, as seen in the first three samples at both stations. This is evident in the higher growth coefficient and asymptotic shell height in Station 4b oysters ($K = 0.47$ yr $^{-1}$, $SH_{\infty} = 16.28$ cm) compared to that of Station 3 ($K = 0.43$ yr $^{-1}$, $SH_{\infty} = 14.78$ cm) as presented in Figure 23. Oysters from Station 4b exhibited the highest growth coefficient, followed by Station 3 and then Station 4a ($K = 0.30$ yr $^{-1}$). This finding suggests that oysters from the deep part (St. 4b) grew faster than their counterparts at the shallow sites (St. 3 and St. 4a). This is not easy to explain as the measured physico-chemical parameters in this study were comparable. Elsewhere, in Bangladesh Amin et al. (2006) and Amin et al. (2008) reported growth coefficients of 0.63 yr^{-1} and 0.35 yr^{-1} for *C. virginica* and *C. madrasensis* respectively with maximum observed respective shell heights of 13.7 cm SH and 20.9 cm SH.

In comparing the maximum observed shell heights of oysters from Stations 3, 4a and 4b (10.40 cm, 13.0 cm and 14.6 cm, respectively) with their asymptotic shell heights 14.78 cm, 16.97 cm and 16.28 cm, accordingly. Oysters at Station 4a had relatively higher asymptotic shell height compared to that of Station 4b and the least at Station 3. Perhaps, this observation is the reason why oysters from Station 4a exhibited the lowest growth coefficient. This corroborates the general knowledge that long-lived organisms have a slower growth rate. The anchor time (t_{anchor}) which denotes the fraction of the year where the growth curve crosses shell height equal to zero (Taylor & Mildenberger, 2017) and the summer point (t_s), representing the portion of the

year where the sinusoidal oscillation turns positive of the various sampling stations (Taylor & Mildenberger, 2017) were estimated at different months (i.e., July, June and May for t_{anchor} and September, February and April for t_s at Stations 3, 4a and 4b, respectively).

The intensity of the sinusoidal oscillation (C) was between 0.5 and 0.6 for all the stations indicating that the oysters underwent seasonality, as presented in Figure 28. This could be due to seasonal variation in rainfall, as reported by Henderson (2006) for tropical fish. According to Pauly (1984) and Henderson (2006), $C = 1$ indicates that growth doubles during 'summer' (i.e., increases by 100 %) and becomes zero at 'winter.' In the current study, the estimated growth oscillations for the various sampling stations indicate that there was no cessation in the growth of the oysters even at 'winter' periods (i.e., periods of reduced growth). In other words, growth is increased and decreased by 50 % at 'summer' and 'winter,' respectively.

Although the growth performance indices (Φ') of the various sampling stations appeared to be comparable (Table 9), Station 4b oysters were better than their counterparts at Stations 3 and 4a. This finding agrees with the observations on growth coefficient (K) of the various stations, which was best in Station 4b oysters. The growth coefficient is used as an index of habitat quality. A habitat with high productivity is expected to support a faster growth rate (King, 2007; Osei, 2015). In Bangladesh, Amin et al. (2006) and Amin et al. (2008) reported the growth performance of *C. virginica* and *C. madrasensis* as 2.07 and 2.18, respectively, which is comparable to the current findings.

Oysters at Station 4a exhibited the highest longevity (t_{max}) followed by Stations 3 and 4b (Table 9). The above results concur with the growth

coefficients at the various stations, in that short-lived organisms have a faster growth rate as compared to the long-lived ones.

Mortality assessment of fisheries is essential in fish population dynamics, as indicated by Gayanilo et al. (1989) and Pauly (1984). Mortality estimates from the various sampling stations must be interpreted with caution, in that, the deeper portion of the Delta (St. 4b) was about one-tenth of the size of Station 4a oyster bed. Also, Station 3 oyster bed was about one-third the size of Station 4b. In view of this, should the same fishing mortality be exerted on these sampling stations, Station 3 is likely to be most impacted, followed by Station 4b. It must be mentioned that the fishing mortality estimate at Station 4b might have been greatly impacted upon by the sampling activity since the site is less exploited due to its depth. For Station 3 oysters, at the time of sampling, the population was recovering from an earlier shock due to massive mortality, as mentioned earlier. Therefore the oysters had not grown to marketable size to engender exploitation. Hence the sampling activity was the sole contributor to the fishing mortality at Station 3 (Table 9).

Instantaneous natural mortality (M) was comparable for Stations 4a (1.26 yr^{-1}) and 4b (1.27 yr^{-1}). This could be attributed to the close proximity of these sites hence the propensity to be affected by possibly similar causes of natural mortality (predation, disease, senescence, starvation, etc.). For Station 3 oysters, natural mortality (1.23) contributed less to the total mortality compared to other stations, which is attributable to the impact of the sampling in relation to the size of the station. The instantaneous total mortality estimates were highest at Station 3 and comparable for Stations 4a and 4b, as presented in Figure 29. As explained earlier, the size of the oyster beds at these locations and

pressure from both fishing and natural mortality might have influenced the estimates.

It is observed that the estimated growth and mortality parameters among the stations differ, which could be ascribed to the differential fishing pressures and natural mortalities as well as the sessile nature of oysters. However, the stations share a common pool of oyster larvae, which suggests that the oyster beds at the three stations constitute a stock. For management purposes, it will be prudent to treat each as a unique entity as fishing mortality is not uniform for all the stations (i.e., oyster pickers fish down the nearest oyster beds before proceeding to the distant oyster beds).

Researchers like Beverton (1993) and Hordyk, Ono, Sainsbury, Loneragan and Prince (2015) have used the M/K ratio to estimate the availability of bigger individuals in a given fish population, where the smaller the ratio the higher the number of bigger fish. In this study, the M/K ratio was highest at Station 4a (4.20), followed by Stations 3 (2.86) and then 4b (2.70). In other words, the order of availability of bigger sized oysters relative to their respective size ranges starts from Stations 4b, 3 and 4a. Hordyk et al. (2015) reported that for species that conform to the Beverton-Holt M/K ratio = 1.5, the maximum observed size (MOS) would be approximately $0.95SL_{\infty}$ and for species with $M/K = 2.3$, the MOS is expected to reach about $0.8L_{\infty}$. By extension, M/K values greater than 2.3 should have its MOS lower than $0.8L_{\infty}$. Essentially, species with $M/K = 1.5$ will have a smaller difference between their MOS and asymptotic size compared to species with $M/K = 2.3$ or more. This could explain why in the present study the difference between the MOS (10.40, 13.00 and 14.60 cm SH) and asymptotic shell heights (14.78, 16.97 and 16.28 cm SH) of Stations 3, 4a

and 4b stations, respectively were wide. Moreover, $M/K > 1.5$ indicates that natural mortality exceeds growth. This implies that oysters from the various stations were mortality dominated, which could be attributed to the massive inundation during the spillage from the Weija Dam with its associated low salinity and high turbidity, as evident in this study. That is the oysters failed to reach their full potential, hence the wide gap between MOS and the asymptotic shell height.

Due to the extermination by natural means and the habit of fishing down the oysters at Stations 3 and 4a, respectively, the Thompson and Bell model for yield/biomass per recruits was carried out for only Station 4b oysters (Fig. 30). Generally, the low current exploitation rate ($E_{cur} = 0.31$) which is below $E_{0.5}$ (the exploitation rate at which 50 % of the virgin biomass is harvested) and E_{msy} (the exploitation rate that gives the maximum sustainable yield) of *C. tulipa* in the deep portion of the Densu Delta (Table 10) could be attributed to the difficulty of fishers to dive and handpick the oysters. This finding indicates that the oyster stock at the deep portion of the Densu Delta is underexploited ($E_{cur} < 0.5$). The estimated yield-per-recruit and biomass-per-recruit of Station 4b were 17.84 tonnes and 40.40 tonnes, respectively (Table 10). From the yield-per-recruit and biomass-per-recruit of the Thompson and Bell model using the ELEFAN_GA_boot fit method, it is evident that the current fishing mortality ($F_{cur} = 0.56$) was lower than the fishing mortality that exploits 50 % of the virgin biomass ($F_{0.5} = 0.70$). It should be noted that the marketa ble oysters at the shallow areas of the Densu Delta are fished by the close of the oyster season. Also, the stress imposed on the oysters by the massive freshwater influx from the Weija Dam, with its attendant high turbidity and low salinity present the

deep water oysters an opportunity to replenish the shallow portions with oyster larvae. It is therefore prudent not to exceed the fishing mortality that harvests 50 % of the virgin biomass ($F_{0.5} = 0.70$) in order to safeguard the stocks at the Densu Delta. Oysters are recruited into the fishery all year round with alternating peaks from the shallow and deep portions (Fig. 31); this has the potential of cushioning the population against harsh environmental conditions.

According to Gosling (2015), majority of bivalves are dioecious and the proportion of males and females are usually distributed equally. In tropical oviparous oysters, Angell (1986) documented that *Crassostrea* spp. undergo seasonal changes in sex, which could affect the sex ratio. In this study, generally, the monthly sex ratios did not deviate from unity for all stations except in June and May 2018 at Stations 3 and 4a, respectively (Table 11 to 13).

It has been documented that the sex ratio of adult oyster populations generally conforms to unity (Galtsoff, 1964; Yankson, 1996). However, in Ghana, Obodai (1990) reported that the sex ratios of *C. tulipa* populations in the Benya lagoon and Pra estuary were dominated by females and males, respectively.

According to Newell et al. (1982), marine bivalves may exhibit yearly, semi-annual or continuous reproductive cycle owing to some intrinsic and extrinsic factors. In the current study, active gametogenic activity was observed at the three sampling stations throughout the period. This is characteristic of tropical bivalves, according to Bayne (2017), Galtsoff (1964) and Quayle and Newkirk (1989).

A gonad index (GI) greater than or equal to 2 has been used as an indicator of maximal gonad development in bivalves by Barber, Fajans, Baker

and Baker (2005) and Krampah et al. (2016). The period of gametogenesis is reflected by increasing GI and condition index (CI), but spawning activity significantly reduces the mass of the soft body, and for that matter, causes a reduction in GI and CI (Gosling, 2015; Quayle & Newkirk, 1989). Regarding spawning periodicity in the present study, the GI trend suggests a major spawning activity from December 2017 to February 2018 and a minor spawning from May to June 2018 for oysters at Station 3 (Fig. 36). The CI of oysters at this station corroborated the major and minor spawning periods (Fig. 37). The same can be said of the analysis of gonadal stages (Fig. 33).

For Station 4a oysters, according to the GI analysis, a major spawning activity occurred from January 2018 which protracted to May 2018 and a minor spawning in September 2018 (Fig. 36). A major decline in CI occurred from December 2017 to March and a minor one from September to October 2018 (Fig. 37), which is in line with the GI trend. The analysis of gonadal stages of Station 4a oysters showed a greater proportion of spawning individuals from November to February and intermittent spawning in June, Aug and October 2018 (Fig. 34). These agree with the major spawning months indicated by the GI analysis.

The GI analysis of Station 4b oysters suggested a minor spawning activity in December 2018 which protracted to March 2018, a weaker spawning from May to June 2018 and a major spawning in October 2018. The CI and analysis of gonadal stages (Figs. 37 & 35, respectively) both agreed with the main spawning events presented by the GI, where spawning periods were from November/December 2017 to February 2018 and September to October 2018.

Besides, unlike Station 4b, oysters from the shallow stations (St. 3 and St. 4a) exhibited continuous spawning based on the analyses of gonadal stages. Perhaps, the difference in depth might be a contributing factor. Blay (1990) attributed a year-long gonadal activity of a freshwater mussel, *Aspatharia sinuate* to high temperatures prevailing in a small Nigerian reservoir. In the current study, it was observed that temperature values were high and generally comparable at all stations during the months Station 4b oysters were not spawning (March, April and June 2018). Temperature was probably not the sole determining factor for the spawning of oysters in the Densu Delta.

Essentially, spawning occurred at similar periods for Stations 4a and 4b oysters but with their major spawning occurring at different times. Perhaps, this is a strategy to optimise recruitment.

In this study, both gonad and condition indices of Station 3 oysters were relatively higher than their Stations 4a and 4b counterparts (see Figs. 36 & 37). Moreover, the analyses of gonadal stages of oysters from the various stations agreed with the above observation, where Station 3 oysters showed relatively higher proportions and continuous spawning activity (Figs. 33 to 34). This lends credence to the earlier reasoning that Station 3 oysters exhibited relatively higher reproductive activity before their depletion in July 2018.

According to Gosling (2015), the mechanism of reproduction involves the complex interplay of exogenous factors such as temperature, food, salinity and light, with endogenous factors such as neuro-endocrine cycles and genotype. In this study, there was no significant relationship between the gonad indices of oysters from the various stations and the physico-chemical parameters (temperature, DO, salinity, pH, turbidity, nitrate and phosphate), see

Table 14. However, the predictors explained 43.54 % of the variation in the gonad indices. This result corroborates an earlier finding by Obodai et al. (1994) in studying the seasonal changes of hydrographic parameters and breeding of *C. tulipa* in Benya lagoon (Ghana).

The condition index of oysters from the various stations, on the other hand, had a significant relationship with salinity, pH and phosphate (indirect estimation of food), where the predictors explained 50.63 % of the variations in condition indices (Table 15 & 16). Hickman and Illingworth (1980) reported that seasonal changes in CI result from multifaceted interactions of a variety of factors, including food, temperature and salinity and the metabolic activities particularly growth and reproductive processes.

5.4 Oyster Culture Experiments

The importance of the oyster fishery in providing a source of livelihood for communities in the Densu Delta area justifies the culturing of the species to boost production. In the current study, oysters cultured by suspension method on oyster-shell cultches grew significantly better than their bottom counterparts (Fig. 38). A similar finding was made by Obodai (1997) in investigating the efficiency of suspension and bottom culture methods in the Benya lagoon using coconut-shell cultches. The author attributed the poor growth performance of oysters cultivated by the bottom method to low bulk density of the sediments. As pointed out earlier in this write-up, the estimated bulk density of sediments at Station 4 (0.17 g/cm^3) of the Densu Delta was lower than that of Benya lagoon (0.41 g/cm^3) as reported by Obodai (1997), which was the lowest among the three lagoons he studied in Ghana. This is in line with findings by Cham (1991) and Newkirk (1995), working in the Gambia River and Tam Giang lagoon in

Vietnam, respectively. Therefore, the low bulk density of sediments at the Densu Delta (particularly St. 4) could explain the better growth rates in suspension than at the bottom. Fine sediment particles at the bottom could interfere with filter-feeding and respiration of the bottom oysters and therefore, negatively impact their growth. Quayle (1988) argued that bottom cultured oysters outperform the suspension cultures in water bodies with hard substratum.

Oysters cultivated on both surfaces of the coconut-shell cultches by suspension appeared to grow better than their bottom counterparts but it was not significant (Fig. 38). The difference in the growth performance of oysters cultivated on the coconut-shell and oyster-shell cultches could be attributed to the unique surfaces presented to sedentary fouling organisms. Arakawa (1980) and Quayle (1980) reported that the minute surface sculpture of oyster shells and its hardness present a better setting surface for epibionts. This explains the relatively high number of epibionts observed on the oyster-shells as compared to the coconut-shell cultches in this study, which resonates with Chuku's (2019) finding. Moreover, according to Tanita et al. (1961, as cited in Arakawa, 1990), the colonisation of epibionts, especially the encrusting forms (like sponges and colonial tunicates) on collectors could excite and stimulate shell growth in oysters as they compete for space. Therefore, oysters cultivated on oyster-shell cultches might have been stimulated more than those on coconut-shell cultches due to the greater attachments of epibionts, though the cultches were cleaned and reset on monthly basis. This could explain the difference in growth performance of oysters cultivated on the coconut-shell and oyster-shell cultches with respect to suspension and bottom culture methods.

There was no statistical difference between the survival of oysters cultured by suspension and bottom culture methods on the coconut-shell and oyster-shell cultches (Fig. 39). However, oysters cultivated using the bottom method on both types of cultches experienced massive mortality in July 2018. This suggests that the suspension culture method be preferred to the bottom method. The massive mortality of oysters cultured by the bottom method could be attributed to smothering by sedimentation, as evidenced by high turbidity from June to July 2018 (Fig. 17) caused by massive freshwater input as well as the low bulk density of sediments (Fig. 20). Spencer (2002) and Quayle (1988) documented twice survival rates of oysters cultivated in suspended trays than those cultured on the ground. The difference was ascribed to the soft nature of the bottom sediments.

The identified sedentary biofouling organisms were *Fistubalanus pallidus* (barnacle), *Brachidontes* sp. (mussel), *Ficopomatus* sp. (tube worm), sea anemone and algae (Fig. 40). Asare (2017) and Obodai and Yankson (2000) documented a similar inventory of biofoulers during their respective studies on culturing of *C. tulipa* in three Ghanaian lagoons (Benya, Nakwa and Jange). All the observed biofoulers in this study can filter-feed except the algae, which are primary producers. Therefore competition is expected should there be no food resource partitioning such as different particle size selection and no difference in feeding efficiency among the epibionts (De Sa et al., 2007: Sievers Fitridge, Dempster & Keough, 2013). Some possible adverse impacts of the observed epibionts on oysters include reduced growth rate, mortality, physical disruption to opening and closing of valves, weakened shell and competition for space on cultches (Fitridge et al., 2012; Hopkins, 1937; Quayle, 1980).

Oysters cultivated on the biofouled cultches appeared to exhibit faster mean growth rate than their counterparts on cleaned cultches (Fig. 41). However, the treatments were not statistically significant except for oysters cultured on the concave surface of oyster-shell cultches. Also, there was no significant difference between the survival of oysters cultured on the biofouled and cleaned cultches (Fig. 42). Biofouling has been reported to have a devastating effect on cultured bivalves (Angell, 1980; De Sa et al., 2007; Pit & Southgate, 2003; Watson & Shumway, 2000). The lack of effect of biofouling on the growth of oysters on coconut-shell cultches is consistent with the findings of Obodai and Yankson (2000), where the authors observed no effect of biofouling on *C. tulipa* in three different lagoons (Benya, Nakwa and Jange). Elsewhere, a lack of effect of biofouling on growth and survival has been documented for *C. rhizophorae*, *C. virginica*, and *C. gigas* by Lodeiros, Pico, Prieto, Narváez and Guerra (2002), Mallet et al. (2009) and Royer et al. (2006), respectively. This observation of no impact of biofouling on growth and survival of oysters could be attributed to a number of factors: food resource partitioning, commensalism and stimulated primary production by biofoulers to make up for limited food resources (Dalby & Young, 1993; Lodeiros, Galindo, Buitrago & Himmelman, 2007: Mallet et al., 2009). According to Quayle (1980), growing oysters can withstand a considerable degree of biofouling before they become harmful enough to call for their control.

A positive effect of biofouling has, however, been reported for oysters (Arakawa, 1990; Dalby & Young, 1993) and scallops (Lopez et al., 2000; Pond, 1992). Arakawa reported that oyster farmers believed that a certain amount of biofouling has a beneficial effect on the development of oyster cultivation. The

underside of suspended or floating substrates has been reported to be a better surface for epibionts like oysters, mussels, barnacles, etc. (Chuku, 2019; Glasby & Connell, 2001; Obodai & Yankson, 2000; Quayle & Newkirk, 1989). Chuku (2019) reported that epibionts relatively prefer colonising oyster-shell to coconut-shell collectors. This finding explains the relatively high biofoulers on the concave surface of the oyster-shell cultches observed in the present study. As pointed out earlier, Tanita et al. (1961, as cited in Arakawa, 1990) indicated that the later attachment of biofoulers could stimulate shell growth in oysters in an attempt to cover more space. This could explain the significant growth rate of oysters on the concave surface of biofouled oyster-shell cultches. However, the voluminous block type of biofoulers like barnacles and mussels have been reported to engage in severe competition with cultured oysters leading to a reduced growth rate (Arakawa, 1990).

Oyster growth and survival on biofouled and cleaned cultches at the top and bottom collectors did not show significant difference, i.e., there was no effect of biofouling on oysters cultured on the top and bottom collectors (Figs. 43 & 44). A likely explanation could be that there might be a comparable community of epibionts on the top and bottom collectors, possibly owing to the shallow depth of water column (≈ 0.61 m at high tide), where the experiment was conducted.

Although it has been noted by Obodai (1997) that the oyster population currently studied was heavily fouled during a survey to ascertain the culture potential of the oyster populations along the coast of Ghana, this present study has brought to the fore the innocuous effect of biofouling on the growth and survival performance of the oysters.

5.5 Nutritional Value and Taste Analysis

The literature on proximate analysis of bivalves indicates that the composition of the meat varies considerably within and among species, sexual condition, environment and the time of the year. In the current study, it is seen in both the wild and cultured oyster meat that the order of importance by composition was protein, carbohydrates (soluble), lipid, ash and fibre (insoluble carbohydrates). Galtsoff (1964), reported that *Crassostrea* spp. and *Ostrea* spp. may contain 50 % or more of proteins, and less than 25 % and 20 % carbohydrate and lipids on dry matter basis, respectively. The above is comparable to the current findings except in carbohydrate.

The current comparative proximate analysis of wild and cultured oyster meat is an innovation for *C. tulipa* and oysters in general. The results indicate that the latter compares favourably with the former in terms of moisture and carbohydrates. It is not clear what might have attributed to the significant difference in moisture and carbohydrate content of wild and cultured oyster meat. Protein, lipid, ash and fibre were comparable for wild and cultured oyster meat in the current. It is conspicuous from the results that culturing of oysters in the Densu Delta presented a better nutritional value compared to wild oyster meat.

The current estimations of protein (51.55 ± 0.57 %) and ash (3.04 ± 0.13 %) in the wild oyster meat (Table 17) were lower than that reported by Yankson et al. (1994) in Benya lagoon (59.3 ± 2.2 and 12.7 ± 1.0 %, respectively) and Pra estuary (67.6 ± 2.2 and 14.4 ± 1.6 %, respectively). The present estimations of carbohydrate (32.77 ± 0.09 %) and fat (10.42 ± 0.12 %) in the wild oyster meat were higher than the estimates by Yankson et al. in Benya lagoon (20.0 ±

2.5 and 8.0 ± 0.6 %, respectively) and Pra estuary (8.1 ± 0.4 and 9.8 ± 1.3 %, respectively) but comparable in the case of moisture (between 80 and 83 %) as well as other Bivalvia populations (Krampah, 2016; Prato et al., 2018). However, lower moisture (76 %) has been recorded for *C. gasar* (= *tulipa*) by Ajana (1980) in Nigeria, with its fat contribution to the dry matter higher than protein and carbohydrate. The variation in the proximate composition of oyster species has been attributed to the season of the year and the prevailing environmental condition (mainly salinity) during harvesting, aside from its genetic make-up (Galtsoff, 1964). This could account for the difference in proximate composition in the three oyster populations in Ghana [Densu Delta (current study), Benya lagoon and Pra estuary]. Yankson et al. (1994) followed the monthly changes in the biochemical composition of *C. tulipa* in two populations in Ghana and concluded that the populations compare with other commercial bivalves elsewhere, hence the potential for their industrial-scale production. Since the nutritional value of the cultured oysters compared favourably with their wild counterparts, it is rational to venture into mass cultivation of *C. tulipa* in the Densu Delta to help address the fish demand gap as well as protein deficiency in Ghana.

The taste evaluation of wild and cultured oyster meat in the current study is an advancement in oyster research in West Africa, which indicated that consumers preferred the latter to the former (Table 18). According to Cochet, Brown, Kube, Elliott and Delahunty (2015), the proximate composition, mainly lipids and glycogen of oyster meat can directly impact on the flavour or indirectly by interacting with other nutrients that have a direct influence on taste. Moreover, it has been reported by Quayle (1980), Quayle and Newkirk (1989)

and Gosling (2015), that the unique oyster flavour is obtained from its glycogen content. In other words, oysters are best enjoyed during periods of high glycogen concentration. This is the period oysters store energy (carbohydrate) in the form of glycogen to fuel the production of gametes and some of the glycogen is converted into lipid, which becomes the energy reserve for the oyster larvae (Angell, 1988; Quayle & Newkirk, 1989). The finding on proximate analysis of wild and cultured oyster meat in this study (Table 17), where carbohydrate (glycogen) was significantly higher in the cultured oyster meat could explain its better taste.

Cochet et al. (2015) reported that the most influential factors that affect the organoleptic characteristics of shellfish are the type of species, harvest location, season, size, gender and growth method (cultured or wild). Similarly, Edmunds and Lillard (1979) reported that cultured shrimps were preferred over wild shrimps. Also, cultured salmon (a finfish) was found superior to troll-caught salmon in terms of taste analysis at the Sea Fare Exposition at Long Beach, California (Anonymous, 1989 as cited in Sylvia, Morrissey, Graham, & Garcia, 1995). However, generally, the literature on organoleptic studies reported the preference of wild fish to cultured fish (Sylvia et al., 1995) while other works reported comparable results (Azpeitia, Rios, Garcia, Pagaldai & Mendiola, 2017; Gokoglu, 2002). The better taste of the cultured oysters in the present study could be a promotion factor to support the commercial production of *C. tulipa* in Ghana.

CHAPTER SIX

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY

The primary goal of the study was to investigate the oyster fishery, aspects of the biology, and some methods for culturing the mangrove oyster, *Crassostrea tulipa* in the Densu Delta, Ghana. For the socioeconomics of the Densu Delta oyster fishery, information on the demography of fisherfolk, oyster exploitation and profitability are presented. The study also presents monthly variations in temperature, dissolved oxygen, salinity, pH, turbidity, nitrate and phosphate concentrations, as well as an estimation of bulk density of sediments. Correlations between breeding and these physico-chemical parameters as well as that of the oyster condition were established. Data on population density, growth, mortality, exploitation rate and recruitment pattern of the oyster fishery with respect to three oyster beds are provided. Information on the reproductive biology and condition index with respect to the three oyster subpopulations are presented. To ascertain the suitability of culture methods, information on oyster growth and survival on suspension and bottom cultures as well as biofouling with respect to the surfaces of coconut-shell and oyster-shell cultches were obtained through experimentation. To promote oyster culture and the popularity of oyster meat, comparisons of the proximate value and taste of wild and cultured oyster meat were undertaken.

6.2 CONCLUSIONS

The economic assessment of the *C. tulipa* fishery in the Densu Delta showed that the estimated annual yield and its appraised value were 294.8 tonnes and GHS 286,650 (USD 65,559), respectively. The total annual cost of

fishing, gross annual income and total annual profit were estimated at GHS 52,018 (USD 11,897), GHS 174,867 (USD 39,993) and GHS 122,850 (USD 28,097), respectively. On the demography, a majority (97 %) of the fisherfolk interviewed were females and 3 % were males, with 35 - 44 years being the modal age group. Married persons were the dominant group (71 %). About 57 % and 37 % of the interviewees had dependants ranging between 1 - 4 and 5 – 9, respectively. Approximately 76 % of the respondents dropped out of Primary school or had no formal education. Fishers of the Ewe tribe dominated the fishery constituting about 86 %, followed by the fishers of the Ga tribe (13 %). The livelihoods of the respondents were mainly fishery-related (76 %). About 92 % of the fishers were engaged in all the three components (harvesting, processing and marketing) of the oyster fishery. A higher proportion (29 %) of the respondents had up to 4 years of experience and a few (8.2 %) over 20 years. Exploitation of the oyster resource was unregulated and had unrestricted access; its peak season was from April to September.

None of the physico-chemical parameters influenced the breeding pattern of *C. tulipa*, while condition index of the oysters was significantly affected by salinity, pH and phosphate concentration.

The population densities of *C. tulipa* in the Densu Delta ranged from 36 ± 8.3 to 1648 ± 93.8 ind/m^2. Generally, the oysters exhibited negative allometry and growth was found to be seasonal. The oysters at the shallow portions (0.61 m depth) were depleted by the close of the fishing season, while oysters at the deep portion (2.13 m depth) of the Densu Delta were underexploited. Oysters were recruited into the fishery all-year-round, with a peak from May to July at

the shallow portions and in the deeper area, higher recruits occurred in January and February as well as in September.

Generally, the monthly sex ratios of *C. tulipa* in the Densu Delta were not significantly different from unity. Oysters from the shallow portions of the Delta showed continuous spawning while that of the deep portions was intermittent. The condition indices generally resonated with the breeding patterns.

The growth and survival performance of *C. tulipa* were better using the suspension method than the bottom method.

Biofouling had no detrimental effect on the growth and survival of *C. tulipa* but rather may be advantageous when cultured on oyster-shell cultches.

A comparison of the proximate composition of wild and cultured *C. tulipa* indicated that cultured oysters had a significantly higher composition of carbohydrate and moisture than wild oysters, with comparable protein, lipids, ash and fibre constituents. Oyster tasters preferred cultured oyster meat to wild oyster meat.

6.3 RECOMMENDATIONS

The following are recommendations drawn from the study:

1. The oyster fishery in the Densu Delta should be regulated and promoted by means of value addition to maximise profit.
2. About the culture of oysters in the Densu Delta, the water spillage from the Weija Dam, which occurs during the main rainy season is the major threat. Nonetheless, culturing could be undertaken during the lean oyster

season (from October to April/May) prior to the spillage from the dam to optimise yield.

3. Large-scale cultivation of oysters should be undertaken by individuals and corporate bodies since the necessary information needed for culturing the species and ready market are available.
4. The suspension culture method should be adopted for the cultivation of oysters in the Densu Delta and other water bodies with low sediment bulk density.
5. Oyster-shell collectors should be used in the cultivation of *C. tulipa* in the Densu Delta because of its durability and ability to support the growth and survival of oysters better than the coconut-shell cultches.
6. There is no need to get rid of biofoulers in the cultivation of oysters in the Densu Delta, because of the lack of negative effect of fouling organisms.

To further support the large-scale cultivation of oysters, the following recommendations for future studies are made:

1. An investigation into the taste characteristics of wild and cultured oyster meat.
2. A study on the quantity and quality of meat production of oysters cultivated on biofouled and cleaned cultches.
3. Estimation of the current yield of all oyster fisheries in Ghana to give a comprehensive idea of its contribution to the overall capture fisheries.
4. A study on the feeding ecology of oysters.

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APPENDICES

Appendix A: Interview Guide for the Socioeconomic Assessment of the Oyster Fishery in the Densu Delta

UNIVERSITY OF CAPE COAST

DEPARTMENT OF FISHERIES AND AQUATIC SCIENCES

SOCIOECONOMIC ASSESSMENT OF (*CRASSOSTREA TULIPA*)

FISHERY IN THE DENSU DELTA, GHANA

FISHERY INTERVIEW GUIDE

I am Isaac Kofi Osei, a PhD student of the University of Cape Coast of the Department of Fisheries and Aquatic Sciences conducting a survey on the Socioeconomics assessment of the oyster fishery in the Densu Delta. I would be grateful if you could respond to the following questions. Information provided by respondents will be treated confidentially and will be used for academic purposes, published as well as provide the basis for sustainable management of the oyster fishery. Thank you for agreeing to be interviewed.

Participant's name: **Date:**

A. BACKGROUND INFORMATION

1. Age .....
2. Gender: Male [ ] Female [ ]
3. Marital status: Single [ ] Married [ ] Divorced [ ] Widowed [ ]
4. How many spouses do you have?.....
5. Level of formal education: None [ ] Primary [ ] Middle/JSS [ ] Secondary/SSS [ ] Tertiary [ ]
6. Origin: Native [ ] Migrant [ ] Settler [ ]

7. Which ethnic group do you belong?.....

8. What is the size of your household?.....

9. Number of dependants in your household?.....

B. EXPERIENCE IN THE OYSTER FISHERY

10. What role do you play in the oyster fishery? Harvester [ ] Processor [ ] Marketer [ ]

11. Is **harvesting/ processing/ marketing** of oysters your main source of income? Yes [ ] No [ ]

a) If yes, how long have you been in the business?..... .....

b) If no, what other work do you engage in?.....

12. Are there any cooperative groups or associations in the oyster fishery? Yes [ ] No [ ]

a) If yes

i) How many are they?.....

ii) Are you a member of any? Yes [ ] No [ ]

iii) Explain if no?.....

iv) What is the purpose of the association?.....

C. HARVESTING

13. Do you need a permit to harvest oysters? Yes [ ] No [ ]

a) If yes, who gives the permit?.....

14. Are there any regulations on the fishery? Yes [ ] No [ ]

a) If yes, what are some of the regulations?.....

15. Are there any taboos and customs associated with the oyster fishery? Yes [ ] No [ ]

a) If yes, mention them?.....

16. How do you harvest the oysters?.....

17. Do you harvest oysters year-round? Yes [ ] No [ ]

18. Is there a restriction on the size of oysters harvested? Yes [ ] No [ ]

    a) If yes, what is the minimum size allowed?.....

19. Is there any restriction on the number of basins one can harvest in a day/week? Yes[ ] No[ ]

    a) If yes, what is the number of basins allowed?.....

20. Do you have off-day(s) for harvesting oysters? Yes [ ] No [ ]

    a) If yes, what is/are the off-day(s)?.....

21. Do your children assist in the harvesting? Yes [ ] No [ ] Not applicabl e [ ]

    a) If yes, how many children?.....

22. How much does it cost to harvest oysters in a day?.....

23. Have you had any support from any organisation (Banks, Government, NGOs)? Yes[ ] No[ ]

    a) If yes, what kind of support?.....

D. PROCESSING (Circle letter, if not applicable)

24. In what forms do you process the oyster meat for market?.....

25. Why do you process the oyster meat in this form?.....

26. What is the cost of processing oysters per a trip?.....

27. Are there any taboos about oyster processing? Yes [ ] No [ ]

    a) If yes, mention?.....

E. MARKETING (Circle letter, if not applicable)

28. In which form(s) do you sell the oysters?.....

29. How much does it cost you to market oysters in a day?.....

30. How much will you sell a basin of shucked oysters?.....

31. How much will you sell a basin of shell-on oysters?.....

32. Who are your main customers? Restaurants [ ] Individuals [ ] Schools [ ] Others [ ]

F. CATCH AND EFFORT

Preamble: During the middle of the oyster fishery (6 months)

33. How many hours do you spend on collecting oysters?.....

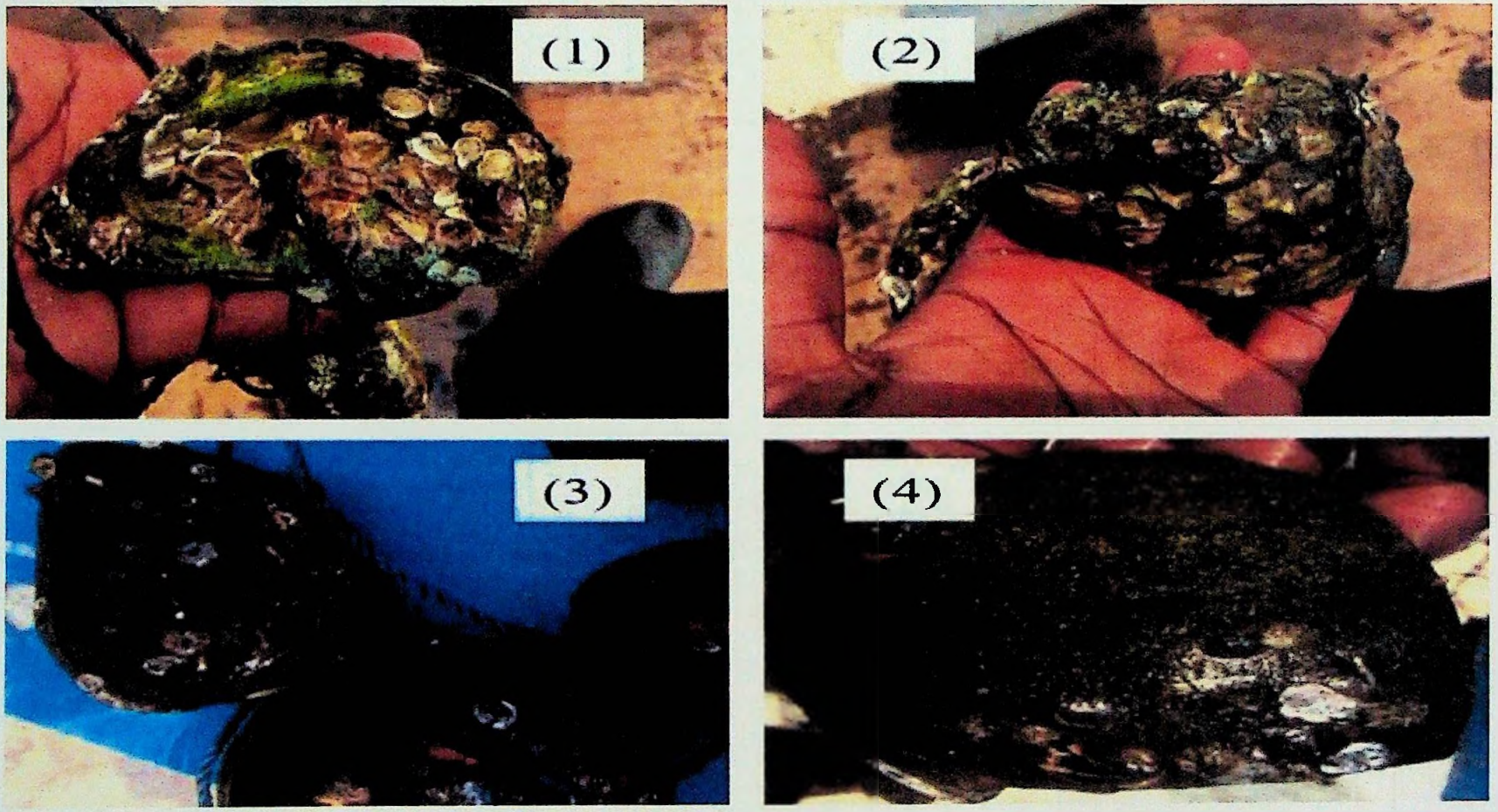
34. How many basins/baskets do you harvest within hours stated?.....

35. How many days in a week do you usually pick oysters?..... .....

36. How many people go fishing in a day?.....

Appendix B: Photographs showing (1) an oyster bed at the shallow portion during low tide, (2) deep portion, (3) fishers picking oysters at high tide and (4) a cluster of oysters cemented together

Appendix C: Photographs of oyster spat on the concave (1); convex (2) sides of oyster-shell; concave (3) and convex (4) sides of coconut-shell collectors prior to thinning-out



Appendix D: Field Data sheets for Suspension and Bottom culture and Biofouling Experiments

Appendix D1: Suspension and Bottom Experiment Data Sheet for Growth

	STATION:				DATE:			
	SUSPENSION CULTURE				BOTTOM CULTURE			
SP	CS-CV	CS-CC	OS-CV	OS-CC	CS-CV	CS-CC	OS-CV	OS-CC
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								
22								
23								
24								
25								
26								
27								
28								
29								
30								

*CS = Coconut-shell; OS = Oyster-shell; CV = convex; CC = concave

* Entries 1-6 are for 1st collector; 7-12 go for 2nd collector etc. for the 5 collectors for a given cultch.

Appendix D2: Suspension and Bottom Experiment Data Sheet for Survival

STATION: DATE:

CULTCH	SPAT COUNTS-SURVIVAL							
	SUSPENSION CULTURE				BOTTOM CULTURE			
	CS-CV	CS-CC	OS-CV	OS-CC	CS-CV	CS-CC	OS-CV	OS-CC
1								
2								
3								
4								
5								
6								
7								
8								

*CS = Coconut-shell; OS = Oyster-shell; CV = convex; CC = concave

*Each entry say 'A' is further divided into 5 boxes, each for the counts of spat/oysters on a given surface of a collector (i.e. 1st collector, 2nd collector…) in that order.

Appendix D3: Biofouling Experiment Data Sheet for Growth

	STATION:				DATE:			
	BIOFOULED CULTCHES				CLEANED CULTCHES			
SP	CS-CV	CS-CC	OS-CV	OS-CC	CS-CV	CS-CC	OS-CV	OS-CC
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
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27								
28								
29								
30								

*CS = Coconut-shell; OS = Oyster-shell; CV = convex; CC = concave

* Entries 1-6 are for 1st collector; 7-12 go for 2nd collector etc. for the 5 collectors for a given cultch.

Appendix D4: Biofouling Experiment Data Sheet for Survival

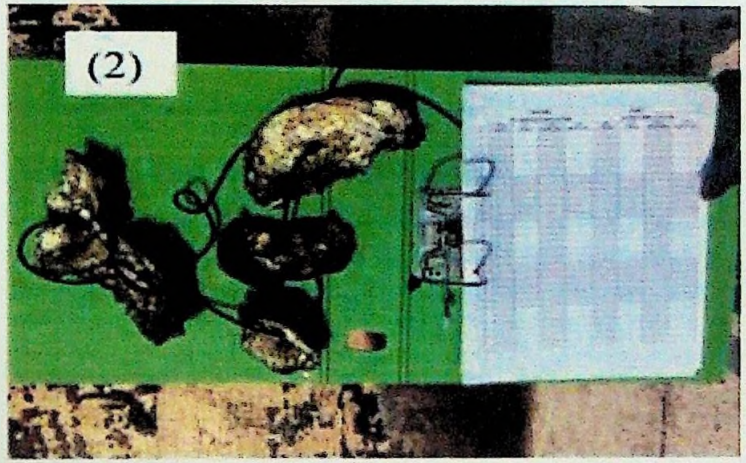
STATION: DATE:

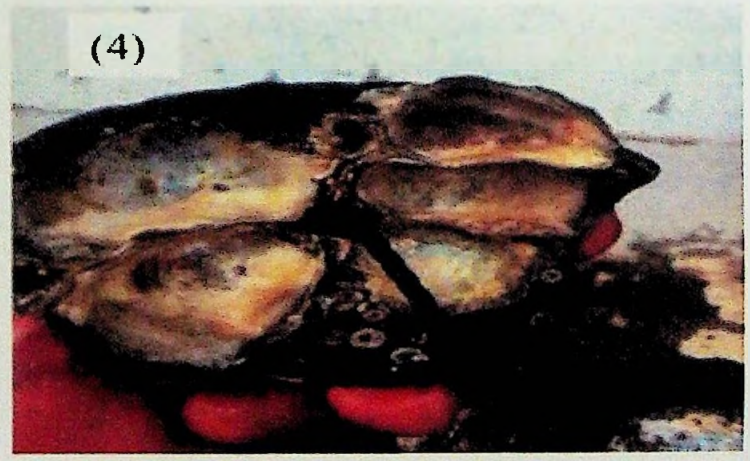
CULTCH	SPAT COUNTS-SURVIVAL							
	BIO-FOULED CULTCHES-SUSPENSION				CLEANED CULTCHES-SUSPENSION			
	CS-CV	CS-CC	OS-CV	OS-CC	CS-CV	CS-CC	OS-CV	OS-CC
1								
2								
3								
4								
5								
6								
7								
8								

*CS = Coconut-shell; OS = Oyster-shell; CV = convex; CC = concave

*Each entry say 'A' is further divided into 5 boxes, each for the counts of spat/oysters on a given surface of a collector (i.e. 1st collector, 2nd collector…) in that order.

Appendix E: Photographs of (1) submerged cultches during high tide at Station 4a (2) data sheet and an oyster-shell cultch with spat (3) last coconut-shell collector with 5 knots, indicated as red dots (4) dead cultured oysters





Appendix F: Growth Rates (GR) of *Crassostrea tulipa* Cultivated on the Convex and Concave Surfaces of Coconut-shell and Oyster-shell Cultches using the Suspension and Bottom Culture Methods

Appendix F1: Convex Surface of Coconut-shell Cultches

	Suspension	Bottom			Suspension	Bottom
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J, 2018	0.33	0.43	0.03	0.03		
F	1.93	1.99	0.08	0.1	1.6	1.56
M	3.08	2.54	0.08	0.09	1.15	0.55
A	3.58	3.53	0.1	0.12	0.47	0.93
M	4.13	4.16	0.1	0.11	0.55	0.63
J	4.77	4.41	0.1	0.13	0.69	0.27
J	5.15		0.09			
				SE	**0.21**	**0.22**
				Mean	**0.89**	**0.79**

Appendix F2: Concave Surface of Coconut-shell Cultches

	Suspension	Bottom			Suspension	Bottom
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.36	0.41	0.02	0.02		
F	2.15	2.27	0.08	0.08	1.79	1.86
M	3	3.5	0.1	0.1	0.85	1.23
A	3.96	4.14	0.09	0.09	0.90	0.60
M	4.25	4.386	0.1	0.1	0.29	0.25
J	4.89	4.74	0.11	0.12	0.69	0.38
J	5.04		0.12			
				SE	**0.25**	**0.30**
				Mean	**0.90**	**0.86**

Appendix F3: Convex Surface of Oyster-shell Cultches

	Suspension	Bottom			Suspension	Bottom
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.43	0.54	0.05	0.03		
F	2.25	2.11	0.07	0.07	1.82	1.57
M	3.43	2.88	0.09	0.08	1.18	0.77
A	4.57	3.79	0.12	0.08	1.07	0.85
M	5.03	4.46	0.15	0.11	0.46	0.67
J	5.55	4.6	0.14	0.14	0.57	0.15
J	5.56		0.1			
				SE	**0.24**	**0.23**
				Mean	**1.02**	**0.80**

Appendix F4: Concave Surface of Oyster-shell Cultches

	Suspension	Bottom			Suspension	Bottom
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.52	0.6	0.05	0.04		
F	2.35	2.17	0.07	0.07	1.83	1.57
M	3.3	2.97	0.09	0.12	0.95	0.8
A	4.57	3.94	0.12	0.11	1.19	0.91
M	5.09	4.57	0.15	0.12	0.52	0.63
J	5.58	4.68	0.14	0.14	0.53	0.12
J	5.59		0.14			
				SE	**0.24**	**0.23**
				Mean	**1.00**	**0.80**

Appendix G: Growth Rates (GR) of *Crassostrea tulipa* Cultivated on the Convex and Concave Surfaces of Biofouled and Cleaned Coconut-shell and Oyster-shell Cultches using the Suspension Culture Method

Appendix G1: Convex Surface of Coconut-shell Cultches

	Biofouled	Cleaned			Biofouled	Cleaned
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.42	0.41	0.04	0.02		
F	1.87	2.03	0.11	0.1	1.45	1.62
M	3.09	3.09	0.15	0.12	1.22	1.06
A	4.12	3.61	0.15	0.15	0.96	0.49
M	4.62	4.22	0.16	0.15	0.5	0.61
J	5.05	4.87	0.14	0.18	0.46	0.70
J	5.38	5.1	0.15	0.13	0.31	0.21
				SE	**0.19**	**0.20**
				Mean	**0.82**	**0.78**

Appendix G2: Concave Surface of Coconut-shell Cultches

	Biofouled	Cleaned			Biofouled	Cleaned
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.55	0.47	0.06	0.04		
F	2.17	2.34	0.11	0.13	1.62	1.87
M	3.26	2.63	0.17	0.18	1.09	0.29
A	4.1	4.24	0.13	0.14	0.79	1.50
M	4.72	4.39	0.13	0.1	0.62	0.15
J	5.01	5.07	0.14	0.17	0.31	0.73
J	5.22	5.14	0.1	0.15	0.20	0.07
				SE	**0.22**	**0.43**
				Mean	**1.03**	**0.95**

Appendix G3: Convex Surface of Oyster-shell Cultches

	Biofouled	Cleaned			Biofouled	Cleaned
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.47	0.49	0.05	0.04		
F	2.16	2.29	0.06	0.09	1.69	1.8
M	3.18	3.27	0.09	0.123	1.02	0.98
A	4.29	4.33	0.11	0.13	1.04	0.99
M	4.87	5	0.14	0.13	0.58	0.67
J	5.5	5.49	0.12	0.15	0.7	0.54
J	5.55	5.56	0.09	0.09	0.05	0.07
				SE	**0.22**	**0.24**
				Mean	**0.85**	**0.84**

Appendix G4: Concave Surface of Oyster-shell Cultches

	Biofouled	Cleaned			Biofouled	Cleaned
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.53	0.61	0.05	0.04		
F	2.37	2.39	0.08	0.09	1.84	1.78
M	3.41	3.5	0.09	0.13	1.04	1.11
A	4.44	4.48	0.15	0.12	0.96	0.92
M	5.47	5.03	0.14	0.1	1.03	0.55
J	5.71	5.33	0.16	0.11	0.26	0.32
J	5.8	5.54	0.15	0.1	0.08	0.20
				SE	**0.26**	**0.24**
				Mean	**0.87**	**0.81**

Appendix H: Growth Rates (GR) of *Crassostrea tulipa* Cultivated on the Top-2-collectors and Bottom-2-collectors of Biofouled and Cleaned Coconut-shell and Oyster-shell Cultches using the Suspension Culture Method

Appendix H1: Top-2-collectors of Coconut-shell Cultches

	Biofouled	Cleaned			Biofouled	Cleaned
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.28	0.3	0.03	0.07		
F	1.5	1.61	0.1	0.13	1.22	1.31
M	2.41	2.13	0.12	0.15	0.91	0.52
A	3.54	3.39	0.11	0.17	1.06	1.18
M	4.28	3.93	0.13	0.21	0.74	0.54
J	4.69	4.47	0.13	0.19	0.44	0.58
J	4.93	4.79	0.11	0.13	0.22	0.30
				SE	**0.10**	**0.21**
				Mean	**0.77**	**0.74**

Appendix H2: Bottom-2-collectors of Coconut-shell Cultches

	Biofouled	Cleaned			Biofouled	Cleaned
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.66	0.57	0.06	0.04		
F	2.37	2.56	0.09	0.1	1.71	1.99
M	3.85	3.47	0.12	0.2	1.48	0.91
A	4.46	4.58	0.13	0.19	0.57	1.04
M	4.81	4.67	0.15	0.17	0.35	0.09
J	5.12	5.3	0.13	0.27	0.33	0.68
J	5.24	5.32	0.08	0.21	0.11	0.02
				SE	**0.27**	**0.29**
				Mean	**0.76**	**0.79**

Appendix H3: Top-2-collectors of Oyster-shell Cultches

	Biofouled	Cleaned			Biofouled	Cleaned
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.34	0.34	0.03	0.02		
F	2.02	1.93	0.05	0.07	1.68	1.59
M	3	2.92	0.1	0.12	0.98	0.99
A	3.9	3.94	0.13	0.1	0.84	0.95
M	4.59	4.77	0.13	0.14	0.69	0.83
J	5.21	5.25	0.13	0.12	0.67	0.52
J	5.36	5.48	0.16	0.13	0.14	0.21
				SE	**0.21**	**0.19**
				Mean	**0.83**	**0.85**

Appendix H4: Bottom-2-collectors of Oyster-shell Cultches

	Biofouled	Cleaned			Biofouled	Cleaned
MONTH	Mean SH	Mean SH	SE	SE	GR (cm/m)	GR (cm/m)
J,2018	0.68	0.73	0.06	0.03		
F	2.43	2.78	0.08	0.07	1.75	2.05
M	3.51	3.84	0.08	0.12	1.08	1.06
A	4.74	4.89	0.14	0.12	1.15	0.98
M	5.53	5.04	0.13	0.09	0.79	0.15
J	5.86	5.29	0.13	0.12	0.35	0.27
J	5.83	5.6	0.12	0.1	-0.03	0.33
				SE	**0.26**	**0.29**
				Mean	**0.85**	**0.81**

Appendix I: Proximate Analysis of Wild and Cultured Oysters

Sample	% Moisture	% Protein	% CHO	% Lipids	% Ash	% Fibre
Wild	80.98	51.30	32.60	10.65	3.25	2.18
Wild	80.68	52.64	32.86	10.22	2.81	1.61
Wild	79.96	50.72	32.85	10.40	3.08	2.14
Cultured	82.95	51.96	36.96	10.54	3.33	1.70
Cultured	82.22	51.23	36.96	10.67	2.71	1.60
Cultured	82.66	51.61	36.55	10.22	3.35	1.49
T-statistic	5.59	0.07	25.24	0.29	0.75	1.96
p value	0.001*	0.95	0.001*	0.79	0.75	0.19

*Significant values